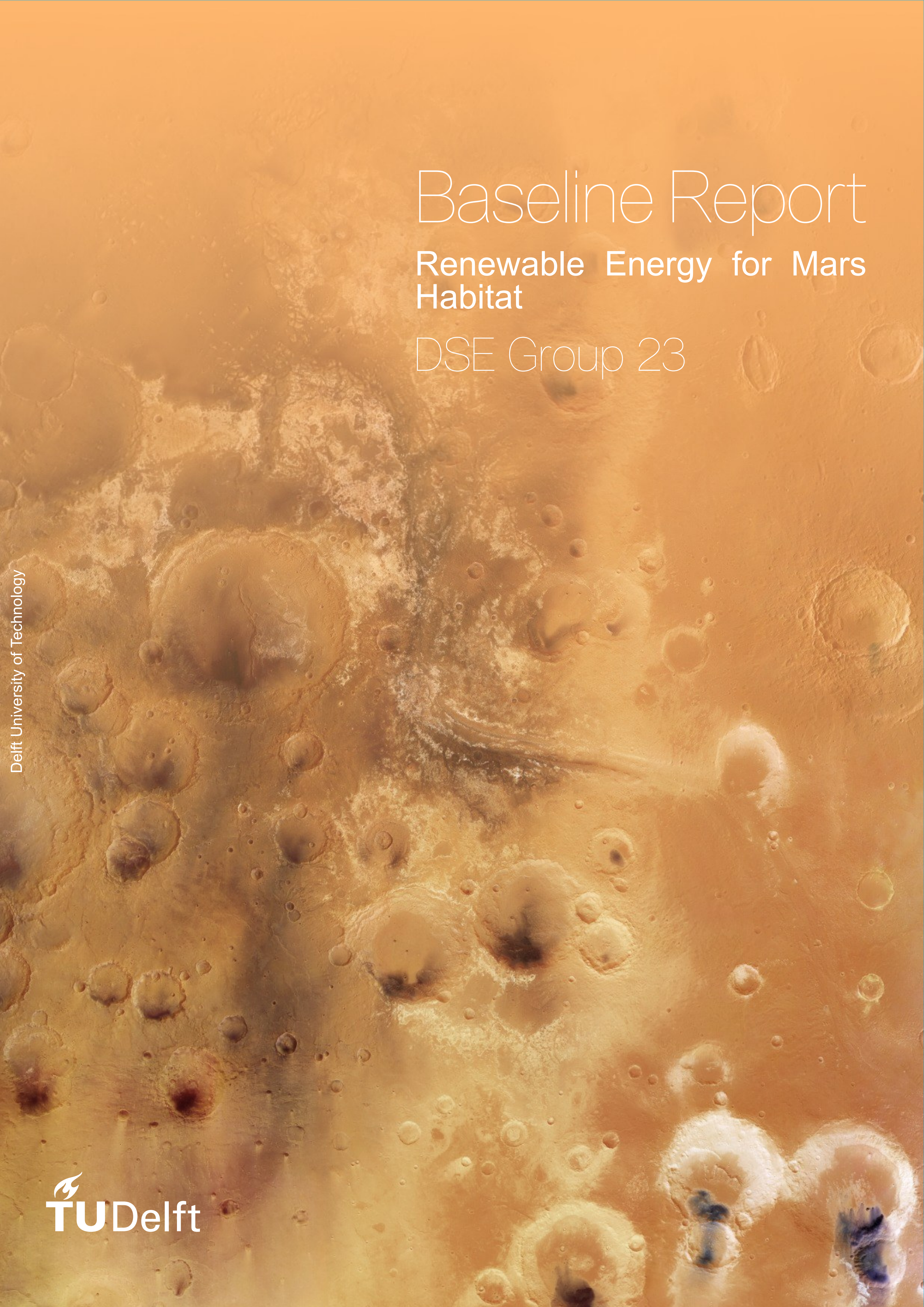


Baseline Report

Renewable Energy for Mars Habitat

DSE Group 23

Delft University of Technology

TU Delft

Baseline Report

Renewable Energy for Mars Habitat

by

DSE Group 23

Tutor:	Dr.-Ing. R. Schmehl	
Coaches:	Prof. Dr. D. A. von Terzi	
	Dr. B. V. S. Jyoti	
	C. Belo Gomes Brito, MSc.	
Students:	F. Corte Vargas	4674529
	M. Géczi	4650379
	S. Heidweiller	4476468
	M. Kempers	4542509
	B. J. Klootwijk	4551516
	F. van Marion	4664965
	D. Mordasov	4658760
	L. H. Ouroumova	4681797
	E. N. Terwindt	4543548
	D. Witte	4670302

Delft University of Technology
Faculty of Aerospace Engineering

May 13, 2020

TUDelft

Contents

Nomenclature

List of Abbreviations

ATES	Aquifer Thermal Energy Storage
AWE	Airborne Wind Energy
BTES	Borehole Thermal Energy Storage
CPV	Concentrator Photovoltaics
CRM	Continuous Risk Management
DOT	Design Option Tree
DSE	Design Synthesis Exercise
EDL	Entry, Descent and Landing
FBS	Functional Breakdown Structure
FFD	Functional Flow Diagram
HAWT	Horizontal Axis Wind Turbine
HGSH	Horizontal Ground Source Heat
HVAC	High Voltage Alternating current
HVDC	High Voltage Direct current
ISRU	In-Situ Resource Utilisation
LVAC	Low Voltage Alternating current
LVDC	Low Voltage Direct current
PEI	Power Electronic Interface
RFB	Redox Flow Battery
RFC	Regenerative Fuel Cell
S/C	Spacecraft
SMES	Superconducting Magnetic Energy Storage
SWOT	Strengths, Weaknesses, Opportunities and Threats
TRA	Technical Risk Assessment
TRL	Technology Readiness Level
VAWT	Vertical Axis Wind Turbine

1

Executive Overview

The Challenge

In recent years, interest in the colonisation of Mars has seen a substantial increase. The reasons behind this is that the space industry has nowadays been increasingly democratised. However, the human species is still yet to set foot on the Red Planet. Following the technological and investment trends, this might only be a question of time. Although the interplanetary travel from Earth to Mars is a quite lengthy, extremely costly and very limited process, the Red Planet still shows great potential for harbouring life. Moreover, evidence has shown that the presence of usable resources on Mars could pave the way to enable continuous human presence in an interplanetary scale. However, energy is nowadays an inescapable necessity for life and for every aspect of functioning society, and it becomes only more necessary when we talk about creating a new branch of an extraterrestrial society on Mars. The "essential-to-life" availability of energy will thus be a key indicator of our success as a species in the colonisation of Mars.

The Solution

A team of students and staff from the faculty of Aerospace Engineering of the Delft University of Technology was formed to undergo a rigorous 10-week Design Synthesis Exercise (DSE) to propose a solution to this problem. The objective of this project is to design a renewable energy system to power the construction as well as the operation of a Mars habitat. The energy system consists of a power grid of complementary renewable energy sources *sustainably* harvested from the local environment and resources to keep the weight budget to a minimum. The project will feature a fully operative 10 kW power system to be integrated and usable for the Martian habitat, in collaboration with a separate team of Architecture students working on a autarkic rhizomatic Mars habitat project for a ESA-ESTEC feasibility study proposal [12]. This means that the work and technical insights of the DSE team will directly influence a more developed, multi-disciplinary mission proposal. This lays the foundation for the motivation to produce a complete, reliable, and highly-detailed design concept as the outcome of the DSE.

The Design

Several things are required to ensure a design that is able to fulfil its purpose. First, a Mission Need Statement (MNS) and a Project Objective Statement (POS) were generated in the project plan, to define exactly what the system needed to do. Both statements are shown below.

MNS: To provide continuous renewable energy supply of 10 kW to a Mars habitat.

POS: 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.

From these statements a requirement list is formed in this baseline report, which includes all the top-level requirements and its child requirements which should be focused on during the design. The most important top-level requirements are that the system should provide a total power of 10 kW to the Mars habitat continuously, its primary energy system shall focus on wind energy and it shall have a lifetime of at least 5 Martian years (i.e. 9.41 years on Earth). Also the primary energy system shall only weigh 200 kg, shall fit in a volume of 3 m^3 and each consecutive payload shall have a maximum mass of 800 kg. And last but not least, the primary energy system shall generate at least 50% of the annual energy production (AEP).

A design needs to be made for the primary energy system, the secondary energy system, the energy storage system and the power management system, that is able to adhere to these requirements. The baseline report is centred around the conceptual part of the design process. A design option tree (DOT) is made to visualise all the options that are available for these systems, it also covers the design considerations for the Mars site location. This DOT is used to eliminate all clearly unfeasible concepts.
For the primary energy system, which will use wind energy as its source, one of the possibilities is using airborne wind energy (AWE), because this technology seems promising when holding them against the top-level requirements (especially the weight and transportation volume requirements). An inflatable spherically shaped vertical axis wind turbine also shows potential and will also be researched further in later design stages. Possible concepts for the secondary energy system are either solar energy, geothermal energy or a combination of the two. For the solar energy system several options are deemed feasible, crystalline silicon (c-Si) solar arrays, multi-junction solar arrays and any other solar arrays using III-V solar cell technology are all found to be good concepts for this mission. On module-level, there are also three feasible concepts, a conventional module, a thin-film module and concentrator photovoltaics. For the solar array orientation, both 1 axis and 2 axis rotation are considered possible. Also certain design options are made for dust accumulation, hydrophobic coating, electrostatic coating, robotic removal, air blowing and removable covers are all feasible concepts for removal of dust from the solar panels. Several options are present for the geothermal energy system, the most simple one being the direct dry steam cycle, another one using the flash cycle and the third one a binary cycle. Many concepts are considered for the energy storage and only a couple will be researched more in later design stages. The following concepts remain for the final trade-off, compressed air storage, lifted storage, secondary batteries, Regenerative Fuel Cells, latent thermal storage, BTES geothermal storage and ATES geothermal storage are all still considered to be feasible options. Finally, for the microgrid some concepts are checked. For transmission, AC and DC are possible and for cable infrastructure, underground, on ground and overhead are all feasible options.

Any combination of these concepts could become the final design and further research is required to find out which will make it through the final trade-off and which will not.

Operations

After the design is finalised, the payload needs to be manufactured, transported to Mars, integrated and operated on Mars, and finally decommissioned at its end of life. To visualise all actions necessary for a successful mission, a functional breakdown structure (FBS) and a functional flow diagram (FFD) are made. Seven functions are stated in the FBS:

1. Manufacture payload
2. Transport payload
3. Perform basic energy system integration on Mars
4. Manufacture on-site structures
5. Perform complete system integration on Mars
6. Operate energy systems
7. Perform communication

All of these functions are further broken down into sub-functions, which represent all the actions required to fulfil these top-level functions. Afterwards, the FFD is made to show the flow of these functions throughout the process, so the order in which the functions will be performed.

Risk Assessment

A range of risk aspects of the project is analysed. Cost risk is the risk associated with achieving unit cost, and life-cycle cost objectives. Schedule risk is associated with not adequately estimating and allocating time for the project or the mission. Technological risks belong to the underpinning technology is not ready within the required time frame. Technical risk refers to risks associated with not reaching required performance due to technological risks. And lastly, programmatic risk, the risk associated with action or inaction from an entity outside the project. The key risks considered in this DSE are, ranked by likelihood and impact metrics;

- OP-3: Power generation system fails
- OP-5: Power distribution system fails
- LA-2: Launcher program cancelled

The team has decided upon 4 risk mitigation procedures. *Accept* states that the risk is either within a tolerable level or the group has no influence over it as it originates from the outside. *Mitigate* means actions can be taken after the risk has happened to reduce the repercussions. *Watch* implies that the risk can be monitored and a contingency plan can be developed. *Research* refers to the process of prior research can be conducted in order to understand the driver of the risk better and reduce the uncertainties to avoid it. For instance, that the payload has to land to carry out the mission thus all actions have to be taken avoid these risks. The mitigation strategies for the above mentioned risks are highlighted below. The second bullet points consolidates the contingency management plan for the respective risks.

- OP-3: Mitigation: To be completed when the subsystems are decided on in the design phase.
- OP-4: Mitigation: same as OP-3
- LA-2: Accept: Companies launching to Mars are not abundant currently, but later possibly many will provide a launcher platform.

Market

Market analysis is a critical effort required to determine the financial sustainability of the Renewable Energy on Mars project. For the longevity and overall success of the project, it is key to be informed about the market and identify its potential segments. The key partners the team considers are EU administration (ESA), launch and launch site operators and the energy system manufacturer. The study also informed the team to consider new requirements based on cost functions and other demands by the competitive market.

On Earth, energy is the biggest industry, valued at over 7.7 trillion euros with a compounded annual growth rate of 4.1% in 2018. The development of space-derived energy technologies is still in its emerging state, whilst the space industry itself is growing. It is expected to rise to 1 trillion euros in revenue from its activities, as reported by the firm Morgan Stanley[1]. This takes into account terrestrial utilisation of space technologies such as navigation and earth observation systems, but also novel endeavours such as space mining and energy harvesting for extraterrestrial projects. This project falls under the latter. Thus, a role is played by the technical developments of this project, supported by the growing space colonisation industry.

The density of the atmosphere of Mars is less than 1% of that on Earth, and it is roughly composed of 95% carbon dioxide. According to a study by McKinsey[2], there is a huge potential for Mars colonisation due to efforts done by NASA, in conjunction with MIT, where experiments are carried out to feed it into an electrolysis system, which converts carbon dioxide to pure oxygen. Although these tests are done in labs on a small-scale basis, research and developments similar to this will incite a larger wave of keen parties willing to participate in Martian colonisation efforts. This means that if technology similar to this progresses further, Mars may experience an exponential growth of interest in colonisation missions as more humans will be able create a new branch of society on Mars. Thus, the growth for the energy demand of Martian systems would naturally follow suit.

The main competition that this DSE team considers in the market study includes, but is not limited to;

- **NASA**[3]: Task order NAS3-2S808, ”Mars Power System Definition Study” researches various energy technologies specifically for Mars.
- **Shackleton Energy Corporation**[4]: Space energy technologies, power transmission, life support systems and autonomous robots.
- **Kilopower**[5] : Conceptual long-duration and affordable fission nuclear energy systems on planetary surfaces demonstration.

[1] https://knowledge.wharton.upenn.edu/article/commercial-space-economy/ [Cited 30 April 2020]
[2] https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/perspectives-on-the-future-of-space-exploration [Cited 30 April 2020]
[3] https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19950015535.pdf [Cited 30 April 2020]
[4] http://www.shackletonenergy.com/technology#power-transmission [Cited 30 April 2020]
[5] https://www.nasa.gov/directorates/spacetech/kilopower [Cited 30 April 2020]

Lastly, a SWOT analysis table is presented, highlighting external and internal strengths and weaknesses for the project. The main internal strengths of the DSE are the use of renewable energy and zero use of nuclear energy, along with the fact that the team operates from home offices, which means that there is no time wasted on commuting. The biggest threats to the project include the launcher not being available currently, launcher program change or cancellations and a delay in Mars habitat project.

Sustainability

Sustainability can be split up in three different aspects: environmental sustainability, social responsibility and financial sustainability. In order to call a design sustainable, all these aspects should be satisfied. To ensure this will be the case for the renewable energy system on Mars, a design development strategy is composed, introducing some tools improving sustainable development. The strategy focuses on two things: sustainable engineering and sustainable analysis.

The sustainable engineering strategy focuses on tools to make sure sustainable resources are used, efficiency is increased, environmental impact is reduced and other aspects of sustainability, like economic affordability, safety and social acceptability are being watched. The S5 Approach[6] is to be applied within the design team, to increase the efficiency, quality of the work and working atmosphere in the team as well as in the production of the system. The space regulations will be regularly checked to ensure the system is designed subjected to the law. To check whether the resources used are as sustainable as possible, a material discovery file and a resource budget sheet will be created. In the material discovery file, all material options for the design are listed, showing their scarcity, impact of harvesting and potential for recycling of reuse. In the resource budget sheet, all used resources, their costs and availability are noted to make sure their sustainability is being monitored. Finally, a production planning chart will be created, to decrease waste and inefficiency while processing.

To test the design on its sustainability, the following tools are used for sustainability analysis: parts documentation, financial sustainability analysis and social sustainability survey. The parts documentation is executed after the design and includes all parts of the system, showing their mass, costs and potential for reuse or recycling. The financial sustainability analysis should be executed also during the design process, and analyses as the name implies, the financial sustainability of the project. A social sustainability survey evaluates the social responsibility of the project afterwards. A survey among the project team and its key partners will give a view on the social responsibility within the design process. Because public opinion is an important factor for the appreciation of a space exploration mission, having impact on its financial support, a survey regarding public's opinion will also be conducted.

[6] https://www.graphicproducts.com/articles/what-is-5s [Cited 30 April 2020]

2
Market Analysis

This section introduces the market analysis for the Renewable Energy on Mars project. For the longevity and overall success of the project, it is critical to be informed about the market milieu and identify the potential sectors that can utilise the technology and its lateral learnings. To provide (financial) sustainability to the project, it is key to identify key partners and resources that can provide support at different stages, even after the project's end-of-life timeline.

Thus, market opportunities, which provides a general framework for market outlook and growth with regards to the energy technology and the value of the Mars mission itself, is critical to ensure longevity and (economic) success of the project. The consequence of the market analysis is to better inform the project team, in how the technology and mission contributes to overall scientific progress and its practical utility in space exploration endeavours. It also informs the project design team to consider new requirements based on cost functions and other demands by the competitive market.

This chapter first introduces the key partners of this project to ensure basic accessibility to the market in section 2.1. Secondly, the target market and opportunities are according highlighted in subsections 2.2.1 and 2.2.2, respectively. Next, a competition analysis is carried out to ensure the maintained competence of unique selling point of the project's outcome in section 2.3. Lastly, a SWOT analysis table is presented, highlighting external and internal strengths and weaknesses for the project in section 2.4.

2.1. Key Partners

Key partners are important to ensure market viability and continued competitiveness in the market. These parties are often economic, technical and political gates (or barriers) from market entry to end-of-life continuity of the project. It takes into account adaptation of legislation, manufacturing facilities and technological innovations from the short to long term.

- **EU administration**: From 2015 to 2020, the EU invested over 12 billion euros in space activities, consolidating world-class space projects like Galileo and Copernicus[1]. The organisation is the biggest institutional customer for launch services and initiator for space exploration missions in Europe. In this way, it is a key partner to ensure project funding and long-term support.
- **Launch Operation and Site**: Launch operations are essential for the successful initial phase of the mission: sending the designed energy technology to Mars. Thus, many factors come into play including technical compatibility and operational awareness.
- **Energy System Producers**: Since the energy systems chosen (wind, solar, storage and miscellaneous hardware components) for this mission are not built from scratch, but are merely designed, reconfigured and adapted for Martian applications, the power units have to purchased directly from an external party. This plays a large role in the budgeting and costs of the project. Hence, it is important to compare the existing technologies and their respective manufacturers in order to reduce project costs and ensure profitability.
- **Manufacturing facilities**: It is also important to ensure efficient and regulated workstations in the production process. Currently, the energy system is designed for a one-time use for a one-time mission. However, following the success of the mission, it is useful to perform an investigation of available mass-production manufacturing facilities and equipment for the continued developments of an extra-terrestrial energy system.

[1] https://www.eib.org/attachments/thematic/future_of_european_space_sector_en.pdf [Cited 30 April 2020]

- **Legislators**: Political support and public perception of the mission is essential. In cases of non-compliance, the entire system would fail to reach its requirements if rules prevent different stages from carrying out. Hence legislative rules can decide the fate of the project's overall success.

2.2. Market

In this section, the target market and market opportunities of the DSE project's outcomes will be analysed.

2.2.1. Target Market

The market for this project is targeted at the space sector, in particular space exploration and colonisation. In recent years, Mars colonisation has received widespread public and private interest, and developments in this direction, whether habitation, materials and energy, are making fast strides. Hence, it is key to keep pace with the critical developments to ensure the project's technical design is still relevant for future projects. The market for the outcomes of this project are directly linked to the habitation study from a separate team of architects and engineers working for ESA-ESTEC [10]. In this way, there is only one target market and the project team is developing the energy system for this particular 'customer'.

However, the outcomes of the project need not just be utilised for a one-off mission, but can be applied to future efforts, which opens the market and economic sustainability of the research and technology. Because one of the main requirements for this project include the use of renewable energy, the technologies identified will undergo a technology transfer process. This means new intrinsic changes in optimisation and adaptation of the energy technology (to different atmospheric conditions etc.) will instigate new uses and utility of the technology. This is a continual market-capturing process. Hence it is not just the hardware design that is brought into the market, but the novel understandings and technical know-how that can be introduced to future developments. The qualitative and quantitative aspects of this understanding can be applied to new project innovations and can spin-out new products to be introduced to the space-energy market. This sustains the long term market share of the DSE project's outcomes.

2.2.2. Market Growth and Opportunities

On Earth, energy is the biggest industry, valued at over 7.7 trillion euros[2] with a compounded annual growth rate of 4.1 % in 2018. While for space-derived energy opportunities, as defined by the white-paper released by the EU[3], energy technologies are still in its infant emerging state. Thus, for missions similar to this, the next decade will see a rise in application of Earth-based energy sources, such as solar, wind, or nuclear. Naturally, there will be new emerging energy technologies that are designed specifically for these efforts. Hence, it is important to keep pace with the innovations and technical breakthroughs that risk longevity of this design project.

Furthermore, the space industry itself is growing[4]. Currently, the global space industry generates a revenue of 320 billion euros, and is expected to rise to 1 trillion euros as reported by the firm Morgan Stanley[5]. This takes into account terrestrial utilisation of space technologies such as navigation and earth observation systems, but also novel endeavours such as space mining and energy harvesting. This project falls under the latter. Thus, a role is played by the technical developments of this project, supported by the growing space colonisation industry.

Currently, the atmospheric composition of Mars is roughly 95 % carbon dioxide. According to a study by McKinsey[6], there is a huge potential for Mars colonisation due to efforts done by NASA, in conjunction with MIT, where experiments are carried out to compress the Martian atmosphere and feed it to an electrolysis system, which converts carbon dioxide to unadulterated oxygen. Although these tests are done in labs on a small-scale basis, research and developments similar to this will incite a larger wave of keen parties willing to participate in Martian colonisation efforts. This means that Mars specifically, the closest planet to Earth, will experience an exponential interest in colonisation missions as more humans are able to breathe in the air and form some sort of livelihood aboard Mars. Thus, the growth for the energy demand of Martian systems would naturally follow suit.

[2] https://www.weforum.org/agenda/2017/11/industries-will-make-money-in-space/ [Cited 30 April 2020]
[3] https://www.eib.org/attachments/thematic/future_of_european_space_sector_en.pdf [Cited 30 April 2020]
[4] https://spacenews.com/investors-cautiously-optimistic-about-continued-space-industry-growth/ [Cited 30 April 2020]
[5] https://knowledge.wharton.upenn.edu/article/commercial-space-economy/ [Cited 30 April 2020]
[6] https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/perspectives-on-the-future-of-space-exploration [Cited 30 April 2020]

2.3. Competition

Competition in the ‘race to space’ colonisation is evident from that fact that governments, space administrations and startups alike are developing solutions for energy production in space. This means that competition their financial competitive capabilities are diverse. Competition incurs risk in the longevity of the project’s outcomes, thus it is key to identify the unique selling points of the competition in order to formulate some for this project, this maintains competitive advantage. The following section summarises the main competition from 3 groups that have projects within this field and can be potential sources of competition.

- **NASA**[7]: NASA has multiple sub-departments that deal with developing a wide range of space colonization technologies. Under NASA’s Lewis Research Center in Ohio, a task order NAS3-2S808, entitled ”Mars Power System Definition Study” researches various energy technologies specifically for Mars; including solar panels, battery characteristics and nuclear and thermionic reactor power systems.
- **Shackleton Energy Corporation**[8]: Shackleton was founded in 2007 in Texas and are primarily engaged in developing equipment for Moon mining. However, they are also engaged heavily in space energy technologies, such as power transmission, life support systems and autonomous robots.
- **Kilopower**[9] : Kilopower is a spin-off project from NASA and is a near-term conceptual and technology effort to introduce long-duration and affordable fission nuclear energy systems on planetary surfaces. Currently, the Kilopower team is designing mission concepts and risk mitigation strategies to prepare for a future flight demonstration.

As can be inspected, these design and engineering groups are also at the conceptual stage or have just begun preliminary design. It is thus reasonable to believe that this DSE project will produce an outcome that will address certain problems that the other groups might not consider, especially taking into account sustainable design and use of renewable sources of energy. In short, this outcomes of this DSE project will be able to compete in the future market. Taking these competitors into account, we can derive the desired functions and their respective requirements as later presented in chapter 7 in order to be competitive on the market. The list below is not exhaustive, but includes:

- Keeping production and operational costs low
- Ensuring technical usability and maintainability of energy systems
- Compact and ergonomic designs for transportation and installation
- Maximising the reliable power output
- Efficient use of materials and maximising in-situ resource utilisation.
- Use of renewable energy sources
- Continual research and developments and innovations

2.4. SWOT Analysis

Table 2.1: SWOT analysis

	Helpful to achieving the objective	**Harmful** to achieving the objective
Internal	• Renewable energy • No use of nuclear energy • During the 10 weeks of the project the team will learn to function fully remotely • Instant messaging: more easily traceable • Home office: no time spent on commuting	• Lack of communication • Insufficient task overview • Lack of face-to-face communication • Instant messaging: longer response • Home office: distracting environment • Physical facilities not available • Team building is more difficult while working remotely
External	• Mars habitat team could help with some aspects (e.g.: site determination) • If Mars habitat project continues, a power system is needed • Use of prefabricated components in subsystems • Limited competition • Experienced tutor and coaches	• Launcher not being available currently • Launcher program changes or cancelled • Delay in Mars habitat will delay the project • Budget reduction • Changes in top level requirements

[7]https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19950015535.pdf [Cited 30 April 2020]
[8]http://www.shackletonenergy.com/technology#power-transmission [Cited 30 April 2020]
[9]https://www.nasa.gov/directorates/spacetech/kilopower [Cited 30 April 2020]

3
Functional Analysis

This chapter aims to document the development, construction, and reiteration of the functional analysis of the system to be developed for the Renewable Energy for a Mars Habitat mission. As documented by Hamann and van Tooren [20]: "The objective of the functional analysis is to create a functional architecture that can provide the foundation for defining the system architecture through the allocation of functions and sub-functions to hardware/software and operations (i.e., personnel)". Based on what the key partners require the system to do, as well as what other competitors design their system functions, a functional analysis for the power system based on renewable energy for a Mars habitat can be generated. As discussed in chapter 2, there are several aspects to take into account for describing the functioning of the system, which do not necessarily relate to the generation of power per se. Therefore, the functional analysis also aims to encompass all the tasks the system must fulfil in order to meet all market expectations.

In essence, the functional analysis describes what the system will do, based on the existing user and operational requirements. As a result, each of the individual functions and sub-functions need to be correctly identified and defined, such that a functional architecture can be constructed and reiterated upon for later stages of the design. Two standard schematics have been developed for this purpose, namely the Functional Breakdown Structure and the Functional Flow Diagram. Section 3.1 will tackle the construction of the Functional Breakdown Diagram (FBS), and section 3.2 will explain the structure of the Functional Flow Diagram (FFD) and its relation with the FBS.

3.1. Functional Breakdown Structure

As explained by Hamann and van Tooren [20], an FBS is a schematic representation of the logical grouping of functions according to a set of criteria. Here, the opportunity arises to bring into play the user's needs (i.e. what the system should be able to do), as well as other operational requirements. These criteria can then be used to formulate what the underlying functions will be, firstly in a general or top-level view, and subsequently in a more extensive way.

In order to come up with a general formulation for these functions, a brainstorming session was performed with the main focus being put on *what* the system should be able to do and not on *how* it will be implemented. Additionally, it must be noted that no effort was made to depict the chronological or sequential order of these functions. Instead, it should be underlined that the FBS is an example of an AND tree (meaning that each of the elements in the tree is equal to the sum of the elements below it and nothing more).

What this implies for the FBS, is that each of the functions can be expressed as the sum of the sub-functions below it. Looking at figure 3.2, it follows that, for example, function F1 can also be expressed as the sum of all the immediate sub-functions below it (i.e. F1.1, F1.2, F1.3, and F1.4). The numbering of each block is put in place in order to illustrate the hierarchical structure of the FBS, as well as to let the FBS act as a starting point for the construction of the FFD, which will be further elaborated upon in the following section.

To clarify the FBS shown in figure 3.2, the top-level functions need to be explained. There are seven top-level functions which are further broken down into smaller sub-functions. All top-level functions will be described below:

1. **Manufacture payload:** This function includes all actions necessary to ensure for a safe and up to quality manufacture process of the payload. So everything from safety equipment to collecting resources to manufacturing and assembling the parts is broken down here.

2. **Transport payload:** The payload, which includes all energy systems and electronics, needs to somehow be transported to Mars. All functions required for this operation are stated here. Functions like

moving the payload into the spacecraft, launch and space travel are mentioned and their sub-functions are also shown.

3. **Perform basic energy system integration on Mars:** To minimise the payload mass that the spacecraft needs to bring, certain structural parts of the energy systems can be made using material found on Mars. In order to harvest and process this material, some preliminary energy needs to be available, since the complete energy system will only be setup when all these parts are done. Therefore, this function describes all functions required to integrate a basic energy system that can be used to create the parts required for the complete energy system. Again safety regulations are stated as well as the deployment of the basic system from the spacecraft and the integration/activation of this basic energy system.
4. **Manufacture on-site structures:** As mentioned in the previous function, part of the mission operation could be generating some structural parts of the energy system from Martian material. This function elaborates on all actions that needs to be included for harvesting and manufacturing these parts.
5. **Perform complete system integration on Mars:** The final action required for the energy system completion is the integration of the total energy system. So the structures, energy systems and electronics are combined and a final pre-operational system check is performed before activating the complete system.
6. **Operate energy systems:** Besides bringing and installing the energy system on Mars, there should also be a function describing how the system should be operated. The performance should be evaluated and the system should be calibrated not only according to this evaluation but also to the martian environmental conditions. This calibration should result in efficient use of the energy system after which energy can be generated, stored and distributed according to the current need. Other than using the energy system, it should also be maintained. Actions for this are also stated in this function and so are any End-of-Life operations.
7. **Perform communication:** The final function shown in the FBS is a small function on communication. Both communication with earth and communication between subsystems is shown here. Both types of communications are used at various points throughout the mission.

Further elaboration on all of these top-level functions together with their sub-functions can be found in the FBS in figure 3.2.

3.2. Functional Flow Diagram

The FFD is a schematic representation that illustrates the relations between the functions that a system has to perform. It provides insight of the inputs and outputs of each of the individual functions, and it provides insight into the flow and sequence between functions and sub-functions. Additionally, it is a step-by-step, multi-level diagram that provides an expansive quality to the FFD.

Generally speaking, the FFD does not depict the flow of information between hardware and software or systems and subsystems/environment [20]. However, as it can be seen on figure 3.2, function F7 directly establishes a function relating to the communication between the space and ground elements of the mission, or the communication between subsystems and/or the environment. This was done because this type of information flow is an essential part of the functionality of the system as a whole.

The FFD does not show the content of each functional step in detail, as well as any kind of duration, concurrent, or timing overlap of the functions [20]. This is partly due to the fact that at this stage in the design development, there is not enough knowledge about the detailed functioning and operation of the system, but rather a preliminary concept that will be further reiterated upon in later stages of the design. More specifically, once the main functions and sub-functions are assigned to the different subsystems, their corresponding FFD's will have to be reviewed and extended considerably. This can moreover bring forward critical interactions between subsystems and/or the environment that will thus have to be taken care of as part of the design of the system

Looking at the FFD in figure 3.2 specifically, a couple of things should be mentioned. The arrows show the direction of the flow throughout the diagram, AND and OR statements are placed to show whether all functions will be done or if a decision needs to be made on which function should be performed. Also, since communication is present throughout the process labels A and B are given for the two types of communication and these labels are used throughout the FFD when necessary.

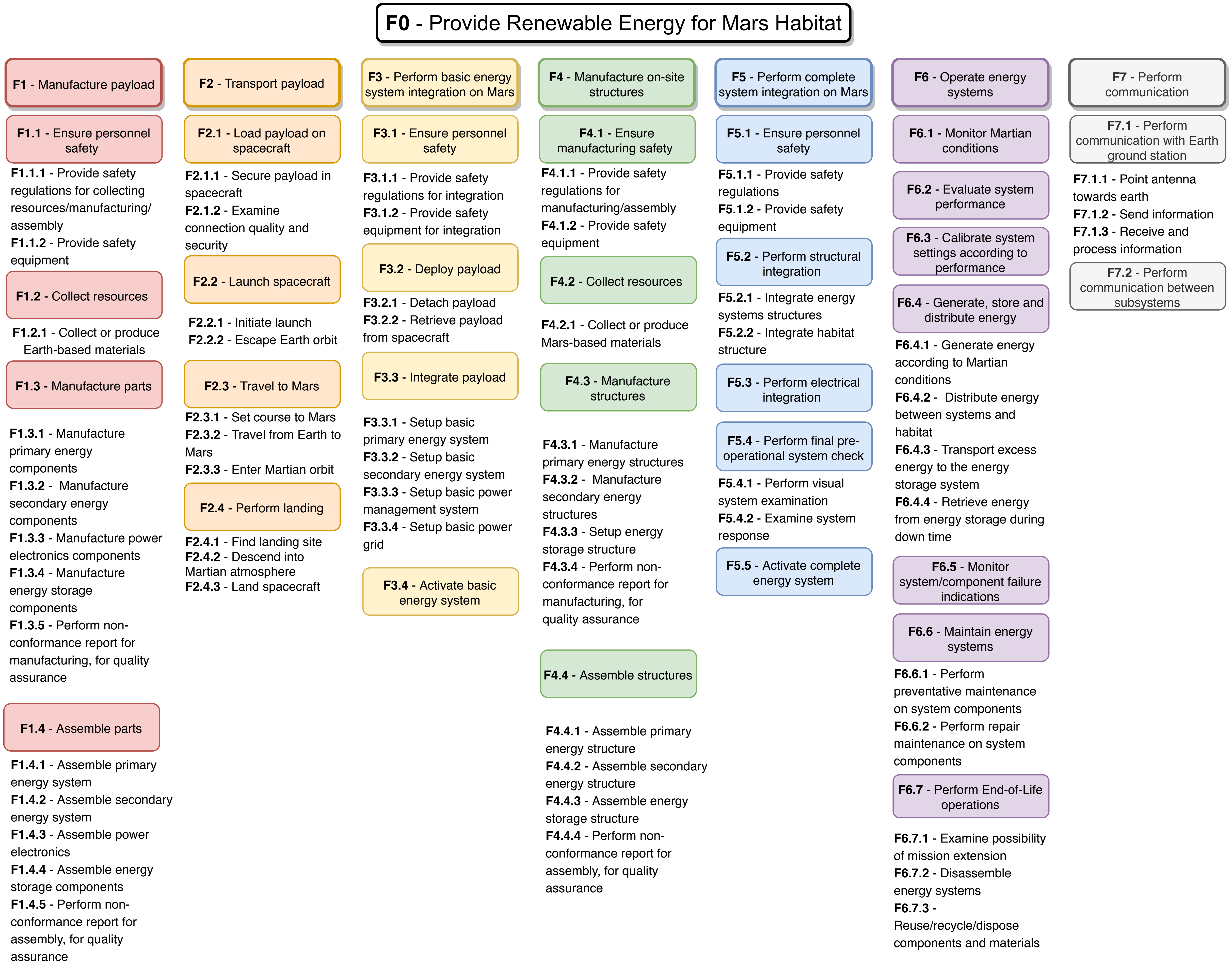


Figure 3.1: Functional Breakdown Structure

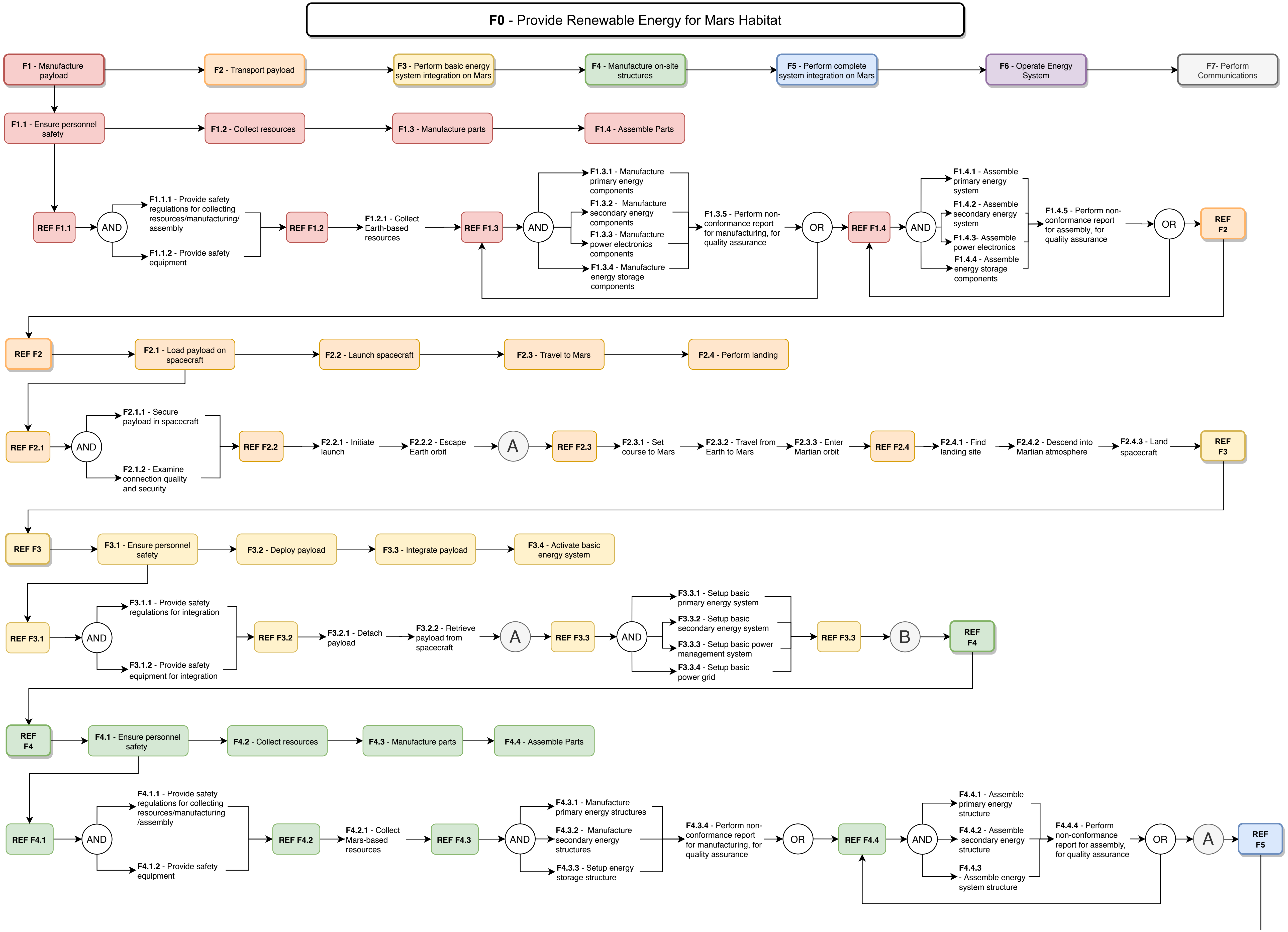
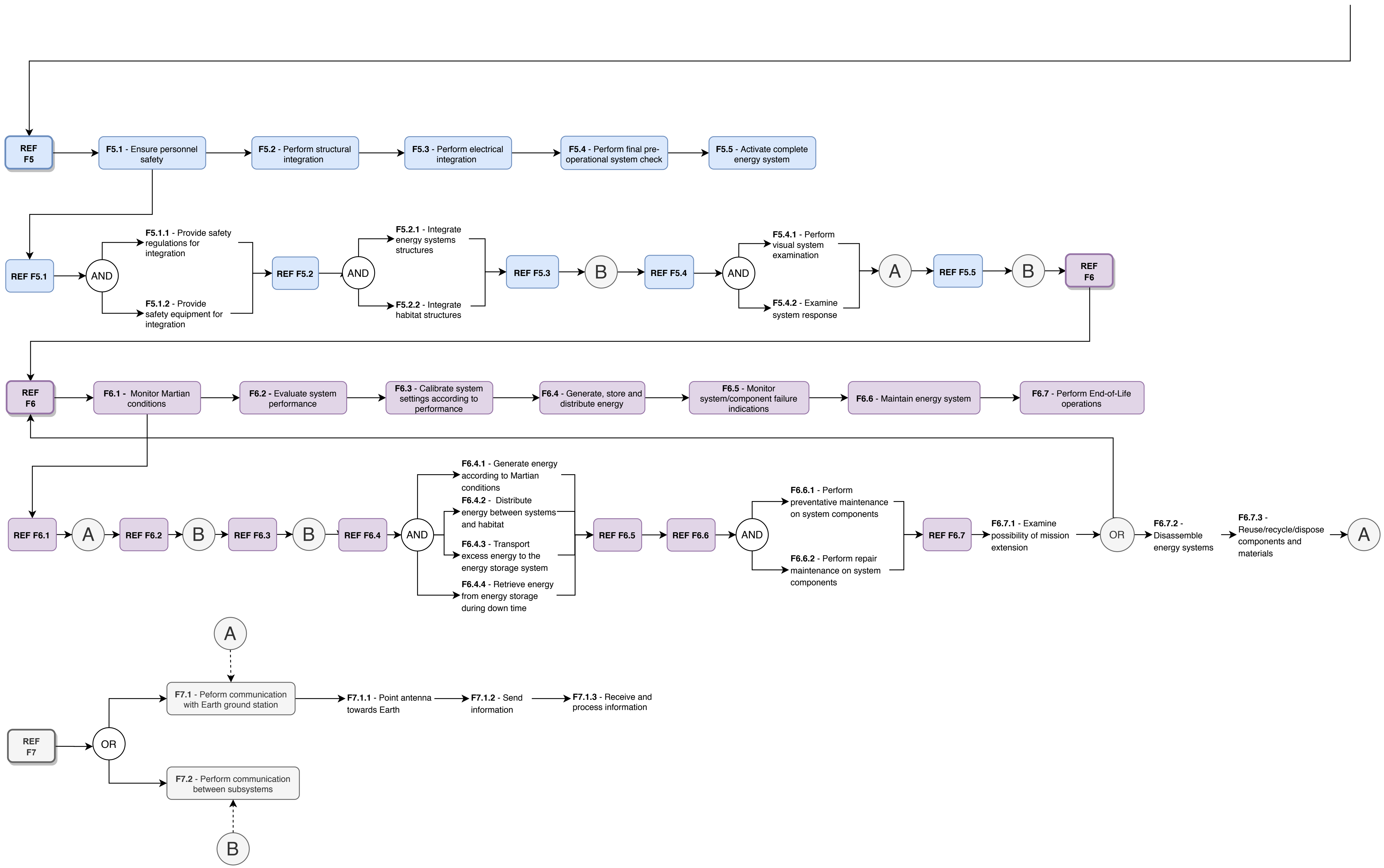


Figure 3.2: Functional Flow Diagram


REF F5
F5.1 - Ensure personnel safety
F5.2 - Perform structural integration
F5.3 - Perform electrical integration
F5.4 - Perform final pre-operational system check
F5.5 - Activate complete energy system
REF F5.1
AND
F5.1.1 - Provide safety regulations for integration
F5.1.2 - Provide safety equipment for integration
REF F5.2
AND
F5.2.1 - Integrate energy systems structures
F5.2.2 - Integrate habitat structures
REF F5.3
B
REF F5.4
AND
F5.4.1 - Perform visual system examination
F5.4.2 - Examine system response
A
REF F5.5
B
REF F6
REF F6
F6.1 - Monitor Martian conditions
F6.2 - Evaluate system performance
F6.3 - Calibrate system settings according to performance
F6.4 - Generate, store and distribute energy
F6.5 - Monitor system/component failure indications
F6.6 - Maintain energy system
F6.7 - Perform End-of-Life operations
REF F6.1
A
REF F6.2
B
REF F6.3
B
REF F6.4
AND
F6.4.1 - Generate energy according to Martian conditions
F6.4.2 - Distribute energy between systems and habitat
F6.4.3 - Transport excess energy to the energy storage system
F6.4.4 - Retrieve energy from energy storage during down time
REF F6.5
REF F6.6
AND
F6.6.1 - Perform preventative maintenance on system components
F6.6.2 - Perform repair maintenance on system components
REF F6.7
F6.7.1 - Examine possibility of mission extension
OR
F6.7.2 - Disassemble energy systems
F6.7.3 - Reuse/recycle/dispose components and materials
A
A
REF F7
OR
F7.1 - Peform communication with Earth ground station
F7.1.1 - Point antenna towards Earth
F7.1.2 - Send information
F7.1.3 - Receive and process information
F7.2 - Perform communication between subsystems
B

4
Sustainable Development Strategy

Sustainability nowadays is a term broadly used in many different contexts. For this project, it is key to define the terms sustainability and sustainable development. According to the ISO 82 Guidelines, sustainability is defined as "The state of the global system, which includes environmental, social and economic subsystems, in which the needs of the present are met without compromising the ability of future generations to meet their own needs." [18]

As design and engineering activities have significant impact on the economic development and the well-being of the human species and its environment, it is necessary that the sustainability of the design is being watched throughout the process. In figure 4.1 the design process has been split up in different design stages, throughout which sustainable development will be applied.

In this chapter, the sustainable development strategy for renewable energy on Mars is introduced. Firstly, the strategy towards sustainable engineering during the design and production is explained in section 4.1. Followed by the approach to analyse the sustainability of the design while the project runs and after completion, in section 4.2.

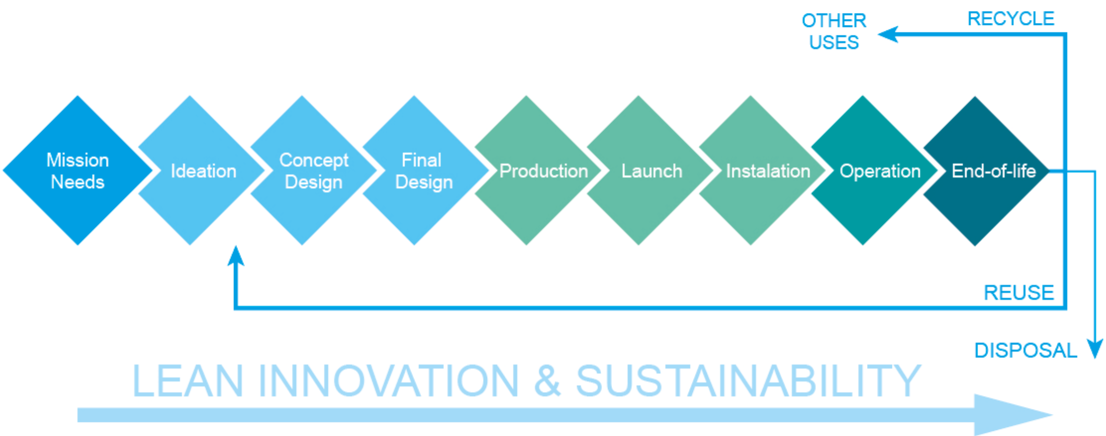


Figure 4.1: Design process involving lean innovation and sustainability design

4.1. Sustainable Engineering

The key requirements to focus on for engineering sustainability include sustainable resources, sustainable processes, increased efficiency, reduced environmental impact and the fulfilment of other aspects of sustainability, like economic affordability, safety and social acceptability. [30] In this section the tools to meet these requirements are discussed.

- **5S Approach:** The 5S approach is a Japanese methodology used to increase efficiency and eliminate waste throughout the development process. The approach makes use of a step-by-step process: *seiri*, *seito*, *seiso*, *seiketsu* and *shitsuke*. These are translated to Sort, Set In order, Shine, Standardize and Sustain. These five words are often supplemented with a sixth S: Safety. Implementing the approach thoroughly in the working environment, increases the working morale, efficiency and quality of the work and health of the team. This results in lean innovation throughout the design process, due to the minimisation of waste and increased productivity.[1]

- **Regulations:** To make sure that the design and the production of the design is legitimate, the space regulations, issued by the United Nations in the International Space Law, will be considered from the beginning of the design. [38]
- **Material Discovery:** All engineering activities make use of resources that are (at some point) derived from nature. The degree to which resources are sustainable depends on many factors, including scarcity and their importance to ecosystems, but also their potential for reuse. For the case of the renewable energy system on Mars, materials and other resources can be gathered on Earth and on Mars. To have a good overview on the materials that can be used for the design, a file will be created with all material options. Within this file, it will be possible to make an overview of their scarcity, impact of harvesting on their environment and potential for recycling or reuse.
- **Resource Documentation:** To have an overview of all resources needed for production, installation and operation of the design besides the materials used for the system, a resource budget sheet is made. In this sheet, the amount of the used resource, availability and costs are documented.
- **Production planning chart:** To decrease the waste and inefficiency while producing, a production planning chart should be created. In the production planning chart, all activities are clearly described and the planning of production shown. This will be done in a chart comparable to a Gantt chart.
- **End-Of-Life operations:** In order to ensure circular design, a strategy to close the loop must be set in place to ensure that the system and its different components can be transformed into something useful for either the Martian environment or the inhabitants of the future Mars colony. This is a process that heavily relies on the definition of the design of the system itself, which is to be determined in a later stage of the design. It is important however to take the EOL operations as a crucial aspect to ensure sustainable development.

4.2. Sustainability Analysis

Throughout the design of the renewable energy system on Mars, the sustainability of the design should also be watched and tested. Here for, three tools are described in this section.

- **Parts Documentation:** The parts documentation includes all parts the renewable energy system consists of and should be executed after the design of the system. Here all parts are evaluated on mass and costs and their potential for reuse or recycling is documented.
- **Financial Sustainability Analysis:** Through the initialisation, design and execution of the project, regular financial sustainability analysis should be carried out. This ensures proper accounting and the continuous updating of risk management plans and quality improvements, which includes investors and stakeholders in important financial decisions. Finances should be analysed in parallel to benchmarks, which composes of consolidating the cost of outcomes on milestone dates.
- **Social Sustainability Survey:** To evaluate the impact of the social responsibility of the project, surveys could be conducted. Public opinion is an important factor for the appreciation of a space exploration mission, which also ensures the continued financial support of the project. A survey regarding the public's perspectives of the mission to Mars should be conducted and showcased. Furthermore, a survey among the project team and its associated key partners would be useful to reflect on the social responsibility within the design process.

[1] https://www.graphicproducts.com/articles/what-is-5s [Cited 30 April 2020]

5

Technical Risk Assessment

This chapter details the technical risk assessment of the project. In section 5.1, an introduction is given about the type of risks and the approach to manage these. The individual top-level risks are identified in section 5.2. The risks have to be kept under control for which the mitigation plan is established in section 5.3. Once, one knows the way to mitigate the risks, it can be visualised in the risk matrix. This can be seen in section 5.4 before and after mitigation. For the risks that cannot be avoided the contingency management plan is described in section 5.5.

5.1. Introduction

Risk management is a crucial part of the DSE in order to succeed and deliver a worthy design at the end of the ten weeks. The TRA comprises several aspects of the projects[1], which are: [28, p. 8]

- **Cost risk:** risk associated with achieving unit cost, life-cycle cost objective or funding
- **Schedule risk:** risk associated with not adequately estimating and allocating time for the project or the mission
- **Technological risk:** risk associated that an underpinning technology is not ready within the required time frame
- **Technical risk:** risk associated with not reaching required performance due to technological risks
- **Programmatic risk:** risk associated with action or inaction from an entity outside the project

All of these have to be considered at every stage of the project in order to get a global picture. The phases for which technical risk is assessed are development (**DM**), production on Earth (**PE**), launching (**LA**), transportation (**TR**), production on Mars (**PM**), deployment (**DP**) and operation (**OP**)

As the project is fast-paced, the risks arise and change constantly. In order to tackle this, Continuous Risk Management is going to be implemented. This is a repeating cycle, in which five tools are executed: [11, p. 251]

- **Identify:** individual risks are described in a risk database, which is regularly updated
- **Analyse:** for each risk the likelihood and consequence are estimated before and after mitigation
- **Plan:** plan the project by use of WBS, WFD, Gantt chart and iterate when needed, decide on the mitigation plan for every identified individual risk
- **Track:** decisions in risk management are monitored
- **Control:** in case the risk mitigation strategy is not influencing the risk as expected, a control action has to be implemented

[1] https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120000033.pdf [Cited 29 April 2020]

5.2. Risk Identification

It is very important to start identifying possible threats to the project at the earliest stage. Although, in this phase no final concept has been chosen yet to be further developed, the top level risk that are not dependent on the type of system can already be distinguished. The identified risks can be seen table 5.2 and the point definition for likelihood and impact scores can be seen in table 5.1.

Table 5.1: Point definition for likelihood and impact

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

Table 5.2: Risk identification

ID	Risk description	Likelihood	Impact
DM-1	Unit is above 200 kg	2	5
DM-2	Unit cannot fit in 3 m^3	2	5
DM-3	Payload is above 800 kg	2	5
PE-1	Component or part cannot be manufactured	2	3
PE-2	Subsystem or component cannot be assembled	2	3
LA-1	Launcher fails due to a technical failure	2	5
LA-2	Launcher program cancelled	3	5
LA-3	Launcher program postponed	3	5
LA-4	Unit cannot be integrated in launcher prior to launch	1	4
LA-5	Unit does not survive launch loads	1	5
TR-1	Launcher cannot reach orbit around Earth	2	5
TR-2	Launcher cannot escape orbit around Earth	2	5
TR-3	S/C cannot enter Martian orbit	2	5
TR-4	Landing module cannot locate landing site	3	3
TR-5	Landing module disintegrates during descent	3	5
TR-6	Landing module crashes upon landing	2	5
TR-7	Landing module performs a hard landing	2	3
PM-1	Materials cannot be collected on Mars	2	5
PM-2	Materials are not as abundant as expected	2	4
PM-3	Structures cannot be manufactured	2	5
PM-4	Structures cannot be assembled	2	5
DP-1	Unit is damaged during transportation	2	3
DP-2	Unit cannot be retrieved from landing module	2	5
DP-3	Unit cannot be connected to habitat	2	5
DP-4	Structural components cannot be integrated	1	5
DP-5	Subsystem cannot be integrated to a system	1	5
OP-1	Martian atmosphere monitoring system fails	3	3
OP-2	Energy system cannot be calibrated on site	3	3
OP-3	Power generation system fails	3	5
OP-4	Energy storage system fails	3	4
OP-5	Power distribution system fails	3	5
OP-6	Electrical grid fails	3	5

Continued on next page

Table 5.2: ***Continued from previous page***

ID	Risk description	Likelihood	Impact
OP-7	System cannot be maintained	3	5
OP-8	System cannot be repaired in case of failure	3	5
OP-9	System cannot be disposed of at end-of-life	3	3

5.3. Risk Mitigation Plan

Several actions can be taken in order to reduce the likelihood or the impact of a risk. These risks are [27, p. 19]:

- **Accept:** The risk is either within a tolerable level or the group has no influence over it as it originates from the outside.
- **Mitigate:** Actions can be taken after the risk has happened to reduce the driver(s).
- **Watch:** The risk can be monitored and contingency plan can be developed.
- **Research:** Prior research can be conducted in order to understand the driver(s) of the risk better and reduce the uncertainties to avoid it.

Table 5.3 shows the risk mitigation plan for each individual risk identified in the previous section. In this table, the mitigation measure is chosen and a brief explanation is given on why this is the best choice. Some risks are grouped as these have the same reason for choosing a certain mitigation measure.

Table 5.3: Risk mitigation plan

ID	Measure	Explanation
DM-1 **DM-2** **DM-3**	Research Research Research	Exceeding the mass or volume budget would lead to the end of the project, so every action has to be taken to avoid it.
PE-1 **PE-2**	Mitigate Mitigate	In case a design is not reviewed correctly, it is possible that parts cannot be manufactured or assembled as expected. If this occurs, the impact has to be mitigated.
LA-1 **LA-2** **LA-3**	Accept Accept Accept	The launcher program is outside the scope of this project as it is sourced out. The risks associated with this program are high, but the group has no influence over these, thus have to be accepted.
LA-4	Research	The design has to be reviewed several times by several people in order to guarantee, this risk does not happen. Also, dress rehearsal can be performed with mock-up models.
LA-5	Research	Detailed research, simulation and testing have to be conducted to avoid the risk.
TR-1 **TR-2**	Research Research	Responsibility of the launcher company. Complete analysis has to be carried out.
TR-3 **TR-4**	Watch Watch	Responsibility of the launcher company. The orbital team has to constantly watch the course.
TR-5 **TR-6**	Research Research	Payload has to land to carry out the mission thus all actions have to be taken avoid these risks.
TR-7	Mitigate	In case of a hard landing, the payload still has to be retrieved from the landing module, so the risk has to be mitigated.

Continued on next page

Table 5.3: ***Continued from previous page***

ID	Measure	Explanation
PM-1	Mitigate	Due to the lack of extensive experiments, actual composition might be different on Mars. In this case, parts or components cannot be manufactured and integrated as planned. These risks thus cannot be avoided, but has to be mitigated.
PM-2	Mitigate	
PM-3	Mitigate	
PM-4	Mitigate	
DP-1	Mitigate	These risks occur when due to an unforeseen reason the payload is damaged during transportation. As this can happen, the impact has to be mitigated.
DP-2	Mitigate	
DP-3	Mitigate	
DP-4	Mitigate	
DP-5	Mitigate	
OP-1	Mitigate	Failures in systems can happen due to unforeseen reasons, so these risks will have to be mitigated.
OP-2	Mitigate	
OP-3	Mitigate	
OP-4	Mitigate	
OP-5	Mitigate	
OP-6	Mitigate	
OP-7	Mitigate	
OP-8	Mitigate	
OP-9	Mitigate	

5.4. Risk Matrix

The risk matrix shows the combination of likelihood and impact to determine how severe a risk is. The situation before mitigation is shown in figure 5.1. The effect of mitigation can be seen in table 5.4. In general, one can observe that *Accept* does not change likelihood nor impact. *Mitigate* reduces the impact as it is used when a risk cannot be avoided. When it can be (in case of *Research*), the likelihood is decreased. *Watch* is a continuous process, which reduces both likelihood and impact.

Table 5.4: Changing likelihood/impact as an effect of risk mitigation

ID	Changing parameter	New point
DM-1	Likelihood	1
DM-2	Likelihood	1
DM-3	Likelihood	1
PE-1	Impact	2
PE-2	Impact	2
LA-1	-	-
LA-2	-	-
LA-3	-	-
LA-4	Likelihood	1
LA-5	Likelihood	1
TR-1	Likelihood	1
TR-2	Likelihood	1
TR-3	Likelihood	1
	Impact	3
TR-4	Likelihood	1
	Impact	2

ID	Changing parameter	New point
PM-1	Impact	2
PM-2	Impact	3
PM-3	Impact	3
PM-4	Impact	3
DP-1	Impact	2
DP-2	Impact	3
DP-3	Impact	3
DP-4	Impact	3
DP-5	Impact	3
OP-1	Impact	1
OP-2	Impact	1
OP-3	Impact	3
OP-4	Impact	2
OP-5	Impact	3
OP-6	Impact	3
OP-7	Impact	3

Continued on next page

Table 5.4: ***Continued from previous page***

ID	Changing parameter	New point
TR-5	Likelihood	2
TR-6	Likelihood	1
TR-7	Impact	2
OP-8	Impact	3
OP-9	Impact	1

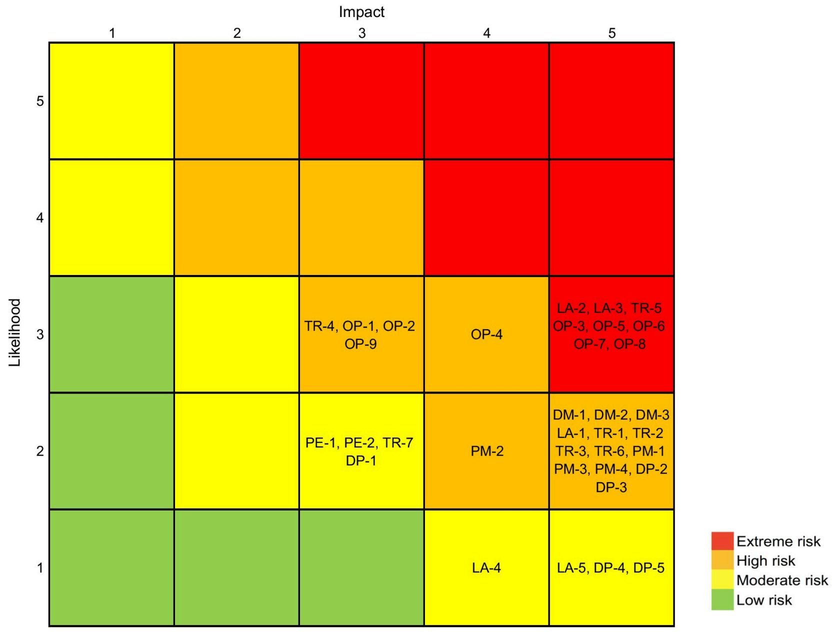


Figure 5.1: Risk matrix before mitigation

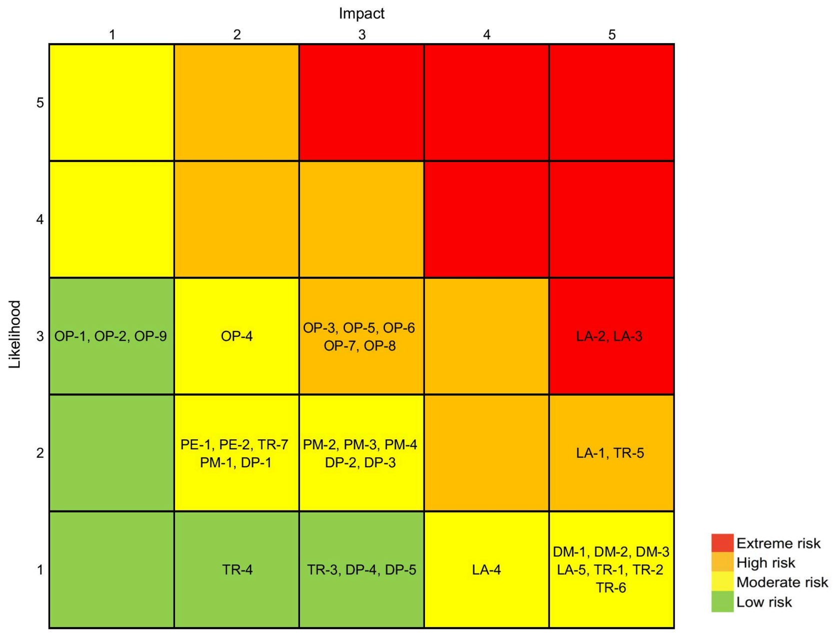


Figure 5.2: Risk matrix after mitigation

5.5. Contingency Management

The risks that cannot be avoided have to be dealt with. To do this a plan has to be established, which is called a contingency management plan and can be seen in table 5.5. In this table, all the risks that are not *Researched*, are included.

Table 5.5: Contingency management plan

ID	Measure	Contingency Plan
PE-1	Mitigate	During the prototype production and assembly phase, if a fault is
PE-2	Mitigate	detected in the production or assembly plan, these have to be modified.
LA-1	Accept	In this case, the payload is lost with the launcher. The finances have to be reassessed to determine if manufacturing of a second unit is possible.
LA-2	Accept	Companies launching to Mars are not abundant currently, but later possibly many will provide a launcher platform. More of these programs have to be looked into to evaluate the feasibility of integration.
LA-3	Accept	Additional research and testing can be conducted in the period when the launcher is postponed.
TR-3	Watch	Responsibility of the launcher company. The orbital team has to
TR-4	Watch	constantly monitor the course of the S/C and adjust when needed.
TR-7	Mitigate	In case of a hard landing, structural components have to ensure integrity for the payload. These have to be researched in advances and the envelope for hard landing has to determined.
PM-1	Mitigate	Mars is not yet known in great detail, so if the materials available
PM-2	Mitigate	are different than expected, the mission has to be modified.
PM-3	Mitigate	Production and assembly plan has to be made for different materials
PM-4	Mitigate	and methods to allow for redundancy.
DP-1	Mitigate	Make a plan to assess the damage and based on the outcome make a mitigation plan.
DP-2	Mitigate	Make a plan to disassemble the landing unit in case it has been damaged.
DP-3	Mitigate	Research an alternative solution prior to launch to connect the power generation unit to the habitat.
DP-4	Mitigate	Make a plan considering the cases when different parts or components
DP-5	Mitigate	cannot be integrated. Allow for versatility in the design.
OP-1	Mitigate	
OP-2	Mitigate	
OP-3	Mitigate	At this stage of the project, none of the systems are known.
OP-4	Mitigate	The mitigation plan cannot be established in this phase and
OP-5	Mitigate	will have to be done when the subsystems are decided on
OP-6	Mitigate	in the design phase.
OP-7	Mitigate	
OP-8	Mitigate	
OP-9	Mitigate	

6
Budget Analysis and Resource Allocation

This chapter is dealing with the budget and resources from all aspects. Human, technological and sustainability resources are given in subsection 6.1.1 to 6.1.3, respectively. At the end of section 6.1, the resource allocation is established. Furthermore, the technical budget and resource allocation with the mass, volume, power and budget contingency is given in section 6.2.

6.1. Financial, Human and Technological Resource Allocation

In order, to evaluate the total mission budget, the required resources on a smaller time scale are quantified. Similarly to the functional breakdown diagram and to the technical risk assessment as presented in chapters 3 and 5, the mission is split in the necessary stages for which the relevant change in the budget categories

6.1.1. Human Resources

Human resources are vital to ensure that managerial, organisational and technical processes are successfully and diligently carried out, by the appropriate people in terms of qualification, training, and expertise. The points below consolidates the key segments of human resources relevant to this project.

- **HM - Managers**: Managers spearhead the respective tasks. There are many types of managers, including human resource manager (team manager), business and financial managers, and technical managers (highly-qualified and experienced engineers) to name a few.
- **HE - Engineers**: (Certified) engineers are involved in all stages of design, development, testing and certification. They are further specialised into different engineering fields: aerospace, chemical, energy, electrical, software, structures etc.
- **HT - Technicians**: Technicians are individuals that received technical training in product development, manufacturing. These individuals often work under the instructions of engineers, that have specific skill sets and work stations in production line.
- **HA - Astronauts**: Individuals that transport, set up (integration to habitat) and operate the energy system on Mars. Astronauts are also engineers, scientists, pilots or highly-qualified technicians.
- **HO - Others**: Ground Station Professionals, Sustainability Officers, Marketing Officers etc.

6.1.2. Technological Resources

Technological resources is the machinery, software, hardware, information, intellectual properties that are required to bring the product from ideation to production and implementation.

- **TM - Machinery**: This includes prototyping, testing, manufacturing and production equipment.
- **TS - Software**: Software consists of simulation tools, computational analysis tools, modelling, application programming interfaces. It also includes components of cyber-security measures like user authentication, encryption tools and firewalls.
- **TH - Hardware**: This includes any functional hardware that supports the project, such as computer systems and storage capacities. It also includes other organisational tools such as air-conditioning, servers, laptops, office work stations.
- **TI - Information**: The relevant information and data sets, at times data acquired from external parties (NASA's Mars Insight Mission). Also includes processes such as transmitting of data to relevant parties such as the launch site or ground control.
- **TIP - Intellectual Property**: The utility and adoption of novel innovation technologies and proprietary tools. As well as new developments of inventions spun from the project's design process.

6.1.3. Sustainability Resources

The allocation of sustainability resources is vital in ensuring that the requirements for sustainable development is met. There are two key metrics that are adopted in this project. A maximum budget for carbon equivalents, which is the main driver to illustrate corporate sustainability, is allocated for the entirety of the project.

- **SW - Waste**: Evaluates the ergonomics and efficiency in reducing the waste of materials and resources through the project. Naturally, the bulk of the waste would be testing and manufacturing processes. It is difficult to have a general category for waste due to the diverse materials applied to the project, however this metric will be rated from 1 to 10, one being little waste budget allocated and 10 being the maximum waste expected to be produced.
- **SEE - Energy and Emissions**: Energy is required at all stages of the project. This can be quantified by carbon equivalents, taking into account energy use on Earth. The total carbon equivalents dedicated to the project's entirety is 2000 kW h and a cap of 500 tons of CO_2.

Table 6.1: Resource Allocation

	Cost (% of total)	Schedule (hours)	Human resources	Technological resources	Sustainability (Waste, CO_2 %)
Conceptual design	1	400	HM, HE, HO	TS, TH	(1, 3)
Preliminary design	3	420	HM, HE, HO	TS, TH, TI	(1, 3)
Detailed design	5	800	HM, HE, HO	TM, TS, TH, TI	(3, 9)
Testing	12	1250	HE, HT	TM, TS, TH	(6, 20)
Production (on Earth)	65% (2.7 M€)	800	HM, HE, HO	TM, TS, TH, TIP	(8, 65)
Installation (on Mars)	8	500	HA	TS, TH, TI	(4, -)
Operations	2	43 800	HA, HO	TS, TH, TI	(1, -)
End-of-life process	4	450	HM, HT, HO	TH, TS	(3, -)

6.2. Technical Budget and Resource Allocation

The technical budget analysis will focus on the mass, volume, power and cost distribution over the largest components. These values have been heavily estimated and as such, contingency management has also been performed. The method of estimation goes as follows. By assuming that one entire functioning system can be flown to Mars on two consecutive flights, the masses and volume were estimated. The mass and volume limits per flight are 800 kg and 3 m^3. respectively. As the maximum mass and cost per unit for the primary energy system are known, these can be easily added to the table. The rest was distributed over the other sections to add up to the total deemed for two full flights. The values that were chosen can be found in table 6.2. As this project is quite out of the box, it was not straight forward to find information on these values. It was decided that it would be safe to assume a potential solar panel set up for the secondary energy unit to be heavier than the primary energy unit being wind energy. It was also safe to assume that a seasonal storage solution will likely be a lot heavier than a day-to-day storage solution. These assumptions also mostly transferred to volume and cost values.

Table 6.2: Technical Budget

	Mass [kg]	Volume [kgm^3]	Power	Cost [€]
Primary energy unit	200 [2x]	1 [2x]	7 [2x] kW	500 000 [2x]
Secondary energy unit	300	1	10 kW	100 000
Day-to-day storage solution	200	0.5	240 kW h	100 000
Seasonal storage solution	600	2	86000 kW h	800 000
Power distribution unit	100	0.5	-	700 000
Total	1600	6	850000 KW h	2 700 000

Following Table 6.2, contingencies of the budget need to be allocated. These are performed for the elements mass, volume, power and cost in tables 6.3, 6.4, 6.5 and 6.6, respectively. Contingencies are essentially margin of errors (in percentages of the elements) taken into account at each stage of the design. As expected, these contingency margins decreases, almost linearly, from (early and vague) conceptual design to the (detailed and validated) final product. This is due to the fact that as the design choices and engineering decisions progress through the project, the level of error from expected elemental results should converge within a small contingency error margin to ensure that the final product meets requirements and is compatible with the overall mission.

Table 6.3: Mass Contingency

	Primary [] energy	Secondary energy	Day-to-day storage	Seasonal storage	Power distribution
Conceptual design	10	50	50	50	50
Preliminary design	8	35	40	40	35
Detailed design	4	10	15	20	10
Final product	2	5	10	15	5

Table 6.4: Volume Contingency

	Primary energy	Secondary energy	Day-to-day storage	Seasonal storage	Power distribution
Conceptual design	40	50	50	50	50
Preliminary design	20	35	40	40	30
Detailed design	10	10	15	20	10
Final product	5	5	10	10	5

Table 6.5: Power Contingency

	Primary energy	Secondary energy	Day-to-day storage	Seasonal storage	Power distribution
Conceptual design	30	20	50	50	-
Preliminary design	10	10	30	30	-
Detailed design	5	5	20	20	-
Final product	2	2	10	10	-

Table 6.6: Budget Contingency

	Primary energy	Secondary energy	Day-to-day storage	Seasonal storage	Power distribution
Conceptual design	10	50	50	50	50
Preliminary design	8	30	30	30	30
Detailed design	5	10	15	15	10
Final product	2	5	10	10	5

7 Requirements

This chapter will go into more detail on the user requirements and system requirements derived from the user requirements. In order to get a good idea of the requirements breakdown, the chapter starts with a requirements option tree in section 7.1. Then the requirements are formulated in section 7.2. The key requirements are elaborated on in section 7.3 with driving requirements in subsection 7.3.1.

7.1. Requirements Discovery Tree

This section contains the requirements discovery tree (RDT) on figure 7.1. It shows how the mission requirements have been separated in technical requirements and constraints that the design needs to comply with.

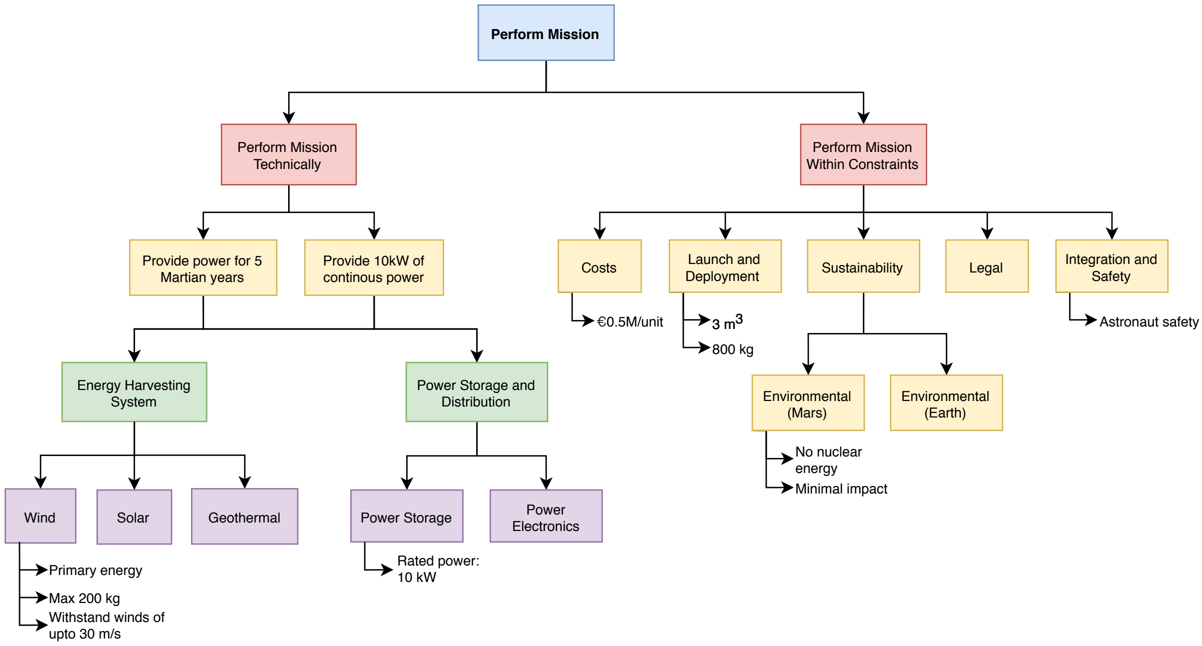


Figure 7.1: Requirements discovery tree

7.2. Requirements

This section lists all the requirements relevant to the design. As mentioned in the previous section, they are separated in the sections given in figure 7.1. Subsystem requirements are also derived and included in this section.

Energy Requirements

- **REM-NRG-01**: Energy system shall provide a continuous power output of 10 kW. *This requirement is a user requirement and needs to be complied with.*
- **REM-NRG-02**: The primary energy system shall be based on wind energy. *This requirement is a user requirement and needs to be complied with.*

- **REM-NRG-03**: The primary energy system shall provide more than 50% of the power output of the entire energy system. *This requirement is a user requirement and needs to be complied with.*
- **REM-NRG-04**: The energy system shall be designed for a lifetime of 5 Martian years. *This requirement is a user requirement and needs to be complied with.*
- **REM-NRG-05**: The power management system shall have an energy storage system. *This requirement is an operative requirement. The entire system cannot function without this. It can be traced to subfunctions F6.4.3 and F6.4.4 in the FFD.*
- **REM-NRG-06**: The power management system shall have a power distribution system. *This requirement is an operative requirement. The entire system cannot function without this.It can be traced to subfunction F6.4.2 in the FFD.*
- **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. *This requirement is a user requirement and needs to be complied with.*
- **REM-NRG-08**: The system shall withstand an impact of [TBD] $N\,m^{-1}$ by flying particles during dust storms. *This requirement originates from the risk assessment and partially mitigates power generation system failure (OP-4).*
- **REM-NRG-09**: The system shall withstand wind speeds[1] up to 30 $m\,s^{-1}$ for 4 Martian months. [23] *This requirement originates from the risk assessment to avoid power generation system failure (OP-4).*
- **REM-Sys-N02-01**: The primary energy system shall have a maximum mass of 200kg. *This requirement is a user requirement and needs to be complied with.*
- **REM-Sys-N02-02**: The primary energy system shall have a cut-in wind speed of [TBD] $m\,s^{-1}$. *This requirement originates from the risk assessment to avoid power generation system failure (OP-5). It can also be traced back to function F6.3 in the FFD.*
- **REM-Sys-N02-03**: The primary energy system shall have a cut-out wind speed of [TBD] $m\,s^{-1}$. *This requirement originates from the risk assessment to avoid power generation system failure (OP-5).It can also be traced back to function F6.3 in the FFD.*
- **REM-Sys-N05-01**: The energy storage system shall have an energy capacity able to sustain life support functions solely for [TBD] time. *This requirement originates from the work breakdown structure, item 7.2. This relates to the system being able to sustain life support even when the energy production systems may be interrupted.*
- **REM-Sys-N05-02**: The energy storage system shall have an energy capacity of [TBD] kWh. *This requirement is based on correct operation of the system.*
- **REM-Sys-N05-03**: The energy storage system shall have a rated power of 10 kW. *This requirement is based on correct operation of the system.*
- **REM-Sys-N05-04**: The energy storage shall have a maximum mass of [TBD] kg. *This requirement ensure the risk of the system being too heavy to be eliminated.*
- **REM-Sys-N05-05**: The energy storage subsystem should make use of ISRU storage options by at least [TBD]%. *This requirement is a user requirement and needs to be complied with.*
- **REM-Sys-N06-01**: The power distribution system shall be able to support a peak power input of [TBD] kW. *This requirement is based on correct operation of the system.*
- **REM-Sys-N06-02**: Cable losses between primary energy unit and the combined unit path shall be less than [TBD]%. *This requirement originates from the risk assessment to avoid power distribution system failure (OP-5).*
- **REM-Sys-N06-03**: Cable losses between secondary energy unit and the combined unit path shall be less than [TBD]%. *This requirement originates from the risk assessment to avoid power distribution system failure (OP-5).*
- **REM-Sys-N06-04**: Cable losses between combined unit and the habitat path shall be less than [TBD]%. *This requirement originates from the risk assessment to avoid power distribution system failure (OP-5).*
- **REM-Sys-N06-05**: The power distribution system shall have a maximum mass of [TBD] kg. *This requirement ensure the risk of the system being too heavy to be eliminated.*

Mars Environmental Requirements

- **REM-MENV-01**: No nuclear energy shall be used. *This requirement is a user requirement and needs to be complied with and is also inline with the sustainability operations.*

[1] https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html [Cited 1 May 2020]

- **REM-MENV-02**: The impact on Mars' environment shall be minimal at end of life. *This requirement is a user requirement and needs to be complied with and is also inline with the sustainability operations.*
- **REM-Sys-M02-01**: At least [TBD]% of the material for this system shall be sourced from Mars. *This requirement is derived from the Sustainability analysis.*
- **REM-Sys-M02-02**: [TBD] % of the system materials shall be reused or recycled at the end-of-life. *This requirement is derived from the Sustainability analysis.*

Earth Environmental Requirements

- **REM-EENV-01**: The impact on Earth's environment shall be minimal. *This requirement is a user requirement and needs to be complied with and is also inline with the sustainability operations.*
- **REM-Sys-E01-01**: The generated manufacturing and production waste shall not exceed [TBD] M€. *This requirement is derived from the Sustainability analysis.*

Launch and Deployment Requirements

- **REM-LD-01**: The maximum volume for transportation shall be 3 m^3. *This requirement is a user requirement and needs to be complied with.*
- **REM-LD-02**: The maximum payload shall be 800 kg per flight. *This requirement is a user requirement and needs to be complied with.*
- **REM-LD-03**: The number of flights shall not exceed [TBD] for the system to be deployed and fully operational. *This requirement is a user requirement and needs to be complied with.*
- **REM-LD-04**: The deployment time on Mars shall not exceed [TBD]. *This requirement is a user requirement and needs to be complied with.*

Cost Requirements

- **REM-COST-01**: The cost shall be a maximum of €500 000 for the primary energy unit (excluding any costs not directly related to the production of the unit). *This requirement is a user requirement and needs to be complied with.*
- **REM-COST-02**: The mission cost shall not exceed [TBD] M€. *This requirement originates from the budget analysis and is important to keep the projet within a certain budget.*
- **REM-Sys-C02-01**: Cost per launch and deployment shall be less than [TBD] M€. *This requirement originates from the budget analysis.*
- **REM-Sys-C02-02**: Cost per primary energy source shall be less than [TBD] M€. *This requirement originates from the budget analysis.*
- **REM-Sys-C02-03**: Cost per secondary energy source shall be less than [TBD] M€. *This requirement originates from the budget analysis.*
- **REM-Sys-C02-04**: Cost of power management system shall be less than [TBD] M€. *This requirement originates from the budget analysis.*

Legal Requirements

- **REM-LEG-01**: The project shall adhere to the legal guidelines established by the resolution 2222 (XXI) of the United Nations General Assembly on space operations.[2] *This requirement is related to the Market Analysis where Legislators are also part of the project's stakeholders.*
- **REM-LEG-02**: The mission shall not interfere or preclude the planning or operation of other missions on Mars. *This requirement is related to the Market Analysis where Legislators are also part of the project's stakeholders.*
- **REM-LEG-03**: The project shall adhere to the legal guidelines working paper A/AC.105/C.2/L.315 of the United Nations General Assembly on space resource activities.[3] *This requirement is related to the Market Analysis where Legislators are also part of the project's stakeholders.*

Integration and Safety Requirements

[2] https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html [Cited 4 May 2020]
[3] https://www.unoosa.org/oosa/oosadoc/data/documents/2020/aac.105c.2l/aac.105c.2l.315_0.html [Cited 4 May 2020]

- **REM-IAS-01**: Astronauts shall be equipped with all necessary safety gear as established by the American Institute of Aeronautics and Astronautics [16].[4]. *This requirement is related to the Market Analysis where Legislators are also part of the project's stakeholders.*
- **REM-IAS-02**: The system's parts and components should be fully replaceable/repairable on site with the existing materials and/or equipment. *This requirement is derived from the risk assessment, such that risk OP-7 can be mitigated.*
- **REM-IAS-03**: The number of maintenance flights shall not exceed [TBD] for the duration of the mission. *This requirement is derived from the risk assessment, such that risk OP-7 can be mitigated.*
- **REM-Sys-I01-01**: The astronauts shall not be exposed to more than 1 Sv of radiation for the duration of the mission. *This requirement is related to the Market Analysis where Legislators are also part of the project's stakeholders.*

7.3. Key Requirements

The key requirements are the requirements which are very important for the stakeholder, so these should be the primary ones considered during the design process. Looking at all the requirements in the previous section, a couple have been chosen to be key requirements.

- **REM-NRG-01**: Energy system shall provide a continuous power output of 10 kW.
- **REM-NRG-02**: The primary energy system shall be based on wind energy.
- **REM-NRG-04**: The energy system shall be designed for a lifetime of 5 Martian years.
- **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.
- **REM-MENV-01**: No nuclear energy shall be used.
- **REM-MENV-02**: The impact on Mars' environment shall be minimal at end of life.
- **REM-Sys-M02-01**: At least [TBD]% of the material for this system shall be sourced on Mars.
- **REM-Sys-N02-01**: The primary energy system shall have a maximum mass of 200kg.
- **REM-Sys-N05-05**: The energy storage subsystem should make use of ISRU storage options by at least [TBD]%.
- **REM-COST-01**: The cost shall be a maximum of €500 000 for the primary energy unit (excluding any costs not directly related to the production of the unit).
- **REM-LD-01**: The maximum volume for transportation shall be 3 m^3.
- **REM-LD-02**: The maximum payload shall be 800 kg per flight.

7.3.1. Driving Requirements

Of the key requirements, some of them are driving requirements:

- **REM-NRG-01**: The goal of the mission is to generate enough energy to build and maintain the Mars Habitat. For this a total of 10kW is needed, making this a driving requirement for the design.
- **REM-NRG-02**: This requirement, which is set by the stakeholder, already implies a design choice for the energy system. Therefore, it is a driving requirement.
- **REM-NRG-04**: The design choices made in the trade-off for the energy system will depend heavily on this requirement. Anything with too short of a lifespan will need to be replaced or maintained too often which will make it hard to guarantee a lifetime of 5 martian years.
- **REM-Sys-M02-01**: This requirement is also set by the stakeholder and simply needs to be complied with by the design team. It will likely influence design choices during the trade-off.
- **REM-COST-01**: As this requirement is given by the customer, it is important to comply with it to ensure that the customer will buy the system.
- **REM-LD-01**: This requirement is considered a driving requirement as the system is not allowed to be too big to transport to Mars. It could have an important impact on the design options trade-off.
- **REM-LD-02**: The requirement is driving because the entire system including energy harvesting devices and power management systems will have to fit in a rocket and therefore cannot be too heavy. I could have an influence on which design are chosen during the trade-off to account for light weight options.

[4] https://ebookcentral-proquest-com.tudelft.idm.oclc.org/lib/delft/detail.action?docID=3111645 [Cited 4 May 2020]

8 Design Option Trees

In this chapter, the design option trees (DOT's) with possible design considerations, configurations and concepts for the Renewable Energy for Mars Habitat project are presented. The DOT's are followed by the elimination of obviously non-feasible concepts, concepts inappropriate for the current mission and requirements and concepts that are workable, yet not worth pursuing further into the preliminary design phase. This concept elimination is presented for each of the systems identified on the DOT. The DOT was split up into several different categories, which are then further broken down in all possible options. The following six categories are shown in the DOT in figure 8:

- Site selection
- Wind energy generation
- Solar energy generation
- Geothermal energy generation
- Energy storage
- Microgrid

The diagram shows all categories and their corresponding option trees separately. Green and red arrows represent an AND and an OR gates respectively, meaning that for all boxes pointed to by a green arrow are always included in the concept from which the arrow points, and that for all boxes on a level that are pointed to by a red arrow, only one must be selected.

Section 8.1 describes all concepts available for Wind Energy systems and their feasibility, section 8.2 explains this for Solar energy systems and section 8.3 for Geothermal energy systems. Furthermore, the microgrid is explained in section 8.4, the Power storage options in section 8.5 and the Site selection description can be found in 8.6.

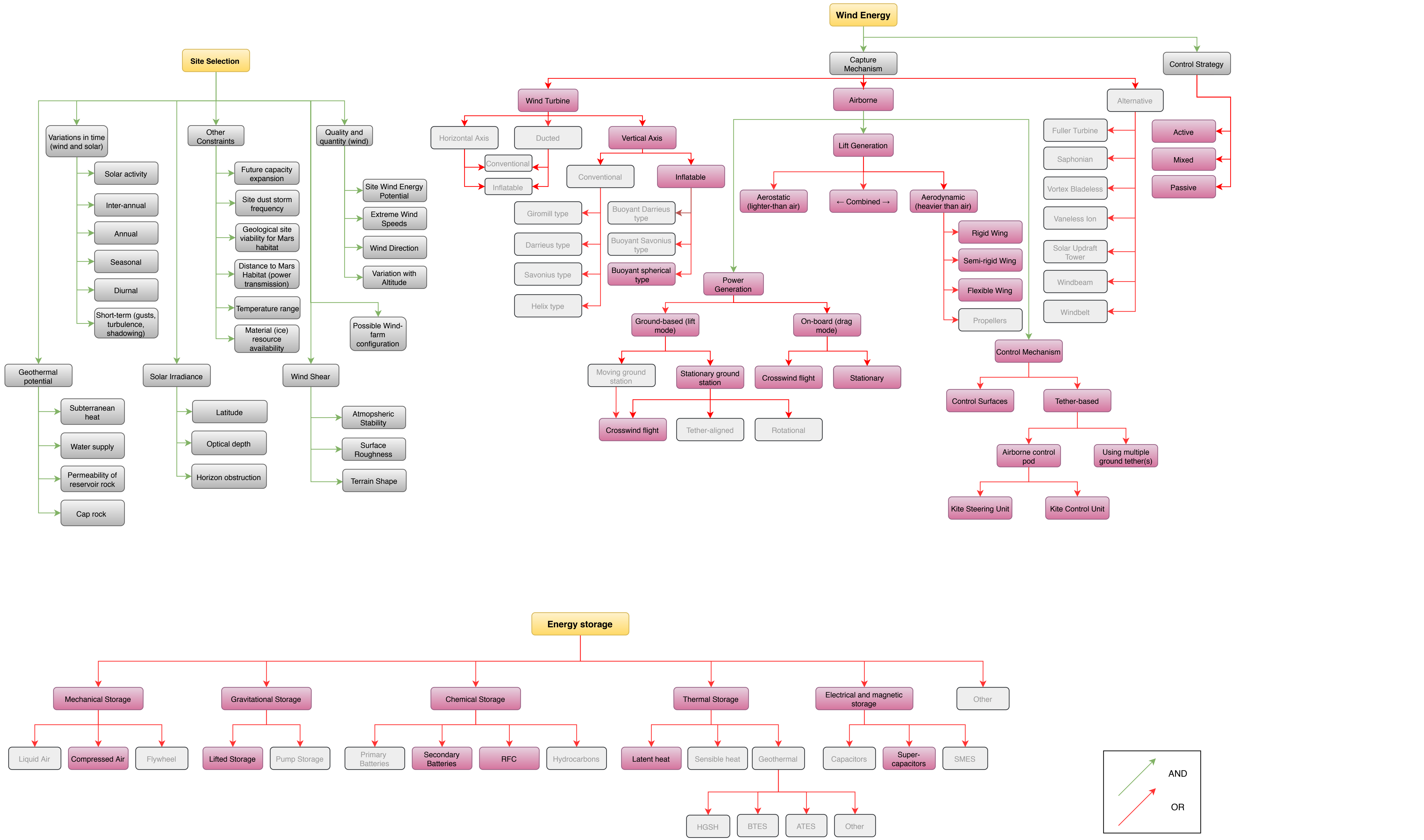
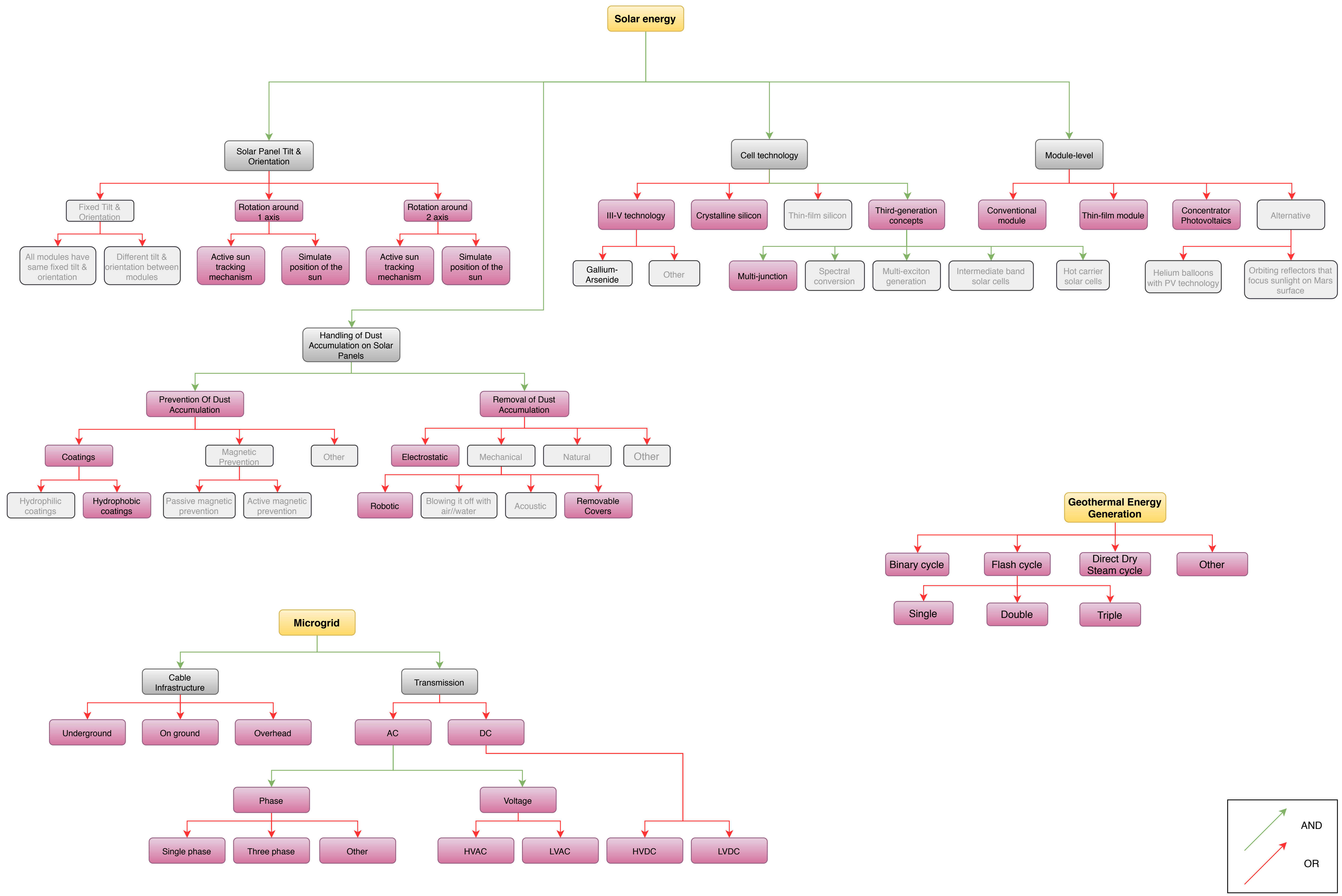


Figure 8.1: Design Option Tree


Solar energy
Solar Panel Tilt & Orientation
Fixed Tilt & Orientation
Rotation around 1 axis
Rotation around 2 axis
All modules have same fixed tilt & orientation
Different tilt & orientation between modules
Active sun tracking mechanism
Simulate position of the sun
Active sun tracking mechanism
Simulate position of the sun
Cell technology
III-V technology
Crystalline silicon
Thin-film silicon
Third-generation concepts
Gallium-Arsenide
Other
Multi-junction
Spectral conversion
Multi-exciton generation
Intermediate band solar cells
Hot carrier solar cells
Module-level
Conventional module
Thin-film module
Concentrator Photovoltaics
Alternative
Helium balloons with PV technology
Orbiting reflectors that focus sunlight on Mars surface
Handling of Dust Accumulation on Solar Panels
Prevention Of Dust Accumulation
Removal of Dust Accumulation
Coatings
Magnetic Prevention
Other
Electrostatic
Mechanical
Natural
Other
Hydrophilic coatings
Hydrophobic coatings
Passive magnetic prevention
Active magnetic prevention
Robotic
Blowing it off with air/water
Acoustic
Removable Covers
Geothermal Energy Generation
Binary cycle
Flash cycle
Direct Dry Steam cycle
Other
Single
Double
Triple
Microgrid
Cable Infrastructure
Transmission
Underground
On ground
Overhead
AC
DC
Phase
Voltage
Single phase
Three phase
Other
HVAC
LVAC
HVDC
LVDC
AND
OR

8.1. Wind Energy

This section contains the concepts considered for the wind energy system and eliminates the ones unfeasible for the given mission.

For the quantitative analysis of the feasibility of some of the concepts, calculations had to be made, for which some information on the wind resource - and thus wind speeds - were required. Data from the Viking 1 Lander site [43] [1] is considered, at which the Mars wind speeds are given to range from 2-7 ms^{-1} during summer, 5-10 ms^{-1} during winter and 17-30 ms^{-1} during dust-storms.

8.1.1. Wind Turbine

- **Horizontal Axis Wind Turbine**: Very little literature considering the use of a HAWT concept on Mars was found. Thus, a calculation was made on the required blade size for maximum available power to be captured, based on a general equation for how much power a wind turbine can produce [42]:

$$P = \frac{1}{2} n \rho S V^3 \tag{8.1}$$

  Where n is the power coefficient, ρ is the atmospheric density at a certain location (between 0.015kgm^{-3} [19, 43] [2]), S is the area swept by the wind turbine and V is the wind speed. A power coefficient of $n = \frac{16}{27} \cong 0.593$, also better known as the Betz limit, would be the theoretical ceiling for power capture of a HAWT under perfect conditions. Using a lower value than this could correspond to a first-level estimation useful for HAWT sizing.

  For the highest attained wind speeds of 30 ms^{-1} during dust storms, 5 kW power capture under perfect conditions would require HAWT blades of 3.2 m length. However, dust storms would only be present for a fraction of the mission - assuming a more realistic mode value of 7 ms^{-1}, power generation of at least 5 kW would already require wind turbine blades 28 m long, and with more realistic considerations the blades grow to 35.2 m length. Multi-sectioned blades concepts on Earth exist, but would still violate the given mass and volume requirements, not to mention the required tower structure. Thus, the HAWT concept is considered unfeasible for the mission.

- **Vertical Axis Wind Turbine**: Two main concepts were seen in literature with regards to wind energy utilisation on Mars for the VAWT, conventional (with a tower) and inflatable (built either with a buoyant hydrogen balloon above or inside the VAWT).
  - **Giromill type**: The Giromill is a lift-type VAWT. A two blade Giromill concept encountered in literature had a 17 m, a diameter of 12 m, a power coefficient of 0.47 and a power output of 12.1 kW [21]. Its system mass is estimated at 275 kg, assuming that the launch vehicle would serve as a tower (21.5 m tall), thus discounting a large portion of mass and transport volume required for the system. The power estimation was done assuming 25 ms^{-1} wind speed, and at a wind speed of even 14 ms^{-1}, the power output drops to 2.1 kW. As the wind speeds will be lower than this for the majority of the operational time, the Giromill concept is thus also non-conforming with the given requirements.
  - **Darrieus type**: The Darrieus VAWT is similar to the Giromill and is also a lift-type VAWT. A concept found in literature examines a Darrieus style wind turbine with troposkein-shaped blades that were 30 m long [23]. A generated power of 14 kW at 25 ms^{-1} was predicted, with a system mass of 944 kg for a conventional configuration, and 808 kg for an inflatable one, though under assumptions of even higher (30 ms^{-1}) wind speeds. Again, accounting for lower power requirements and wind speeds, this concept would still be unfeasible given the mass and volume requirements.
  - **Savonius type**: The third examined concept for the VAWT class is the Savonius type, which is a drag-type wind turbine. Its predicted geometry, performance and mass [23] does not vary too much from the two VAWT concepts examined above, both in the conventional and inflatable configuration, and hence is considered unfeasible.
  - **Helix type**: The final conventional VAWT concept explored is the lift-type helix, which also fails the requirements when non-dust-storm conditions are considered in a similar fashion to the VAWT concepts examined above.

[1] https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html [Cited 1 May 2020]
[2] https://www.grc.nasa.gov/WWW/K-12/airplane/atmosmrm.html [Cited 4 May 2020]

– **Buoyant Spherical Type**: A conceptual design could weigh 428 kg with blade length of 25 m and a power output of 19 kW at 25 ms^{-1} [23]. These numbers reveal this design to be the most promising VAWT concept. On a first level estimation the power output for it would drop down to 4.2 kW at 7 ms^{-1}. The blade lengths, whilst large, are not completely prohibitive yet as they do not take up so much volume because they only surround the buoyant balloon. This concept is 20 years old by now, so it is considered that it may warrant a closer look in the next design stage as it does not seem to be completely unfeasible given the mission requirements.

Airborne Wind Energy

Based on Bier et al. [12], an airborne wind energy system based (presumably) on the prototype described by van der Vlught et al. [39] is considered to be a possible concept for the particular Mars habitat around which the mission is designed. The weight and volume estimations are about 150-200 kg and 2 m^3 respectively, which clearly conforms to the given mission requirements. However, there are a few clearly unfeasible concepts that can be eliminated.

- **Moving Ground Station**: Moving ground-station concepts are immediately discarded for our purposes, as they seem to be both scaled more towards the larger GW scale of energy production [5], and are still considered to be far from being realised [32].
- **Rotational**: Whilst rotational flight-operation AWE systems seem to be a great technology for our purpose, providing massive specific energy and energy density values, the technology is also in its early design stage and very little information on its design is available, with its patent still pending [3].
- **Tether-aligned**: A representative of this concept is the Laddermill. It consists of several power kites flying in a string or loop configuration, which are connected to the same main tether to increase their shared total wing area. The airflow of the kites influences each other, so the output does not increase linearly with the number of kites. The reliability of the interconnected kites seems to be an issue as well. Furthermore, the start-up of a multiple wing system is way more challenging compared to a single wing system [7]. Due to these issues, the fact that there seem to be few advantages compared to using a single and the inadequate knowledge on tether-aligned AWE system design, it is discarded.
- **Propeller**: This drone-like configuration was for example realised by the Sky Windpower team, using 4 rotor-generator propellers that first lift the system up to a required altitude, to generate power afterwards. The team uses the same equation 8.1 for their basic system analysis [4]. To check for concept feasibility, preliminary calculation for Martian conditions is performed. For this concept to provide 5 kW of power on Mars for the same wind speed used by the teams' calculations (presumed very high), an even larger rotor diameter of 13.9 m would be required - four of them. As this would violate the given volume requirements, this concept is considered unfeasible.

Alternative

The following alternative concepts were all removed from further consideration in the preliminary design phase:

- **Fuller Turbine**: The technology is still unproven and in its' pre-prototype stage, with very little information on its design and analysis available. Only one startup 'Solar Aero' seemed to be working on developing this technology more than a decade ago [5].
- **Saphonian Turbine**: The technology is still unproven and in its pre-prototype stage, with very little information on its design and analysis available. Only one startup 'Saphon Energy' seemed to be working on developing this technology in the last decade, with the last update being six years old [6].
- **Vortex Bladeless**: The technology is in its prototype stage, with promising implications for the given mission, especially with respect to fatigue life [41]. A prototype is currently being developed, however as a 2.75 m tall model should be able to produce only a 100 W nominal power output, it seems that this concept would not be able to conform to the mission requirements.

[3] https://windswept-and-interesting.co.uk/ [Cited 12/5/2020]
[4] https://www.skywindpower.com/science_windpower.htm?_p=Y[Cited 12 May 2020]
[4] https://www.skywindpower.com/technology.htm?_p=Y[Cited 12 May 2020]
[5] https://www.treehugger.com/clean-technology/solar-aero-develops-bladeless-tesla-inspired-wind-turbine.html [Cited 4 May 2020]
[6] https://www.enn.com/articles/45171 [Cited 4 May 2020]

- **Vaneless Ion**: The technology seems not to have went past its prototype stage, with limited information on its design and analysis available. However, knowing that its efficiency of wind energy capture is about half of the values for HAWT [8], this technology is considered unfeasible for the mission as too great of an area would need to be covered.
- **Solar Up-draft Tower**: The technology is considered unfeasible for the mission, due to the massive material use and solar collection areas (chimney heights of 100+ m, collection areas of 10+ ha) required for power generation [44].
- **Windbeam**: The technology is unfeasible for the mission, as it is not prototyped for energy production of required mission scale yet. The largest scaled prototype design should produce 3 W power [7].
- **Windbelt**: The technology is unfeasible for the mission, as it is not prototyped for energy production of required mission scale yet. A working prototype is apparently capable of charging one AA cell in 125 days. The largest scaled prototype design is claimed to be capable of generating up to 3-10 W power [8]. No updates on the technology in about a decade.

Baseline Design Options

The following concepts were not eliminated in the baseline review and thus go on to be further explored in the next design phase:

- Vertical Axis Wind Turbine - Inflatable - Buoyant spherical type
- Airborne Wind Energy

8.2. Solar Energy

Over the past thirty years the application of PV systems has grown exponentially and they have developed into a mature technology. Solar energy has been an important energy source for many spacecraft (satellites, landers and rovers) and it will remain so for many years. Even though Mars is further away from the sun in comparison to Earth, solar energy has a big potential. There are various aspects to be taken into account if one is to design a solar energy supply system for a Mars habitat. These are presented in the DOT and are discussed in the following subsections. For each aspect, the feasibility of the different options is examined for application in a renewable energy system for Mars habitats.

Cell technology

With cell technology, the electrical device is meant which generates electric current in response to electromagnetic radiation. All solar cells rely on the junction of different semiconductor materials. Based on the latter, however, the solar cell will experience varying efficiencies and cell technology can optimised for specific applications. Finally, third generation concepts refer to novel approaches that aim to overcome certain theoretical limits [34]. Before discussing the different cell technologies, it is important to mention that the solar spectrum has an important effect on the energy yield. The spectrum on the Martian surface is different from Earth's spectrum. Due to the dust present in Mars' atmosphere, a decrease in overall intensity of incident sunlight is observed, as well as a spectrum shift. In effect, the diffused irradiance is much enriched in the long-wavelength (red) part of the spectrum [9][25].

- **Crystalline silicon (c-Si)**: This PV technology is the most prominent technology on the market, while the vast majority of commercial PV systems are based on this type of solar cell. It is often referred to as the first generation PV technology, and it is a cheap option. Nevertheless, it is not commonly used in space missions due to the low band gap of the semiconductor material. Because of the low band gap, a great portion of energy from incident photons is lost inside the cell which limits its efficiency considerably. It must be noted however, that due to the red spectrum of the sunlight received on Mars' surface, c-Si solar cells are more efficient on Mars than on Earth or in space. Still, the possibilities to optimise c-Si cells for Mars' spectrum are limited, in contrary to some of the technologies that will be discussed subsequently. Nevertheless, the cost advantage of c-Si solar arrays leaves them as a considerable candidate for the trade-off.

[7] http://zephyrenergy.com/?page_id=440 [Cited 4 May 2020]
[8] https://www.pcmag.com/archive/humdinger-windbelt-achieves-a-new-milestone-280148 [Cited 4 May 2020]
[9] https://ntrs.nasa.gov/search.jsp?R=20110000777

- **Thin-film Silicon**: thin-film solar cells are referred to as the second generation PV technology. As the name suggests, they are made from films much thinner than the traditional c-Si wafers. Thin-film solar cells have lower mass, lower stowed volume and the possibility to be fabricated on a flexible substrate. Yet, in general thin-film cells have a lower efficiency than c-Si solar cells. Currently, the highest efficiencies are in the range of 10-12 % under AM1.5 conditions [17]. Considering the 10 kW power output requirement that must be satisfied, this technology is not considered feasible due to the low efficiency. Thin-film silicon cells will therefore not be selected for the trade-off. It must be noted though, that III-V based solar cells can also be considered as thin-film technologies, which is why ”thin-film” is still mentioned at the module level.
- **III-V technology**: of all different cell technologies, the highest conversion efficiencies result from III-V technology [34]. Being too expensive for Earth applications, it is mainly used in space applications, and therefore an important technology to consider in the trade-off. In the tree, the only III-V semiconductor mentioned is gallium arsenide (GaAs), because it is the most common. It must be pointed out that at this stage it is too early to choose which III-V technology would be the most optimal for application in a renewable energy system on Mars. It would require a thorough research on spectral utilisation of different semiconductor materials which is not possible at this stage due to time constraints. It is noteworthy that two Mars Exploration Rovers, deployed on Mars in 2004, used GaInP/GaAs/Ge triple-junction cell technology [24] [10]. The multi-junction concept is elaborated in the next item. To conclude this item: III-V PV technology has potential for high efficiencies and is definitely to be selected for the trade-off.

Third-generation concepts

As explained before, third-generation concepts aim to overcome certain theoretical limits. These concepts can be applied to the different cell technologies that were described in the previous subsection. Five of these concepts are itemised below.

- **Multi-junction solar cells**: ”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.” [34]. The top cells absorb photons in the low wavelength part of the spectrum, and the bottom cells absorb photons with higher wavelengths. In this way, the spectrum from the available sunlight is optimally used, maximising the efficiency. Almost all state-of-the-art solar cells for space applications rely on this technology, as mass and volume constraints demand for high efficiency solar cells. Therefore, multi-junction technology is definitely a good option to consider for the trade-off.
- **Spectral conversion**: Energy from photons with wavelengths different than the bandgap wavelength of the semiconductor material can be lost because it cannot be absorbed by the cell. This problem can be overcome by spectral conversion, which consists of adding a layer on top of the cell that alters the incident spectrum. By spectral up- or downconversion, the energy absorbed from incident photons is maximised. A way of implementing spectral conversion is by making use of quantum dots [34]. This technique can greatly enhance the efficiency of solar cells. However, still a lot of research is being done and it is not readily available for space missions yet. Also, the focus of this project is more on designing the wind energy system. Therefore it is chosen not to include this concept in the trade-off.
- **Multi-exciton generation**: This concept, in a comparable manner as for spectral conversion, also makes use of quantum dots to maximise the energy absorbed from incident sunlight. For similar reasons, it is not considered a feasible design option.
- **Intermediate band solar cells**: photons with energies below the bandgap cannot be absorbed by the solar cell. Using the intermediate band concept, this problem is tackled. It should be stressed however that this technique still needs significant development, and therefore is deemed unfeasible.
- **Hot carrier solar cells**: The idea of hot carrier solar cells is to minimise energy losses due to relaxation (and hence thermalisation) mechanisms inside the semiconductor material [34]. However, this concept is also still at a very low TRL, and relies on concepts that are outside of the scope of this design project. Therefore it is not selected for the final trade-off.

[10] http://www.sti.nasa.gov

Module-level

In the previous subsection, different cell technologies are described. A PV module is an assembly of multiple of these solar cells. These can be arranged in different ways. The module-level technology is examined in this subsection.

- **Conventional module**: with conventional module, the typical flat-plate panels are meant that are e.g. commercially available, or used on satellites. The conventional module consists of multiple solar cells, electrically connected and mounted on one supporting structure. The conventional modules are often used in PV farms on Earth for large scale electricity generation because of their simplicity, low cost and structural rigidity. Although different support structures are available for conventional modules, they are definitely heavier than thin-film modules, which is to be taken into account during the trade-off. Altogether, it is noteworthy that the conventional module is a feasible option for the module design of the solar energy system.
- **Thin-film module**: as already stated in the previous subsection, these modules are much thinner than the conventional modules. They can be either flexible or rigid (e.g. glass), which allows for many possible configurations in terms of tilt, orientation and mounting of the solar modules on existing structures belonging to the Mars habitat. Not all kind of solar cells can be assembled on a thin-film module. ”While for c-Si technology producing cells and modules are two distinct steps, in thin-film technology producing cells and modules cannot be separated from each other” [34]. Thin-film modules have the advantage of lower mass, stowed volume, they may limit the maximum possible efficiency of the solar cells. These are all important aspects to take into account during the trade-off. That being said, it is a considerable design option.
- **Concentrator photovoltaics (CPV)**: by concentrating sunlight, the irradiance is increased. If a solar cell is illuminated by concentrated sunlight, the cell will yield a higher output power, increasing its efficiency. This concept is highly interesting for high end cell technologies such as III-V multi-junction cells. Combining all these concepts, record lab-scale efficiencies of 46 % have been realised [34]. As Mars receives less than half of the solar irradiance received on Earth, CPV is an very interesting for application in a renewable energy system on Mars. It is a very feasible concept and will be considered in the trade-off.
- **Alternative**: in the DOT, two alternatives are mentioned, namely: helium balloons with PV technology, and orbiting reflectors that focus sunlight on Mars surface. The former concept is proposed by V. Badescu in 2009 [4] and consists of a helium balloon with an embedded PV array that collects sunlight high up in the atmosphere. In this manner, incident sunlight can be collected in the dust-free part of the atmosphere. Although it is an interesting concept, the TRL is low and it will not be considered during the trade-off. The same holds for the futuristic concept of having reflectors orbiting Mars. The concept here is to focus sunlight from outside the Martian atmosphere onto solar arrays on Mars. This option is cumbersome and does not way up to the ease of implementing CPV.

Solar panel tilt & orientation

For the solar panel tilt and orientation there are three important methods to take into account: fixed tilt & orientation, rotation around 1 axis or rotation around 2 axis.

- **Fixed tilt & orientation**: In this configuration tilt and orientation will be fixed for each individual solar panel. The tilt and orientation could be the same for each module or could be different for each one. Either way, the option of keeping the tilt and orientation fixed does not seem like the most effective way to use the sun for energy. Essentially, one would prefer to ensure an incident angle of 90 degrees by the sun-rays for most of the day in order to harvest as much energy as possible. In order to do this, rotating solar panels would be preferable. As such, this option will be discarded in favour of the next two options.
- **Rotation around 1 axis**: For rotation around 1 axis, there is either the option to use an active sun tracking mechanism or to simply simulate and calculate the position of the sun at each time of the day. Those inputs are then used to set the most efficient angle for the solar panels. Both these methods are viable options, though the active sun tracking mechanism is probably more complex than the simulation, however it will be more accurate. Thus, both options will still be taking into account during the trade-off.
- **Rotation around 2 axis**: For this method, the two options described in the single axis rotation also exist and stay relevant as options to choose from. The difference here though is that the panel can rotate around 2 axis rather than just 1. This could allow for extra precision in sun pointing. However, the

trade-off will have to help decide whether this added complexity is worth implementing over a simpler 1 axis version.

Handling of dust accumulation on solar modules

To make sure the solar panels will be able to perform at the necessary levels, it is important to consider the martian dust which will fall down onto the panels. This will reduce performance and can be accounted for by either the prevention of dust accumulation, the removal of the dust or both if necessary.

Prevention of dust accumulation can be done using several methods. Coatings can be used, and possibly magnetic prevention can be used.

- **Coatings:** The surface of the solar panels can be treated using a nano-structured coating. This coating will be either superhydrophilic, meaning it attracts water, or superhydrophobic, meaning it repels water. The former cleans itself, by building up a thin layer of water which it uses to guide away any particles that attach. As water is very clear it does not inhibit the performance of the panels[36]. However due to the lack of water in the martian atmosphere, this coating will not be applicable as there would be no buildup of water on the panel and thus no way to clean away the dust.
  The superhydrophobic coating, acts in a similar matter. However with in this instance the dust falls on the panel and is then cleared away by use of water droplets that do not adhere to the panel, but immediately flow off and taking the dust with in the process[36]. This comes with the same challenge as before as there is no rain on Mars. There have been recent development however that use a hydrophobic coating that was engineered using nano structures, for dust removal under gravity instead of using water[22]. There have been tests performed with this coating and it seems highly promising. Therefore it will be considered in the trade-off.
- **Magnetic Prevention:** It has been found that the dust on Mars contains the ferromagnetic magnetite[33]. Thus a study was completed to see if it was possible to repel the dust from the solar panel, to keep it from adhering to the panel, by use of magnets[14]. However there have been no conclusive tests performed, and there is a risk of the magnetic field attracting the dust and thus bombarding the panel with particles. Due to the uncertainty of the performance, this method will not be considered for the trade-off.

It is also possible to remove any dust accumulation of the panels by using electrostatic, mechanical or natural means.

- **Electrostatic:** This method uses high-voltage polyphase waveforms at various frequencies[36]. These waves would be able to move the charged particles and guide them off the panel when necessary. This could work especially well due to the magnetite dust, as was mentioned previously. As this method has already been widely used on Earth and has been proven to be functional it is worth considering for the final design.
- **Mechanical:** There are several types of mechanical dust removal that can be considered, as mechanical can take many forms. There is the possibility of robotic, blowing, acoustic and covers.
  Robotic: This uses mechanics, such as wipers to brush the dust away. This method has also been widely used on Earth and has been proven to be very effective[36]. Therefore it is worth to consider robotic in the final design.
  Blowing it off with air/water: Blowing it off uses either water or air at high velocities to blow off the dust. However due to the scarcity of water on Mars, it is not a viable option to use it to clean the solar panels in an open system.
  As for the air blowing, due to the thin atmosphere an air compressor would be needed to give the air an appropriate density to be able to blow off the dust. Furthermore to remove the adhered dust, high wind speeds would have to be generated and a relatively high pressure when compared to the martian atmosphere. This is due to the energy needed to remove the dust. As this would be unlikely to be realised for every panel, the air blowing will no longer be considered as an option for trade-off.
  Acoustic: This method of removing dust is similar to the electrostatic method as it also uses waves. However it uses acoustic waves in contrast to electromagnetic waves[2]. However it is a recent invention, and very high voltages would be required for it to perform up to par. Furthermore, a secondary system would be required as the acoustic waves only loosen the sand and do not remove it from the panel. Moreover there is a possibility of the acoustic waves damaging the panel due to its strong vibrations. As not enough is known about there dangers, this method will eliminated as an option for trade-off.

Removable covers: This is a way of keeping dust off the solar panels during the night, by putting a cover on the panel to keep the dust from falling onto the panel[36]. This would come with the added benefit as it could protect the solar panels. However this would not protect the panel during the day. There is no reason to discard this method in this stage of the design.

- **Natural:** The easiest method of cleaning the solar panels, is to let the wind clean of the panels. However, if there is build up of dust during times where astronauts are unable to exit the habitat there is no way of cleaning the panels. Furthermore you are reliant on the wind, and as that is not constant or predictable, this is not a proper way to keep the panels clean, as dust buildup can reduce the performance up to 80%[14]. Therefore this would not be optional for the mission, as reliable power is required.

Baseline Design Options

The following concepts for each branch of the design option tree will continue to be investigated during the trade-off part of the next design phase:

Cell technology

- Crystalline silicon (c-Si)
- III-V technology
- Multi-junction solar cells

Module-Level

- Conventional module
- Thin-film module
- Concentrator photovoltaics (CPV)

Solar Panel tilt & orientation

- Rotation around 1 axis
- Rotation around 2 axis

Handling of dust accumulation on solar modules

- Hydrophobic
- Electrostatic
- Robotic
- Removable covers

8.3. Geothermal Energy

Research has been done to examine whether Mars is suited to be utilised for geothermal energy harvesting or not. Even tough no direct Martian geothermal measurements have been taken, “orbital imaging spacecrafts and landers have greatly improved the resolution of Mars’ surface mapping, and together with modelling studies, have increased the understanding of the thermal structure and evolution of Mars” [4]. Hence, substantial data and analyses supporting the possible existence of geothermal energy has been gathered and examined for the purposes of proving renewable energy supply to a Martian habitat. While black body radiation analyses and computations of Mars’ global heat flow strongly deem the radiated heat as not sufficient, other observed phenomena such as volcanism and tectonism allow for further investigation into this concept.

Nevertheless, other aspects and specification of the site location of geothermal power plants also limit the design solution suitable for Martian environment. In order to implement geothermal energy resource on Mars, the following four environmental conditions must be met as stated and identified by Fogg in 1996 [15]:

1. Powerful and natural subterranean heat source must present
2. Sufficient water supply must present
3. Permeable rock reservoir to serve as an aquifer must present
4. A cap rock must present

Once those criteria are identified, suitable site locations such as Cerberus Plain, Medusae Fossae Formation, Northwestern Tharsis and Valles Marineris that could possibly meet the requirements are presented and discussed [15]. Nevertheless, one of the challenges of geothermal energy harvesting is actually assuring all your needs are met and will remain for the life duration of the geothermal power plant. As no physical and direct evidence has yet been gathered, all the research and observations which would lead to the construction of a geothermal power plant, are still to be done and analysed. Such kind of thorough studies do require years of research when done on Earth, and surely longer if considered to be done on another plant. Hence, the possibility that in the next ten years, a site location, which does meet the above mentioned requirements while also complying with the necessitates of the Martian habitat and the renewable wind energy farm, has been certainly identified and validated through testing or simulations, is extremely low. Therefore, even if geothermal technology itself could be mature enough, the available information and data gathered might be insufficient.

Furthermore, the logistical and construction elements of implementing geothermal energy harvesting on Mars, introduces further technical complications and complexities. As geothermal power plants utilise subterranean heat, a mean for reaching that heat must be present. A study from 2008, presents an average depth of geothermal energy harvesting wells of approximately 3 km [13]; the depth is evaluated based on the desired temperature of the heat source. Nevertheless, the constructional requirements and necessities of such deep wells are extremely costly, time consuming and depended on industrial scale machinery. Hence, translating such process to another planet suggests way greater costs and project duration. In addition, as the digging and drilling machines implemented for that purposes are extremely heavy and fuel based. Interplanetary transportation of such equipment seems unfeasible and unreasonable for the next ten year. In addition, since Martian atmosphere is mainly composed of carbon dioxide and the oxygen fraction is about 0.13%[11] [43], energy production as a result of combustion process involving fossil fuels is impractical borderline impossible. Hence, an alternative lighter, electrical digging solutions should be developed for the Martian environment.

Moreover, if the validated site location and developed technology allows for utilisation of Mars' geothermal potential, there are several different geothermal power plant configurations which could be implemented as design options. The classification of geothermal power plants is based on the number and type of heating cycles involved in the energy generation process and are as following:

- **Direct dry steam cycle**: This is the most simplistic configuration and uses hydrothermal fluids which are primarily steam. The steam is then fed to a turbine connected to a generator with which electricity is produced.
- **Flash cycle**: A flash cycle would address the power plant configuration which include flash tanks. As liquid and steam are extracted from the underground wells, it first enters a flash tank which is at way lower pressure and instantly vaporises. Later the vapour runs a turbine connected to a generator for electricity production. Moreover, there are single or multiple flash cycles power plants. This refers to the number of times the non-vaporised liquid fraction is flashed into a tank medium.
- **Binary cycle**: Binary cycle power plants rely on secondary cycle fluids with way lower boiling points than the primary fluid. Through a heat exchanger, the heat extracted from the ground is used to rapidly boil the secondary fluid making it into a steam and it runs a turbine and generates electricity.

Lastly, it is paramount to mentioned that other geothermal energy configuration might be possible based on the choice of primary working hydrothermal fluid. For example, the possibility to use carbon dioxide is currently being examined [12] [9]. Nevertheless, liquefying carbon dioxide comes with its own challenges as elaborated below. Hence, a trade-off between geothermal and solar, in order to decide which type of renewable energy source would be utilised as secondary for the purposes of this project, will be later performed.

8.4. Microgrid

The electrical grid is part of the power management system and it connects all energy subsystems (i.e. primary and secondary supply unit, energy storage system and load) to a common bus. A schematic of the microgrid is shown in figure 8.2. In the figure, the blocks P.E.I. designate a power electronic interface and consist of a combination of inverters, rectifiers, transformers, etc. The exact structure of this interface will depend on choices made during the trade-off.

[11] https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html [Cited 1 May 2020]

[12] https://www.forbes.com/sites/brucedorminey/2016/09/30/why-geothermal-energy-will-be-key-to-mars-colonization/#405474904b25 [Cited 1 May 2020]

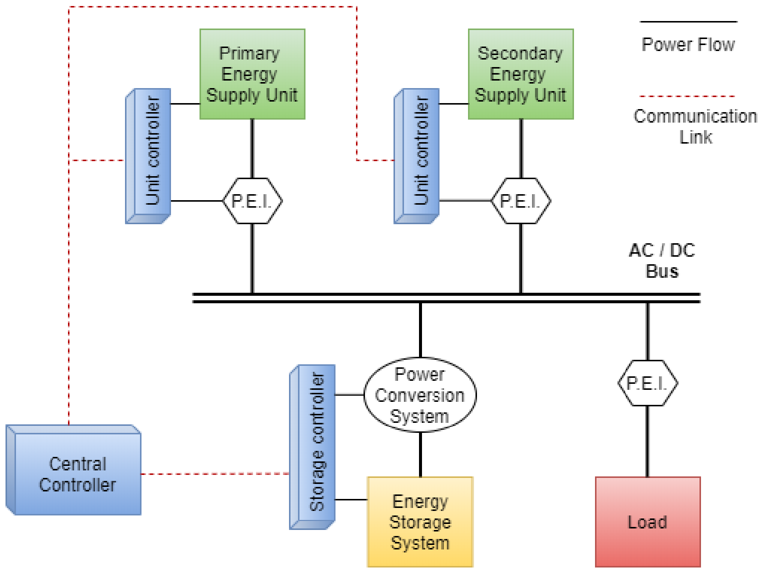


Figure 8.2: Diagram of the Renewable energy microgrid structure for the Mars habitat. A centralised controller monitors the power flow and gives commands to local controllers, which control the power input to the system and the energy storage.

At the conceptual design stage, the relevant options to consider for the microgrid are presented in the DOT. The main decision to take during the trade-off process will be whether the distribution of electrical power relies on AC or DC transmission. On Earth, technology is severely based on AC power transmission. However, DC is currently being investigated for application in microgrids and shows a lot of potential. Both have benefits and drawbacks, which will be further investigated before the trade-off process.

If AC power transmission is considered, a few concepts can already be eliminated from the DOT because they are deemed unfeasible.

- Phase: three phase is preferred rather than single phase. Because of the pulsating nature of AC, only having a single phase would result in a fluctuating power supply. Furthermore, a higher power output can be achieved for three-phase power, with much higher efficiency [31]. Multi phase power is not cost effective and does not add considerable advantage over three phase power and is therefore also discarded.
- Voltage: electric power loss increases with the square of the current. As electric power is defined as the product of voltage and electric current, transmission commonly occurs at high voltages. Therefore, LVAC is an unfeasible design option.

As for DC transmission, LVDC transmission is discarded for similar reasons, explained in the previous item. The cable infrastructure does not have an impact on the performance of the power system. Therefore it is not crucial in the trade-off process. Nevertheless, from a logistics point of view, the infrastructure should be decided upon in the future.

Baseline Design Options

The following options have been taken into account for the trade-off in the next design phase:

- Cable infrastructure: underground, on ground and overhead
- Transmission: AC and DC

8.5. Energy Storage

This section considers the options for energy storage, and their feasibility. For every concept a closer look was taken at their applicability in Martian conditions and conformity with the requirements. The energy storage systems must be able to back up the the direct energy supply in case of low energy gain from the primary and secondary units, maintaining the 10 kW power output required. Furthermore, the storage system must be able to be set up in as little launches as possible, making large infrastructures improbable.

Mechanical Storage

The systems that will be discussed next, store the electrical energy by means of mechanical energy conversion, changing it to e.g. kinetic energy. The available technologies are liquid and gaseous compressed air storage solutions along with flywheel installations.

- **Liquid air:** The use of liquid air to store energy is known as cryogenic energy storage. This process is done by storing air (per the atmospheric composition of Earth) at very low temperatures and pressures using cheap electricity during the night. This liquefies the gas, allowing for a much smaller storage volume. When more energy is required, the liquid is released from its controlled environment. This makes it return to it gaseous state, where this rapid expansion of volume can be used to drive a turbine to generate electricity[13]. This however is heavily dependent on the compound of the air. As air on Earth has high contents of Nitrogen and Oxygen and low counts of Carbon Dioxide, it is relatively easy to liquefy. The Martian atmosphere however, largely exists out of Carbon Dioxide. Due to its thermodynamic properties, Carbon Dioxide is hard to keep in a liquid state. One would need a pressure above 5.1atm and a temperature between 216.55K and 304.25K[14]. Given the infrastructure and energy required to maintain such a controlled environment, such an energy storage system would be improbable within the limits of this mission.
- **Compressed Air:** This method of energy storage uses excess energy to compress air, and store it in e.g. existing cave systems. When more energy is required, the air is decompressed and used to generate energy. This method of energy storage would be applicable to the mission, as it is possible to use already existing caves on Mars to store the compressed air. Furthermore this concept can be scaled up as desired, without needing many extra resources from Earth, making it fit the requirements.
- **Flywheel:** This is a classical method of storing energy, still used to day. Excess energy is used to spin a wheel, and when energy is required the slowing of the wheel generates the energy again. There are qualities to the flywheel that make it interesting for this mission, such as the fast response time and high efficiency. However, flywheels are used to balance energy usage on the short term, and the capacity directly correlates to the weight [3]. If it needs to store enough energy to maintain continuous supply through the night, the size of the flywheel would make it unsuitable for the requirements.

Gravitational Storage

In this section options for energy storage using gravity are discussed. This is done by changing the potential energy in a medium. First lifted storage is discussed followed by pumped storage.

- **Lifted Storage:** There are many ways this method can be implemented. One such example is using excess energy to lift a set mass into a high tower, and then dropping it again at a later time to generate energy when necessary[15]. Within the requirements it is unlikely a high enough tower can be built, however this can be adapted to suit the mission. For example, the sloping sides of a crater can be used to lift a mass along. With many options available to modify this method it is too soon to discard it, thus it will be left for the trade-off to decide.
- **Pumped Storage:** Using pumps, water can be moved up to a higher reservoir when the demand for energy is low. When demand is high, the water will be allowed to flow back to a lower reservoir, driving a turbine in the process. While this is a widely used method on Earth, due to water being a scarce commodity on Mars it will be impossible to realise there. Any other liquid would also work, however the surface temperatures are much too low. Combined with low atmospheric pressure, there is no way this energy storage method can be realised within the current mission.

Chemical Storage

This section focuses on energy storing methods, that store electrical energy within chemical reactions. First Primary batteries and secondary batteries will be discussed, followed by Regenerative Fuel Cells (RFC) and lastly Hydrocarbons.

- **Primary Batteries:** These are batteries that use an irreversible chemical reaction to generate electrical energy. However this means they cannot be recharged making them single use only. This immediately

[13]https://www.highviewpower.com/technology/ [Cited May 4 2020]
[14]https://webbook.nist.gov/chemistry/fluid/ [Cited May 4 2020]
[15]https://heindl-energy.com/ [Cited 1 May 2020]

means this would be unfeasible as an energy storage system, as this would require an immense supply of primary batteries, that cannot be loaded with excess energy.

- **Secondary Batteries:** Secondary batteries differ from primary batteries, as they can be recharged. There exist many types of secondary batteries. For space applications lithium based and Vanadium Redox Flow Batteries (RFB) would be amongst the ones of interest. Secondary batteries can have a specific energy of up to 600Wh/kg [35] and are expected to be perfected further in the coming years. With these specific energies it will be impossible to build a large enough facility for the seasonal energy fluctuations, however it would be a possible solution for the sol cycles. This would have to be examined closer during the trade-off phase.
- **RFC:** The Regenerative Fuel Cell most commonly uses water which it coverts into hydrogen and oxygen by process of electrolysis using excess energy. Then the hydrogen is stored, and when energy is needed it is reverted back to water using the same fuel cell generating energy. Previous studies have also considered RFC a viable option for space missions due to the higher specific energy and extended operation time when compared to secondary batteries[35].
To apply this in a Martian environment some considerations must be made. Due to the temperatures on Mars, the water would have to be stored in a controlled environment. However the storage of hydrogen would be a lot less complicated due to the low evaporation temperature of hydrogen. These points will have to be researched more and considered in the trade-off. Thus this cannot be discarded as of yet and should be further examined.
- **Hydrocarbons:** This method makes use of another chemical process, where oxygen, hydrogen and carbon dioxide, produce methane and water using the Sabatier reaction. The excess energy could be stored as methane, and the reaction can be reversed by combustion to regain the energy. The limiting factor however are the conditions under which this reaction takes place. The Sabatier reaction only occurs under high pressures of $50 - 200$bar and at temperatures of around 573K[26]. To obtain this environment, large facilities are necessary to carry out the reaction. This would be hard to realise on Mars given the current mission, due to the mass and volume restrictions. Therefore this method will not be able to be realised within the scope of the mission.

Thermal Storage

Thermal Storage, stores energy as heat. Excess energy is used to heat up a medium, which maintains the temperature until energy is needed. The heat is then transferred back and used to drive e.g. a turbine to regenerate the energy used to heat the medium. There are three methods that will be discussed to complete the energy transfer. First the option using latent heat is discussed, followed by sensible heat and finally geothermal energy storage solutions are presented.

- **Latent Heat:** Latent heat, is energy stored in terms of heat in phase change materials. The additionally generated energy is transformed into heat with which a phase changing material is heated up and used as a storage medium. Phase changing materials are characterised by higher energy levels required for changing from solid to liquid to gaseous phases [6]. Hence, they could be utilised as storage mediums and depending of the phase change temperature they would required lesser or greater isolation. Either, that material should be borough to Mars from Earth, or on site resources should be examined along with their phase change properties. Nevertheless, the heat storage potential of phase change materials is most favourable when utilised for heat isolation purposes rather than for direct energy storage. Hence, most likely phase change materials will be implemented in the system design for electronics and habitat isolation but they will not be considered in the energy storage solutions trade-off.
- **Sensible Heat:** This type of energy storage addresses storage solutions which conserve the internal energy levels of a material through isolating it from the surroundings. Most commonly used storage medium is water due to its abundance and relative cheapness on Earth [6]. Nevertheless, this statement does not hold true for implementing this solution in Martian environment. Even if more suitable abundant storage medium is selected for the purposes of utilising sensible heat storage, the required storage isolation would result to be extremely costly and heavy if decided to be done overground. Hence, this design option results not to be an adequate choice for the purposes of this project. Underground sensible heat storage solutions are also known as geothermal energy storage and are discussed below.
- **Geothermal storage:** This type of energy storage solution relies on accumulating energy in terms of heat by warming a fluid and storing it underground. The benefits and possibilities of geothermal energy storage have been examined and developed in the recent years. This solution greatly relies, firstly, on

minimising heat dissipation of the fluid medium while being stored underground. Secondly, it relies on that conditions that, for Earth through out year, atmospheric temperatures vary with seasons, while, at some depth, underground temperatures remain more or less constant. Hence, this suggest the possibility of having smaller differences between ambient and storage temperature and this is extremely beneficial for minimising energy losses as following second law thermodynamics analysis. Moreover, those benefits are especially favourable when a heat pump is implemented in the system [40]. Nevertheless, achieving that smaller temperature difference between ambient and storage temperature is not that straightforward on Mars as it is on Earth due to the way negative average atmospheric temperatures. Those observations and the properties of Martian tectonic layers suggest way lower underground temperatures than the desirable range. Hence, implying that more likely deeper storage solutions and other isolation considerations are necessary In addition, there are different types of geothermal storage solutions based on depth and the liquid transportation medium. Those are classified as following:

- **HGSH**: This type of system on Earth deals with horizontally placed tubing containing the fluid medium which is stored in the ground and either cools down or warms up depending on the ambient temperature. Typical depths vary from -2m to -5m [40]. While on Mars shallow geothermal energy storage is deemed infeasible due to the yearly negative surface temperatures which are way under the desirable range for life support.
- **BTES**: This type of geothermal energy storage is also know as Vertical Ground Source Heat and is greatly similar to the above mentioned concept, except, tubing is placed vertically in ground. Hence, this kind of installations requires typical depths of -5m to -150m [40]. Other challenges come with the construction and operation of borehole energy storage systems. As energy dissipation should be as little as possible, some kind of isolation material is often laid around the tubing itself. That material has to be either brought from Earth or the possibilities for on cite sourcing and mixing should be researched. Nevertheless, such closed-loop systems are almost impossible to maintain and do experience a significant amount of efficiency losses due to freezing of circulation fluids. Therefore, it is considered that even if included in the trade-off, ATES would result to be a losing option due to its bad performance with respect to system installation, maintenance, retirement and sustainability.
- **ATES**: Rather than being closed loop fluid circulation systems like the previous two configurations, ATES systems make use of natural or artificial aquifers [40]. Their typical depths are in the range of -20m to -250m. The thermal storage capacity and energy losses of ATES systems are depended on the fluid and ground storage mediums. For example, for the fluid, properties such as viscosity, boiling and freezing points are of interest; while, for the ground properties, most relevant are the volumetric heat capacity of a material, along its thermal conductivity and permeability. Therefore, a geological survey must be conducted in order to examine if there are suitable porous ground layers with a non-reactive fluid, which could be implemented as a storage facility. However, that could make the development, research and validation costs extremely high. Furthermore, the equipment necessary for the conventional installations of such systems would make the transportation and system installation costs very high. Hence, this design option would result loosing in an engineering trade-off and will not be included in the baseline design options.

Electrical and Magnetic Storage

The energy storage options discussed in this section make use of electromagnetic fields and potentials to trap and store electrons to hold a charge. First the capacitor is discussed, followed by the super capacitor and finally the Superconducting Magnetic Energy Storage (SMES).

- **Capacitor:** This method uses the same basics as all the electrical magnetic storage systems. Namely using two charged plates to create an electric field to load a positive charge on the positive plate and a negative charge on the negative plate. This allows capacitors to hold a charge fast and also discharge quickly. Current capacitors also have a high specific energy of up to 1kW/kg [35]. However capacitors are mainly used to release this charge in short bursts, in e.g. camera flashes making them unsuitable for an energy storage system which has to slowly release the energy into a system as demanded. Therefore it will not be considered as an option from here on.
- **Super capacitor:** These are similar in their operations when compared to capacitors, however they have a higher capacitance. This allows them to have higher specific energies [29]. However super capacitors are also designed to release a charge very quickly. Even tough, they cannot be implemented as day-

to-day or seasonal storage solutions, they have become commonly used in wind energy harvesting systems. Their characteristics have made them extremely suitable for smoothing out the wind-induced power oscillations resulting in a superior transient system behaviour [1]. Hence, this technology will be implemented in the system design but is not relevant to the energy storage trade-offs.

- **SMES:** Contrary to the capacitor and super capacitor, the SMES does not use plates to hold a charge, but uses a coil that is cooled to its superconducting temperature. The SMES has an efficiency greater than 95% with a specific power of up to 100000kW/kg [37]. It is a useful system to balance fluctuations in the energy grid due to its capability to manage large charges in a very short time. However as development stands now, this is not a feasible option for our mission due to the size required for such a system and the cost that comes with it.

Baseline Design Options

While phase change materials and super capacitors will surely be implemented in the system design, the following options have to be taken into account for the trade-off in the next design phase:

- Mechanical Storage: Compressed air
- Gravitational Storage: Lifted storage
- Chemical storage: Secondary batteries
- Chemical storage: RFC

8.6. Site Selection

The energy system designed by this DSE team has to supply a Mars habitat designed by the Rhizome project [12]. The site location is jointly decided on by the two teams. After a meeting with the leader of the habitat project, Henriette Bier, the consensus was made that as their team is not actively looking for a location, the DSE team will propose 3 to 4 sites to choose from. In the meantime, a final site is going to be selected for the purposes of this project like sizing.

As one can observe from figure 8, there are many aspects to consider. First and foremost, the primary energy resource is wind, thus this is of top priority. Its average and peak speeds, direction and variation with altitude. Solar irradiance is an important point to consider as this is going to supply the secondary energy system. For both wind and solar, their variation needs to be taken into account on both short- as well as long-term. Geothermal potential can be the key to store energy for longer period, thus this also goes into the trade-off. Other constraints include the frequency and severity of dust storms, scientific potential, temperature ranges and available resources like ice or materials for building.

8.7. Conclusion and further developments

To conclude, many options have been eliminated from the design options trees, however those that remain, need to be traded-off in the midterm report. Noticeably, this report does not end with 4-5 concepts of the entire system. That is because our system is built up of a few separate systems which will need to work together to provide a renewable energy system. This means for each of these systems, a distinct trade-off needs to be performed. The latter will be the next step in this project and the interrelations between all the systems will be thoroughly analysed and explained.

Bibliography

[1] C. Abbey and G. Joos. Supercapacitor energy storage for wind energy applications. *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS*, 43, 2007.

[2] S. Alagoz and Y. Apak. Removal of spoiling materials from solar panel surfaces by applying surface acoustic waves. *Journal of Cleaner Production*, 253, 2020.

[3] M.E. Amiryar and K.R. Pullen. A review of flywheel energy storage system technologies and their applications. Technical report, School of Mathematics, Computer Science and Engineering, University of London, 2017.

[4] V. Badescu. *Mars Prospective Energy and Material Resources*. Springer, 2009.

[5] A. Cherubini, A. Papini, R. Vertechy, and M. Fontana. *Airborne Wind Energy Systems: A review of the technologies*. University of Bologna, 2015.

[6] W. de Jong. Wb3580: Energy storage - other thermal storage systems. sensible heat, phase change materials, thermo-chemical, 2019.

[7] M. Diehl. *Airborne Wind Energy: Basic Concepts and Physical Foundations*. Delft University of Technology, 2013.

[8] D. Djairam, A.N. Hubacz, P.H.F. Morshuis J.C.M. Marijnissen, and J.J. Smit. The development of an electrostatic wind energy converter (ewicon). Technical report, High Voltage Technology & Management Group, Delft University of Technology, 2005.

[9] . Dorminey. Why geothermal energy will be key to mars colonization, 2016. Accessed on May 4, 2020.

[10] M. A. Dornheim. Planetary flight surge faces budget realities. *Aviation Week and Space Technology*, 145:44–46, 1996.

[11] A.J. Dorofee, J.A. Walker, C.J. Alberts, R.P. Higuera, Murphy R.L., and R.C. Williams. *Continuous Risk Management Guidebook*. Carnegie Mellon Software Engineering Institute, 1996.

[12] H. Bier et al. Rhizome: Development of an autarkic design-to-robotic-production and -operation system for building off-earth rhizomatic habitats, 2019. 2nd stage of ESA competition.

[13] I. B. Fridleifsson et. al. The possible role and contribution of geothermal energy to the mitigation of climate change. *Scoping Meeting on Renewable Energy Sources*, pages 20–25, 2008.

[14] S. De Las Heras F.J. Arias. Magnetic mars dust□removal technology. *CEAS Space Journal*, 11:235–239, 2019.

[15] M. J. Fogg. The utility of geothermal energy on mars. *Journal of The British Interplanetary Society*, 49: 403–422, 1996.

[16] J. W. Fozard. *Space Exploration and Astronaut Safety*. American Institute of Aeronautics and Astronautics, 2000.

[17] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop. Prog. photovolt: Res. appl. 22. *Wiley InterScience*, 2014.

[18] ISO Technical Management Board Sustainability Guide Drafting Group. *ISO 82. Guidelines for addressing sustainability in standards*. International Organisation for Standardisation, 2014.

[19] N. Hall. Mars atmosphere model, 2015. NASA Glenn Research Centre. Accessed on May 4, 2020.

[20] R.J. Hamann and M.J.L. van Tooren. *Systems Engineering & Technical Management Techniques Part I*. Faculty of Aerospace Engineering. Delft University of Technology, 2006.

[21] H.W. Haslach. *Wind Energy, A Resource For A Human Mission To Mars*. University of Maryland, 1989.

[22] S. Zhou H. Yang C. Chen J. Zhang, W. Wang. Transparent dust removal coatings for solar cell on mars and its anti-dust mechanism. *Progress in Organic Coatings*, 134:312–322, 2019.

[23] G. James, G. Chamitoff, and D. Barker. *Design And Resource Requirements For Successful Wind Energy Production On Mars*. NASA, 1999.

[24] G. A. Landis, T. W. Kerslake, P. P. Jenkins, and D. A. Scheiman. Mars Solar Power. Technical report, NASA, 2004.

[25] G.A. Landis, D. Hyatt, and Athena Science Team. THE SOLAR SPECTRUM ON THE MARTIAN SURFACE AND ITS EFFECT ON PHOTOVOLTAIC PERFORMANCE. Technical report, NASA, 2006.

[26] G. Leonzio. Process analysis of biological sabatier reaction for bio-methaneproduction. *Chemical Engineering Journal*, 290:490–498, 2016.

[27] *NASA Risk Management Handbook*. National Aeronautics and Space Administration, November 2011.

[28] J. O'Neill, N. Thakur, and A. Duus. *Technical Risk Assessment: a Practitioner's Guide*. Australian Government, Department of Defense, 2007.

[29] Z. Qi and G.M. Koenig Jr. Flow battery systems with solid electroactive materials. *Journal of Vacuum Science & Technology B*, 35, 2017.

[30] M. A. Rosen. Engineering sustainability: A technical approach to sustainability. *Sustainability*, 4:2270–2292, 2012.

[31] P. Schavemaker and et al. *Electrical Power System Essentials*. Wiley, 2017.

[32] R. Schmehl. Airborne wind energy: An introduction to an emerging technology. 2019. AWESCO - Airborne Wind Energy System Modelling, Control and Optimisation.

[33] *The nature of Martian airborne dust. Indication of long-lasting dry periods on the surface of Mars*, 2007. Seventh International Conference on Mars.

[34] A. Smets, K. Jäger, O. Isabella, R. van Swaaij, and M. Zeman. *Solar Energy, the physics and engineering of photovoltaic conversion technologies and systems*. UIT Cambridge Ltd, 2016.

[35] R. Surampudi, et al. Energy storage technologies for future planetary science missions. Technical Report JPL D-101146, Jet Propulsion Laboratory, 2017.

[36] A. Syafiq, A.K. Pandey, N.N. Adzman, and N.A. Rahim. Advances in approaches and methods for self-cleaning of solar photovoltaic panels. *Solar Energy*, 162:597–619, 2018.

[37] P. Tixador. Superconducting magnetic energy storage: Status and perspective. Technical report, IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM, 2008.

[38] *International Space Law: United Nations Instruments*. United Nations Office for Outer Space Affairs, May 2017.

[39] R. van der Vlught, J. Peschel, and R. Schmehl. *Design and Experimental Characterization of a Pumping Kite Power System*. Faculty of Aerospace Engineering. Delft University of Technology, 2013.

[40] P. Vardon. Wb3580: Energy storage - shallow geothermal / ground source heat / borehole thermal energy storage (btes), 2019.

[41] D. J. Y. Villarreal. Viv resonant wind generators, 2018. Vortex Bladeless S. L.

[42] J. Wiley, J. F. Manwell, J. G. McGowan, and A. L. Rogers. *Wind Energy Explained: Theory, Design and Application*. John Wiley & Sons, 2009.

[43] Dr. D. R. Williams. Mars fact sheet, 2020. Accessed on May 4, 2020.

[44] X. Zhou and Y. Xu. Solar updraft tower power generation. *Solar Energy 128 (2016) 95-125*, 2014.