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Study of the Sustainability of a Permanent Martian Outpost

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Study of the Sustainability of a Permanent Martian Outpost

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Abstract

This document contains a sustainability study of a permanent Martian outpost. It involves a preliminary introduction to the exploration of Mars and concepts related to sustainability such as sustainable development, carrying capacity or impact, as well as an overview of previous studies regarding human exploration of Mars.

The methodology proposed to carry out the sustainability study is a brand-new approach to the analysis of space exploration missions that focus on the impact of the mission elements regarding the Earth, the Outer Space, and Mars itself. It also provides a framework that will allow to extend the study to location-related carrying capacity assessment, and In Situ Resource Utilization and Environmental Control and Life Support Systems' circularity.

After a discussion of the results obtained from the quantitative analysis performed, an extensive proposal of future work is provided, as well as orientation on what to expect from future missions to the red planet.

Preface

This project is the last step of what has been a 7-year walk on the way to become an Aeronautical Engineer. It has been a beautiful journey, full of challenges, ups and downs, wins and losses, and a huge amount of learning. I could not imagine a better way to end than focusing on one of my favourite areas, space exploration.

This has been a demanding project that has required extensive bibliographical research, not only to provide information regarding the topics treated on the study, but also to fully understand what is the position of mankind in space exploration matters, what are our plans for the future, and what are we doing today, or have done in the past, in order to fulfil them.

But the study is not about a where we are or what we are doing. The study goes way beyond that and focuses on the next big leap on planetary exploration, a permanent outpost in the surface of Mars. Linking the still immature sustainability concepts to the extremely uncertain technologies to arise is an arduous task. The true challenge has been to provide a flexible framework from where to develop quantitative analysis that will adapt and grow as we learn more about sustainability and about exploration technologies.

This is just the first step of what I hope will become an area of extensive study on the future. Sustainable development is the only possible development if we want to ensure the future of mankind in our world or others and it must be taken into account in any technological endeavour from now on.

I hope this project can become an easily understandable and global introduction to what a sustainability study of a permanent outpost is, so future works can use some of the new ideas exposed to take sustainability into consideration.

Summary

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List of abbreviations

AR: Ability to Repair

BOL: Beginning Of Life

CEO: Chief of the Executive Office

CRE: Crew Radiation Exposure

DL: Design Life

DRA: Design Reference Architecture

ECLSS: Environmental Control and Life Support System

EDL: Entry Descent and Landing

EMC: Evolvable Mars Campaign

EOL: End Of Life

ESA: European Space Agency

EVA: Extra Vehicular Activities

FOM: Figure Of Merit

FSPS: Fission Surface Power System

GPHS: General Purpose Heat Source

IMLEO: Initial Mass at Low Earth Orbit

ISM: In Situ Manufacturing

ISRU: In Situ Resource Utilization

ISS: International Space Station

ITO: Indium Tin Oxide

KRUSTY: Kilopower Reactor Using Stirling TechnologY.

LEO: Low Earth Orbit

LOX: Liquid OXygen

MAFSA: Mars Autonomous and Foldable Solar Array

MAV: Mars Ascent Vehicle

MCC: Martian Carrying Capacity

MER: Mars Exploration Rover

MMRTG: Multi-Mission Radioisotope Thermoelectric Generator

MOXIE: Mars OXygen In situ resources utilisation Experiment

NASA: National Aeronautics and Space Administration

NIMSA: Norwich Inflatable Mars Solar Array

NPS: Nuclear Power Sources

PET: Polyethylene Terephthalate (PET)

PMD: Power Management and Distribution

PV: PhotoVoltaic

RASSOR: Regolith Advanced Surface systems Operations Robot (RASSOR)

RC: Recurring Costs

RTG: Radioisotope Thermoelectric Generator

S: Scalability

SEP: Solar Electric Propulsion

SRG: Stirling Radioisotope Generator

SRZ: Surface Restriction Zone

TLM: Total Landed Mass

TRAC: Triangular Rollable and Collapsible

VDC: Voltage Direct Current

1. Introduction

Mars has been an objective of space exploration for a long time now. Its study has occupied the minds of multiple astronomers, physicians and scientist for centuries and, today, we are closer than ever to uncover its mysteries.

The Viking landers were the first successful human devices to land and communicate from the red planet back in 1976. Years later, Pathfinder's Sojourner, Spirit and Opportunity, Phoenix, Curiosity, and more recently, InSight have followed.

These devices have grown bigger, much more powerful and way more ambitious in their scientific objectives as the technology has become better. The next rover to Mars, Mars 2020, will carry an In-Situ Resource Utilisation demonstrator, MOXIE, that will bring human exploration a little bit closer to the planet.

Exploration of Mars has been qualified as desperately slow for some and completely unnecessary for others. There have always been sceptics to any space exploration activities, mainly because these are rather expensive initiatives. However, the economic outcome coming from technologies that has been specifically design for space exploration purposes is too big to quantify. Internet is the biggest example of that, one of the life changing technologies that has only been available thanks to developments related to space exploration. A human mission to Mars is full of challenges and they are bigger than anything we have faced before, and that is the exact reason why so much good can come from it. Developments on space transportation, radiation shelter, solar activities observation and understanding, communications, solar and nuclear energies, ISRU technologies, and self-sustaining environments, just to name a few, can and must be accomplished.

Moreover, Mars is the only planet on the solar system where robotic and human surface activities can be held and prolonged indefinitely, due to its environmental characteristics. This means that it is the only potential and foreseeable 'second home' for mankind, the only chance we have to 'make human an interplanetary species', which is precisely the vision of SpaceX's and Tesla's CEO, Elon Musk, and other supporters of Mars exploration. It is also an extremely interesting point from a scientific perspective, with currently active investigations on the discovery of ancient (or present) life, the origin of the solar system and the formation of rocky planets, just to name a few.

Robotic exploration of Mars is very useful, it allows scientist to get to places considered too dangerous for humans and actually perform experiments to learn more about them without the need of risking any human life. However, it has the big inconvenience of being tremendously slow when compared to human exploration. In the future, the human capacities will necessarily expand and robotic missions will keep on exploring the frontier, reducing the risks associated to new places through knowledge acquisition.

A permanent human outpost in the surface of Mars would be a tremendous boost in the scientific exploration of the planet. It would also be very valuable for understanding the effects of a prolonged stay on Mars in the human body, similarly to what ISS have been doing at Low Earth Orbit. But exploration of Mars cannot exist if it is reliable on the exploitation of resources from Earth. This is a big challenge because getting to Mars requires a lot of resources. A sustainable approach that minimizes the need to resupply from Earth is the only viable way.

Sustainability and viability are often confused when talking about space exploration. This is because space environments are so extremely hostile that missions are not viable unless a high degree of sustainability is achieved. This occurs both in outer space and other planetary bodies different than the Earth. However, a mission can be viable but still need a huge amount of Earth resources to succeed, which is not a sustainable approach.

'*The term sustainability should be viewed as humanity's target goal of human-ecosystem equilibrium (homeostasis), while sustainable development refers to the holistic approach and temporal processes that lead us to the point of sustainability'*(Shaker, 2015)

This sustainable development is the process of progressing in a way that the exploitation of resources, the direction of investments, the technological development and the institutional change enhance both current and future potential to meet human needs and aspirations. This implies that the concept is broader than an environmental issue. In fact, a primitive conception of sustainability considered three 'dimensions of sustainability.

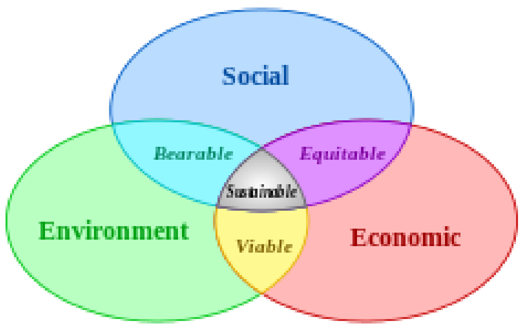

Figure 1: Venn diagram on sustainable development at the confluence of three constituent parts.(Adams)

According to this model, sustainability could only be achieved when environment, social and economic development are all sustainable.

More sophisticated schemes have been arising along the last years. Some sustainability experts and practitioners have illustrated four pillars of sustainability, or a quadruple bottom line.

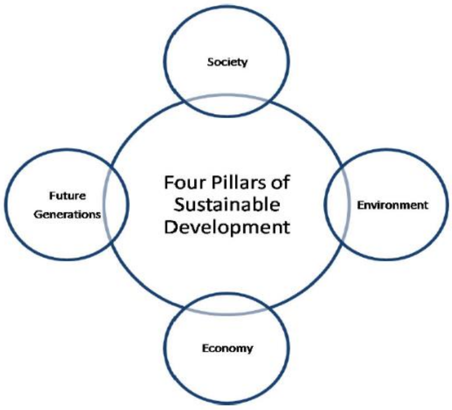

Figure 2: Quadruple Bottom Line (QBL) of sustainable development.(Waite, 2013)

The fourth 'pillar' according to this model is future generations, which emphasizes the long-term thinking associated with sustainability.

Ecological economist Herman Daly once asked:

'What use is a sawmill without a forest?'

With this question he was trying to point out that the relationship between the different 'pillars' or 'dimensions' of sustainability was actually more profound. Economy is a subsystem of human society, which is itself a subsystem of the biosphere. This approach is clearly expressed in the following diagram.

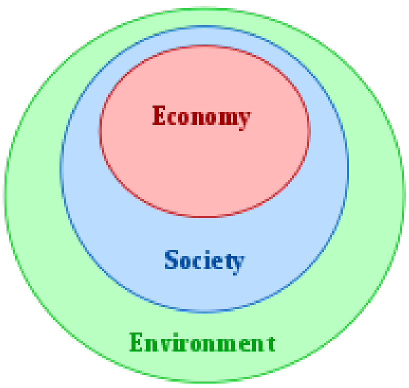

Figure 3: A diagram indicating the relationship between the three pillars of sustainability, in which both economy and society are constrained by environmental limits.(Adams)

Others go further and, recognizing the progressive nature of sustainable development, add a political subsystem to the problem.

A key concept when studying sustainability that is especially understandable in the case of environmental development is resiliency. **Resiliency** is defined as the capability of an ecosystem to absorb disturbance and still retain its basic structure and viability. This concept evolved from the need to manage interactions between human-constructed systems and natural ecosystems in a sustainable way.

It refers to the fact that, no matter what, any foreign interaction with an environment will unavoidably modify it and destroy it. Thus, environments need to have some sort of recovery capability. This happens from the smaller scale to the largest. A simple example would be how, when an animal eats, the environment is able to continue producing enough food to feed it. We have been pushing through Earth's resiliency for a long time, and we have been forced to find ways to artificially generate the resources that Earth is no longer able to naturally provide to us, for example food. Agriculture is one of the first developments that really set us apart from sustainable development.

This idea is brilliantly captured by the concept carrying capacity, one of the most powerful tools we have to quantitatively analysing sustainability. The **carrying capacity** is the maximum population size of the species that the environment can sustain indefinitely, given the food, habitat, water and other necessities available in the environment.

Consumption or **impact** is very related to this idea. The environmental impact of a community depends on two factors: the individual impact, and the size of the community. This directly relates to the amount of resources being used.

$$I = P \cdot A \cdot T \quad (1)$$

This expression, known as the I PAT formula, simply illustrates the relationship between the three components of impact: population numbers (P); levels of consumption, or affluence (A), and impact per unit of resource use, or technology (T).

A proper technological development should not find ways to overextend this number artificially, like we have been doing for centuries. Instead, according to sustainable development definition, it should increase the carrying capacity of a system, by reducing the impact of each individual.

As impact is so narrowly related with resources utilization, the **circularity** or (re)cycling of resources is an excellent way to reduce it. This applies to recycling and also to reusability. The reduction of resource inputs into and emission leakage out of the system reduces resource depletion and environmental pollution.

Sustainability is very hard to study given planetary sized ecosystems. Explorer and sustainability campaigner Jason Lewis draw parallels to other, more tangible closed systems that resemble the isolation of planets in space. A small boat isolated by water is usually used. For this project, our field of study fits this mentality just perfectly. Our small, isolated system will be the Martian Outpost.

There is another model for the analysis of sustainability that fits our scenario particularly well. This model defines seven modalities that describes human aspirations: economy, community, occupational groups, government, culture and physiology(Thomas, 2016). These 'modalities' apply to several hierarchical levels and human sustainability is achieved by attaining it in all levels of the seven modalities. For the case of our outpost, this will be way simpler than a planetary scale environment.

Economy, community, occupational groups, government and culture are out of the scope of this project, so we will focus on environment and physiology. These are studying the interaction of the outpost with the Earth and Martian environment and analysing the conditions that need to be provided to the astronauts.

Several aspects need to be studied, from the exploitation of Martian atmosphere, solid water reservation and land, to the management of human consumption in terms of energy, water, food and breathable air, and handling of waste materials and toxic substances.

Viability of space missions usually requires a high level of sustainability. Environmental conditions in space are completely hostile for human life. Therefore, the use of resources needs to be absolutely optimized. This means that circulation has to be almost 100% efficient, because there is no other possible resupply than the Earth. Launching resources from the Earth is extremely expensive, and it requires a huge amount of extra resources to be spent into it.

To put it simple, in order to deliver food into the ISS the amount of fuel required increases greatly with every kilogram. Not to mention the resources employed to build the launcher, that is traditionally dropped to the ocean after its first and only flight. But again, there is no other option, as obtaining food from the outer space environment is completely impossible.

Outer space has zero carrying capability. Foreign celestial bodies have zero carrying capability. Unless an artificially built habitat is provided, human activities are not viable, not for present nor future generations. Applying sustainability principles under these circumstances may seem difficult, and indeed, a wider look is required compared to activities directly developed on our planet's surface.

The sustainability of space activities can be defined in three different levels:

1. Sustainability regarding Earth

This is considering the impact space activities have on the Earth environment. As stated before, this impact is huge compared to similar activities performed in the Earth, due to the amount of resources necessary to escape Earth's gravity.

2. Sustainability regarding Outer Space

Even though outer space offers few, if any, tangible resources, it can be contaminated. As big as it is, space is not endless and activities developed in this environment do leave waste behind. This waste is actually congesting Low Earth Orbits (LEO) and other specific orbits such as the Geostationary (GEO), and space debris have become a real sustainability issue, even though they do not directly affect Earth surface.

3. Sustainability regarding other Bodies

This is the most unexplored of the three levels of space sustainability, as interactions between humans and other space bodies like moons or planets have been scarce. However, one clear example of how our presence can alter and contaminate a planet is found in Apollo missions. The regolith clouds that the lunar modules left when launching from the Moon are still swirling, and they will keep this way for centuries.

So, before even thinking about interacting and exploring outside Earth, we need to apply the Precautionary Principle. This means that we need to asses and manage risks inherent to the uncertainty of our research. We cannot be completely sure of how our activities will affect the objects we are studying. However, it is clear that, in order to achieve more knowledge and thus a better idea on how we can sustainably interact with new environments, we need to study them. We need to interact with them. A sustainable approach to this issue is to radically reduce our impact in these new environments, minimizing our waste and maximizing our efficiency in resource management.

This simple idea will have positive consequences in all the levels of sustainability. By reducing our impact in other planets and moons, the amount of resources needed and our impact on the Earth environment is also minimized.

2. State of the Art

2.1. Outer space sustainability initiatives

While sustainability issues regarding other celestial bodies remain unexplored, some initiatives have been undertaken regarding Earth environmental sustainability and outer space sustainability of space activities.

United Nations have recently created a Safety Framework for Nuclear Power Source Applications in Outer Space(United Nations, 2018) and some guidelines regarding Long-term Sustainability of Outer Space Activities (United Nations 2017).

2.1.1. Long-term Sustainability of Outer Space Activities

The Committee on the Peaceful Uses of Outer Space agreed to some guidelines regarding this topic, as well as the Working Group on the Long-term Sustainability of Outer Space Activities, which was held in Vienna from 2 to 6 October 2017.

These guidelines consider policy and regulatory framework for space activities, safety of space operations, international cooperation, capacity-building and awareness and scientific and technical research and development.

'The long-term sustainability of outer space activities is defined as the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space [solely] for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations.'(United Nations 2017).

The application of these guidelines is voluntary for all the states and encouraged by the United Nations.

Guidelines regarding policy and regulatory framework for space activities consider:

- Adopt, revise and amend, as necessary, national regulatory frameworks for outer space activities.
- Consider a number of elements when developing, revising or amending, as necessary, national regulatory frameworks for outer space activities.
- Supervise national space activities.
- Ensure the equitable, rational and efficient use of the radio frequency spectrum and various orbital regions used by satellites.
- Enhance the practice of registering space objects.
- Provide, in national legal and/or policy frameworks, for a commitment to conducting space activities solely for peaceful purposes.

These mean that it is recommended to revise the regulatory framework to adapt to a sustainable model and that supervision to ensure proper radio frequency spectrum use, space objects control and peace is undertaken.

Safety of space operations are addressed through the following guidelines:

- Improve accuracy of orbital data on space objects and enhance the practice and utility of sharing orbital information on space objects.
- Promote the collection, sharing and dissemination of space debris monitoring information.
- Share operational space weather data and forecasts.
- Develop space weather models and tools and collect established practices on the mitigation of space weather effects.
- Provide updated contact information and share information on space objects and orbital events.
- Prevent conjunction assessment during all orbital phases of controlled flight.
- Develop practical approaches for pre-launch assessment of possible conjunctions of space objects to be launched with (manned) space objects already present in near-Earth space.
- Ensure the safety and security of terrestrial infrastructure that supports the operation of orbital systems.
- Observe procedures for preparing and conducting operations on active removal and intentional destruction of space objects.
- Develop criteria and procedures for the active removal of space objectives and for the intentional destruction of space objects, specifically as applied to non-registered objects.
- Design and operation of space objects, in particular small-size space objects.
- Mitigate or take measures to address risks associated with the uncontrolled re-entry of space objects.
- Observe measures of precaution when using sources of laser beams passing through outer space.
- Implement operational and technological measures for the safe conduct of close proximity space operations.
- Implement measures for the safe conduct of activities involving intentional modification of the natural space environment.
- Support observance of standards related to the non-use of malicious tools and techniques as a part of ensuring safety of space operations.

Which in the end, refer to a way bigger control of all the agents involved in orbital activities in order to prevent an uncontrollable increase in space debris. Considering also, ways to mitigate this problem.

In terms of international cooperation, capacity-building and awareness:

- Promote and support capacity-building.
- Raise awareness of space activities.
- Promote and facilitate international cooperation in support of the long-term sustainability of outer space.
- Share experience related to the long-term sustainability of outer space activities and develop new procedures, as appropriate for information exchange.

These refer to enhancing international cooperation and communication and awareness, as well as sharing knowledge in support of long-term sustainability of outer space.

And last, regarding scientific and technical research:

- Promote and support research into and the development of ways to support sustainable exploration and use of outer space.
- Investigate and consider new measures to manage space debris population in the long term.

Which address to minimizing the environmental impact of manufacturing and launching space assets and maximizing the use of renewable resources and the reusability or repurposing of space assets, protect the Earth and the space environments from harmful contamination and act on the space debris population problem.

Summarizing, these guidelines identify space debris as the major long-term sustainability issue and enhance national and international cooperation in order to work on this and other important topics, like frequency band occupancy and sustainable exploration.

2.1.2. Safety Framework for Nuclear Power Sources (NPS) use in Outer Space

The Safety Framework is intended to be a guide for national purposes that provides voluntary guidance and is not legally binding. Its focus is the protection of people and the environment in Earth from potential hazards associated with launch operation and end-of-service mission phases of NPS space applications. Protection of humans in space and other celestial bodies is beyond the scope of the Safety Framework. In fact, the effects of using NPS in outer space on either humans or the environment have not been identified yet. In that sense, the Safety Framework is considered still insufficient.

It purposes a model safety framework which provides foundation for the development of national and international safety frameworks while allowing for flexibility in adapting such frameworks to specific space NPS applications and organizational structures. This means that it is strictly what it is, a framework, it does not define specific actions, but purposes the adequate point of view and structure that governments need to have when addressing these issues.

Its guidance for governments includes considering safety policies, requirements and processes, justification for space power source applications, mission launch authorization and emergency preparedness and response. In terms of management, it talks about responsibility for safety, as well as leadership and management for safety. The technical aspects refer to competence in nuclear safety, safety in design and development, risk assessments and accident consequence mitigation.

To sum up, the biggest sustainability problem regarding NPS is the tremendous impact that failure can have on the Earth environment. This affects both to launch and end-of-mission and this is why the Safety Framework is defined in these two particular cases. However, more considerations need to be investigated when using NPS both in outer space and in other celestial bodies.

3. Previous studies

3.1. Mars Surface Power System Options

Up to this date, Martian exploration has been executed by using either landed energy resources (RTG, MMRTG, primary batteries) or surface solar energy utilization.

RTGs were operated in combination with rechargeable batteries for intermediate energy storage purposes while surface solar energy was combined with either secondary or primary batteries in order to handle diurnal power variations.

The performance of the different possibilities is perfectly summarized in Table 1:

Table 1: Surface solar energy utilization versus nuclear power generation(2009)

Issue	Surface solar energy utilisation (PV, dynamic system)	Nuclear scenario (RTG, DIPS, fission reactors)
Specific energy with respect to the Earth launch mass	Very high; depends on location and operational lifetime[1]	Very high; depends on operational lifetime or mission duration[2]
System lifetime	Very long, but depends on maintenance[1]	Very long[2]
Continuous power output	Not available; intermittent storage system necessary	Available
Reliably	Very high, but depends on installation, location and operation[1]	Very high
Onsite-installation	Regularly required with large solar panels	Not required with RTGs; tbd with fission reactors
Maintenance	Maintenance may be required[1]	No maintenance with RTGs; tbd with fission reactors
Operation in harsh environmental conditions	Dust suspended in atmosphere is a problem	No problem
Output power predictability	Limited; depends on weather, season and dust deposition	Very high; output power degradation rate of RTGs is known a priori
Dependence on orientation	Limited; problem with mobile systems	No problem
Check prior to launch	Limited; no full check if panels have to be unfolded or installed	Possible
Power during launch and transfer to Mars	Normally not possible	Possible
Safety during launch	No problem	Launch failure may have catastrophic effect
Public opinion	Very positive	Problem, particularly in Europe

[1] Dust deposition is a major problem affecting lifetime, maintenance and useable energy output of surface solar power systems (0.28% sol^{-1} performance reduction due to dust deposition with Pathfinder)
[2] Useable energy output often limited by mission duration rather than RTG lifetime

These are the two most promising possibilities in terms of power supply for Martian exploration. The choice of one or the other is very dependent on the requirements for the mission. However, the compact, robust and reliable nuclear power sources generally are a hard match for surface solar energy utilisation in mobile applications and in high-power applications where a continuous supply with electrical energy is required day and night. This mission profile matches robotic exploration using rovers and also human exploration.

Of course, the richness of Mars' environment makes it possible to extract energy from other sources of energy, although they are not quite interesting as the two already mentioned, the other alternatives are worth mentioning.

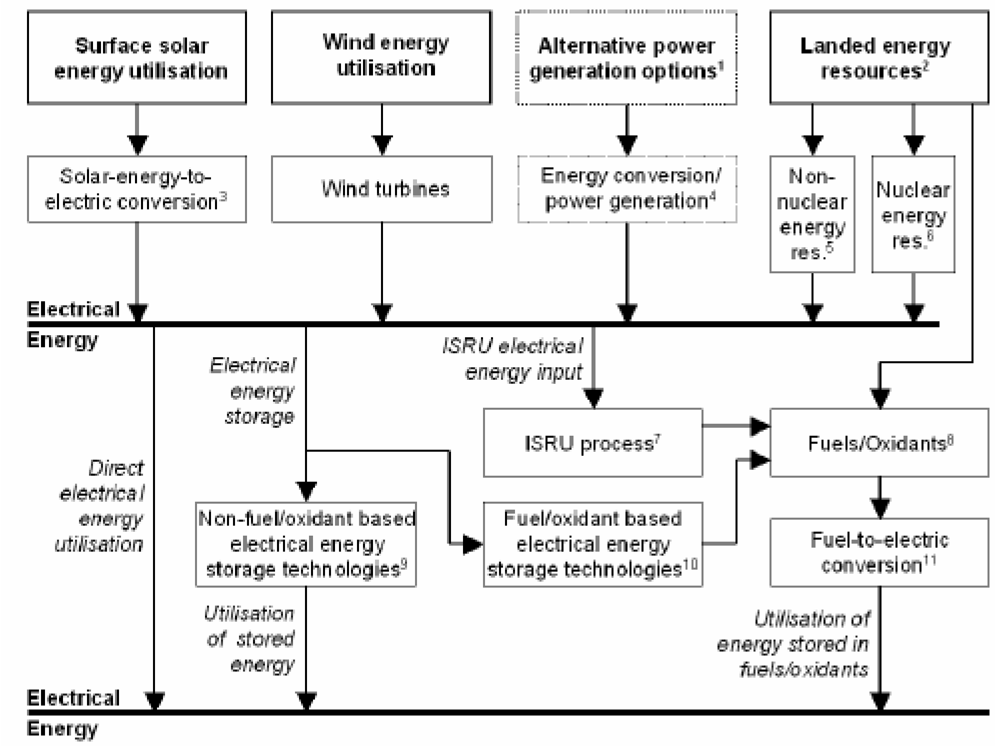

Figure 4: Power generation options and energy pathways for Mars (2009)

However, the huge amount of power required to sustain human activities in the surface of Mars limits the number of viable options to provide outpost power to solar and nuclear fission. Additionally, backup power needs and surface transportation applications can be covered with large scale radioisotope power systems as well as regenerative fuel cells. This topic has been studied a number of occasions, from the detailed analysis of NASA's Design Reference Architecture 5.0, to the development of the Evolvable Mars Campaign by the same agency.

3.1.1. Design Reference Architecture 5.0

3.1.1.1. Power requirement

Power requirement is imposed by each particular mission. However, considering the case of a permanent outpost that has to support human activities, two major phases are clearly distinguished, which define separate power requirements.

The first stage can be referred as the ISRU phase. In a pre-deployed strategy, the cargo responsible for the production of consumables for the crew and fuel for the ascent vehicle is sent to the red planet in the immediately previous launch window than the crew. The power requirements vary depending on the consumables considered. The most demanding case considers the production of all the consumables for both the crew and EVA and also the production of both liquid oxygen and methane to be used as propellant by the ascent vehicle.

The choice of one power source over the other is especially critical for this stage as it is the most energy demanding phase of the mission. Both energy sources considered (nuclear fission and solar) would have to be operated continuously for at least 300 days to produce the necessary resources, as it is required that all consumables are ready before the crew departs from Earth. The energy demand is the exact same for the two, but the operation of the ISRU plant powered by solar energy is limited to 8 hours per day, which means it requires three times the power level of the nuclear case.

Estimates in the Design Reference Architecture 5.0 placed the power requirements at 26 kWe continuous and approximately 96 kWe for 8 hours/day operations. But such estimates only consider consumable productions and the oxidizer for the ascent vehicle.

When considering methane production as well and recalculating for a crew of 4, the power requirements are 43 kWe continuous and 160 kWe for 8 hours/day operations.

The second major stage of the mission is the crewed phase. It begins with the arrival of the crew at the outpost site and ends with its departure to Earth. Here, power requirements are associated with the mission architecture needed. Such architecture includes a central habitat in addition to one small pressurized rover. The central habitat provide service to the full crew in between rover excursion and maintains half of it when a rover is on the field (the rover carries a expedition of two people). DRA 5.0 estimates power requirement of the habitat to be 12 kWe during both day and night.

The pressurized rover requires 3.4 kWe daytime power for the crew, dropping to 2.4 kWe at night. This does not include mobility power. Assuming a mass of 7,500 kg, the rover would require 25 kWe for a speed of 3 km/hr.

The power system considered will be used for both phases of the mission. As displayed in Figure 5, the ISRU phase requires substantially more power than crewed phase to ensure sufficient resource production. This difference is even bigger when considering methane production. This means that the main power system must be delivered and autonomously deployed with the cargo and ISRU equipment.

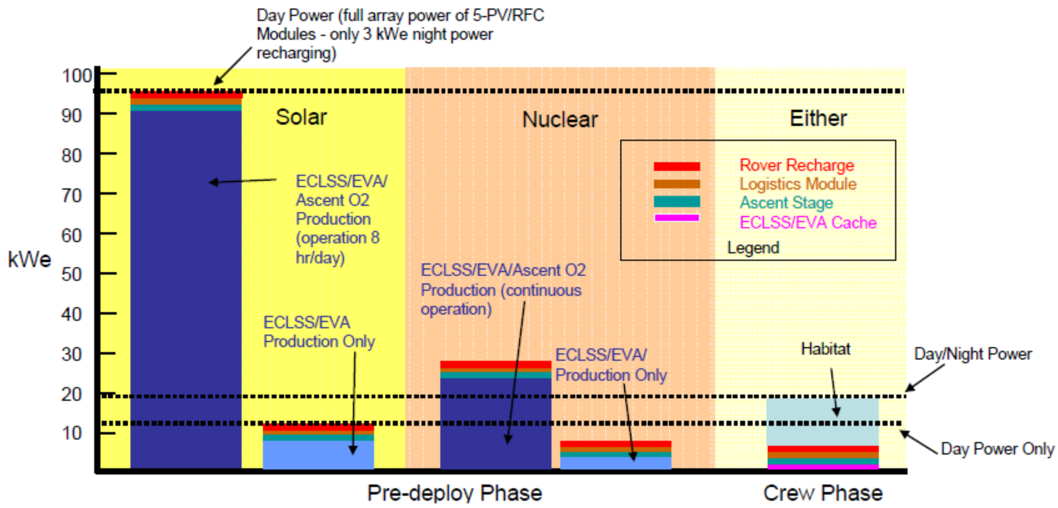

Figure 5: Power requirement profile (Drake, 2009)

Figure 5 also shows additional power to be considered: about 1.5 kWe each for logistics module, ECLSS/EVA cache, and ascend vehicle maintenance power, as well as charging the unpressurized rovers and other miscellaneous power loads.

3.1.1.2. Power system concept

The possibilities considered are solar, nuclear fission, and large-scale radioisotope systems.

- Solar power system concept

NASA's experience with rovers and landers has shown that solar photovoltaic cells are a reliable source of energy for long duration operation on the Martian surface. This same experience has also revealed the challenges this technology faces in the surface of Mars. However, the simplicity, technical maturity and social acceptance of this renewable source of energy makes them a contender for power supply in a human Martian outpost.

DRA 5.0 considered that the optimal approach was to develop a modular PV capable of providing 5 kWe of continuous power. The number of units was optimized and additional units were provided for redundancy. Each module would have had an area of 290 m^2 and would be made of triple junction cells with a 29% efficiency. The inclination angle provided would have even output power over the day and facilitate automated dust removal. Watch Figure 6 for an artist illustration of such power system.

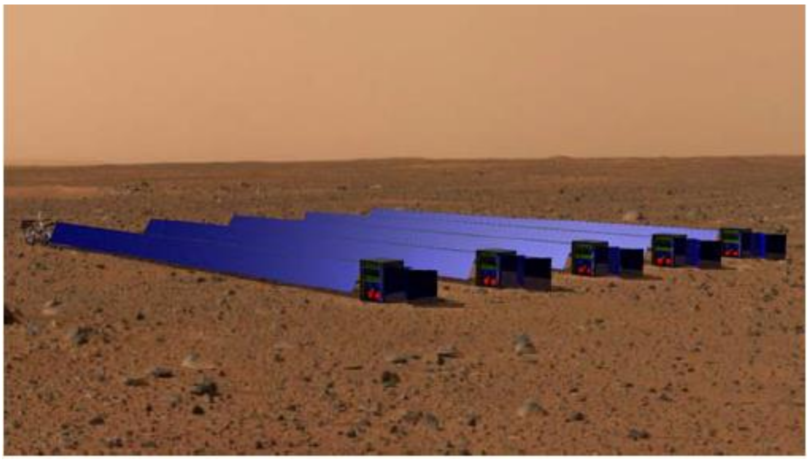

Figure 6: Solar power concept (Drake, 2009)

Five regenerative fuel cells were proposed in order to provide 5 kWe of power during night time operation. Five modules (four for nominal power plus one for redundancy) would have been enough for both the crew and ISRU phases. During ISRU, solar arrays would operate at approximately 100 kWe for 8 hours/day, while supplying approximately 3 kWe night time power through the RFCs.

The mass of the entire system was estimated to be about 10,000 kg, considering 1,980 kg for each module (including 20% contingency). Production of propellant would require the addition 450 m^2 of solar array, which would increase the overall power system mass to about 12,500 kg.

- Fission surface power system concept

FSPS scenario from DRA 5.0 considered a reactor capable of providing 20-30 kWe located at the base of the power system and surrounded by a radiation shield thickened in the direction of the base. If sited at 1 km, dose rate would have been under 5 rem/year at the base and under 50 rem/year at other directions. The autonomous deployment of such a system would have required its own mobility system, autonomous drive to the distance and deployment cable, deployment of radiators and start-up. The power provided is limited by the radiator size required to reject waste heat. Mass estimated ranged from 6,800 kg for 20 kWe, to 7,800 kg for 30 kWe. The later could have accommodated propellant ISRU.

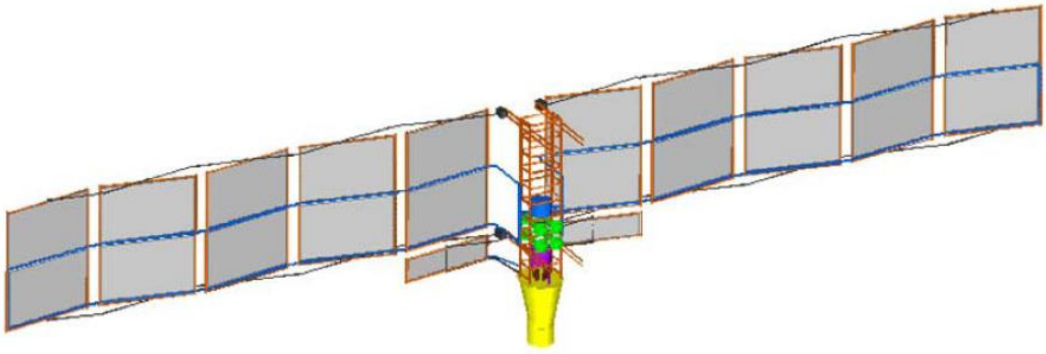

Figure 7: FSPS power configuration (Drake, 2009)

- Large-scale radioisotope power system

For applications such as backup power and mobility, an additional power system to be considered is the large-scale RPS. This technology, when combined with Sterling engines could provide power levels up to 10 kWe. For the DRA 5.0 study, 5 kWe RPS were considered, made up of 54 general-purpose heat source (GPHS) containing a total of 32.4 kg of ^{238}Pu. This system would provide continuous power from the time that it is fuelled, with a power output estimated to fall off by 0.8% each year as a result of the natural decay of its fuel. The mass of the system would be about 450 kg (including 20% contingency).

3.1.2. Evolvable Mars Campaign

In 2016, there was a paradigm shift in the concept of the mission. DRA 5.0 considered multiple landing sites while the new Evolvable Mars Campaign (EMC) considered multiple landers to the same site. This new approach allows for infrastructure build-up and also considers some new advances in both solar and nuclear devices such as the Kilopower, higher density batteries and more efficient solar arrays.

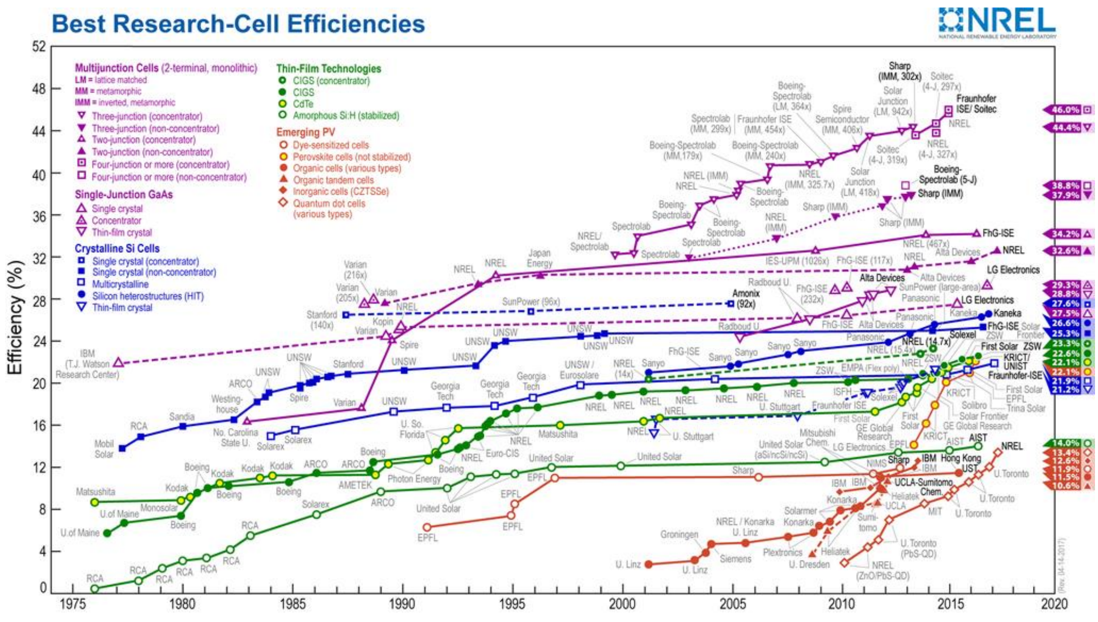

Figure 8: Historical evolution of solar cell efficiencies (NREL, 2018)

Like in DRA 5.0, the Mars Ascent Vehicle (MAV) would be sent to Mars with empty liquid oxygen (LOX) tanks. LOX would be obtained from Martian atmosphere, like in the MOXIE experiment contained in Mars 2020 rover. Methane would be brought from Earth. Once LOX tanks are full crew is clear to take off from Earth and upon crew arrival to the surface of Mars, power operation is switched to crew life support and propellant cryogenic conditioning. Dust storms up to 120 sols are considered a possible scenario.

Two missions are considered as part of the EMC, a Pre-cursor Demonstration mission of ISRU and a Crewed Surface Mission, with a cargo phase and a crew phase.

Pre-cursor demonstration mission of ISRU would be focused on producing 1/5 LOX and four different power systems are considered in the study: Kilopower, daylight-only ISRU solar, around the clock ISRU solar with battery reserves and daylight only ISRU solar with twice as power to compensate for the night period. The study is based in the following assumptions:

- Data was extracted from Opportunity such as solar array performance, favourable night durations and seasonal variations
- One dust storm is assumed to occur during the mission with 20 m/s wind speed and a total irradiance of 30-40% of the direct light on a clear day
- Optical depth varies from 1.0 (clear day) to 5.0 (dust storm). Effect of the optical depth on the incident radiation can be seen in Figure 9.
- Average 12 hours sunlight per sol (10 h/sol of ISRU to allow for warm-up).
- ISRU sized for 0.45 kg/h LOX with a target of 4,500 kg.

- LOX tank sized at 1,500 kg with the excess production vented overboard.

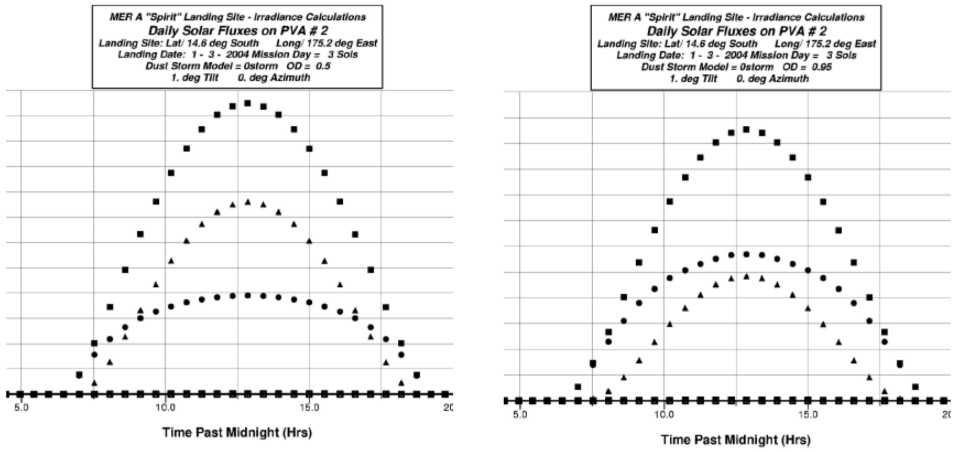

Figure 9: Diurnal Profile of Solar Energy on a Horizontal Surface on Mars for a Low Dust Case (left) and a High Dust Case (right). Showint the Direct (Triangles), Scattered (Circles), and Total Isolation During the course of a Martian Sol (Jenkins and Scheiman, 2004)

A 10 kWe Kilopower would provide 6.45 kWe (6.52 kWe at night) with a conical upper radiator that requires no autonomous deployment strategy. The weight of the Kilopower unit would be 1,754 kg, which includes 15% mass growth allowance and radiation shield for a crew exposure lower than 3 mR/h within 500 m from the device. The system would have a 6 m diameter footprint, 5.14 height and would require 106 W keep-live power after landing for a total mass of 2,751 kg. It is important to consider that a 10 kWe Kilopower is oversized, but it still allows to demonstrate some important technologies of a crew mission architecture.

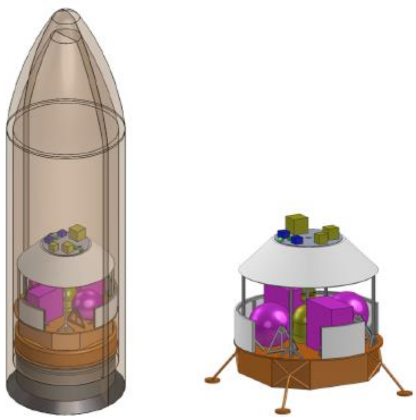

Figure 10: Mars ISRU fission power lander concept in launch vehicle (left), and deployed on Martian surface (right) (Gibson et al., 2017)

Solar concepts would utilize 120 V Orbital ATK UltraFlex® arrays, a kind of inverted metamorphic multi-junction solar cells with 33% conversion efficiency, or equivalent. A 45º inclination is provided for sun tracking and dust removal.

Batteries are Panasonic cell type Li-ion batteries with 60 % depth of discharge and 165 Wh/kg.

Figure 11: Mars ISRU solar powered lander concept in launch vehicle (left), and deployed on Martian surface (right)

Daytime-only solar power options have the lowest landed mass but requires a high number of on/off cycles of the ISRU devices, which could result in undesirable reliability issues. Fission power is at mass disadvantage because the device is oversized and requires additional shielding. Also, the equatorial location benefits the performance of solar power systems. Regardless, all options are within allowable payload limits, which means that mass will not be the decisive factor when choosing the power system. Technology investment strategies, program budgets and risk mitigation need for later crewed missions might be as important for the decision as mass. Another factor to consider is that the cost for solar hardware is 100$ M less than Kilopower, and this does not include the differences in readiness between Kilopower and solar technologies.

Table 2: Solar vs. Fission for In-Situ Resource Utilization Demonstration Mission on Mars surface (Gibson et al., 2017)

Option	Solar 1A: 1/5 rate Daytime Only	Solar 1B: 1/5 rate Around the Clock	Solar 1C: 2/5 Rate Daytime Only	Fission 2: 1/5 Rate Around the Clock Fission Power
Total Payload Mass (including growth)	1,128 kg	2,425 kg	1,531 kg	2,751 kg
Electrical Subsystem Mass	455 kg	1,733 kg	639 kg	1,804 kg
ISRU Subsystem Mass	192 kg	192 kg	335 kg	192 kg
Power	~8 kW Daylight	~8 kW Continuous (with 16 kW of arrays)	~16 kW Daylight	~7 kW Continuous
Solar Arrays	4 each x 5.6 m diameter	4 each x 7.5 m dia.	4 each x 7.5 m diameter	None
Night Production?	No	Yes	No	Yes
LOX Production	4.5 kg/sol	10.8 kg/sol	9.0 kg/sol	10.8 kg/sol
Time to Produce 4,400 kg LOX, including 120-Day Dust Storm Outage	1,098 sols	527 sols	609 sols	407 sols
ISRU On/Off Cycles	1,098	<5	609	<5
Radiation Tolerance	100 kilorad (krad) electronics and ISRU			300 krad electronics, 10 Mega ad (Mrad) ISRU

The Crewed Surface Mission is the following step of the EMC. The mission would consist in several expeditions to a single location, each expedition would require several landers, as seen in Table 3.

Table 3:Mission concept of operation (Rucker, Michelle A., 2016)

Expedition 1 *Four Landers*	Expedition 2+ *Three Landers per Expedition*
1. Power System + Cargo	1. MAV + ISRU
2. MAV + ISRU	2. Cargo and Consumables
3. Mixed Cargo and Consumables	
4. Habitat Module + Crew	3. Habitat Module + Crew

Landers would be located no more than 1 km away from each other and the power system configuration varies depending in the energy source. For FSPS, all Kilopower units will remain together on/near the first lander and robotic connections would be required to subsequent landers. This opens the possibility to disconnect a lander when it is no longer in use. For solar, arrays are needed in every lander, at least through expedition 3. This means that all landers must be connected into a power grid and remain connected even when the lander is no longer active.

As can be seen in Table 4 and Figure 12, in the cargo phase of the mission, the power will be dedicated to ISRU production of 22,728 kg of LOX in 420 Earth days, with extra power dedicated to keep-alive MAV power needs. The crew phase main demands will be Surface Habitat, and Science Laboratory, as well as MAV keep-alive power. Crew Phase considers a Keep-Alive power scenario in order to adjust the consumption in dust storm cases.

Table 4: Surface power needs for the crewed mission (Rucker, Michelle A., 2016)

	Peak Power Needed (W)		Keep-Alive Power Needed (W)	
Element	Cargo Phase	Crew Phase	Cargo Phase	Crew Phase
ISRU	19,700	0	19,700	0
MAV	6,655	6,655	6,655	6,655
Surface Habitat	0	14,900	0	8,000
***Science Laboratory**	0	9,544	0	174
Total	26,355	31,099	26,355	14,829

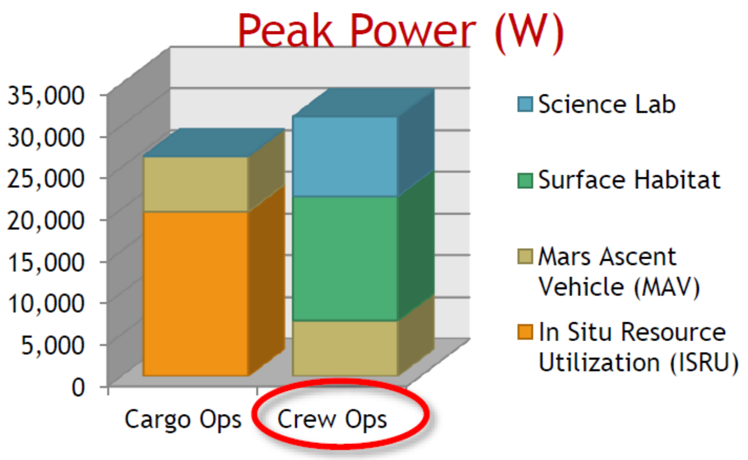

Figure 12: Surface power needs for the crewed mission (Rucker, Michelle A., 2016)

Four 10 kWe Kilopower units would generate 35 kWe continuous for all mission phases and subsequent expeditions at any landing site. The mass of the power generation system would be 9,154 kg, which includes one spare Kilopower for contingency and does not include farm-to-lander Power Management and Distribution (PMD). The weight of PMD could be up to 1,038 kg on the first lander, including 1,000 – 120 VDC conversion and possible connection to the power plant depending on the final placement of the power system. Other landers would require up to 1 km spool of high voltage cabling, as well as connectors and voltage converters.

If solar arrays were to be used, each lander in expedition 1 would require four 12 m diameter UltraFlex® arrays or equivalent. Considering a 9 m diameter lander, the whole system would have a 33 m footprint. With arrays in neutral position on a 2.66 high lander neck, the overall height would be 9.69 m. Height minimizes interactions with surface and payloads and inclination acts as dust shielding and solar tracking. Decking to the lander provides stronger anchoring and thus more stable operation, it also allows them to be quickly brought on-line. Under nominal conditions at Jezero Crater, 34.2 kWe are required during the day and 35 kWe at night for around-the-clock propellant production. During a dust storms, these numbers would be reduced to 10,985 W during the day and 11,728 W at night. Once crew arrived, the system would need to supply 21,915 W during the day and 26,790 W at night time, reduced to 22,945 W during the day and 24,060 at night in case of storm.

Mass comparison needs to take into consideration all the expeditions, as the totality of the fission power arrives with expedition 1, while solar power needs to be constantly expanded until expedition 3.

Solar performance does not catch up until the third expedition. Fission is more tolerant to dust, but the distributed solar power network is more tolerant to cable damage. Before MAV departure, solar arrays will have to be removed, which posts additional risk on handling large arrays close to the MAV. Service life is expected to be 12 years for both systems.

Results from this analysis are mainly influenced by the production rate, time available to make the propellant, dust storm duration considered and transmission voltage.

By the third expedition, cumulative solar arrays mass is more than twice the FSPS, but at that point, the solar network would be tolerant to a 120-sol dust storm with no significant disruption to operations, which clears one of the main disadvantages of solar power towards nuclear. Of course, mass differential is greater at Columbus Crater, placed at a higher southern latitude than Jezero Crater.

Table 5: Solar vs. Fission mass comparison for the three expedition Astronaut crew phase of a Mars surface mission (Gibson et al., 2017).

Crew Expedition	Power Generation/Storage Mass (kg)		
	Fission Power	Solar Power	
		Jezero Crater	Columbus Crater
Expedition 1	**9,154**	**11,713**	**12,679**
Lander 1	9,154	5,611	5,909
Lander 2	0	2,034	*2,704
Lander 3	0	2,034	2,033
Lander 4	0	2,034	2,033
Expedition 2	**0**	**6,102**	**6,770**
Lander 1	0	2,034	*2,704
Lander 2	0	2,034	2,033
Lander 3	0	2,034	2,033
Expedition 3	**0**	**0**	**0**
Lander 1	0	0	0
Lander 2	0	0	0
Lander 3	0	0	0
Three Mission Total (kg)	**9,154**	**17,815**	**19,449**

In the end, it is clear that both options are viable for low latitudes. Solar has a high technology readiness, and thus, lower development cost. It also has quicker switch from on-board stored energy to surface power. In the other hand, its high mass penalty may limit landing site options and presents higher risk during a storm. Fission is reliable, requires lower mass for most landing sites and mass does not depend on the site, season, day/night cycle, or weather. However, it has lower technology readiness and higher development costs.

3.1.3. Implementation considerations

Mars is a hostile environment. A number of issues affect the power system trade. This section will highlight the most important ones as well as some considerations to be considered.

3.1.3.1. Dust deposition

The measured power drop of solar panels due to dust deposition in the Martian surface is approximately 0.2 % per day. The only reason for the extremely long operational longevity of the MERs has been the somewhat lucky removal of such deposition by dust devils. These so called "clearing events" mitigated the output loses in a regular basis.

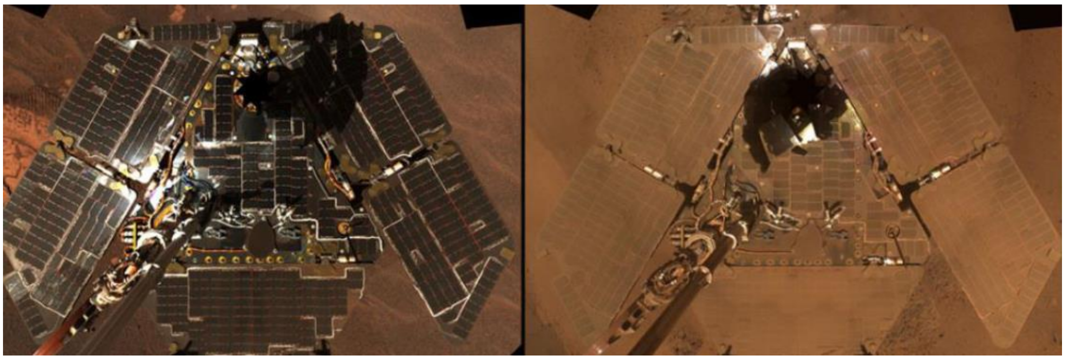

Figure 13: MER solar panels before (left) and after (right) dust deposition (Pappa, 2017)

However, we cannot trust these cleaning events to be a reliable mitigation strategy, as their behaviour is incompletely understood. Consequently, it is necessary to implement some kind of autonomous dust-mitigation technology to clean the solar panels, specially prior to crew arrival.

Given the rising popularity of solar energy in the Earth, there are several studies about this issue. Arid areas such as Thuwal or Saudi Arabia, great analogous to Mars due to their environmental conditions, have great importance in these studies. There are different kinds of dust mitigation or anti-soiling strategies.

The first possibility is to make use of the natural means to prevent dust deposition or even clean the arrays. Dust devils are an example of this strategy, but as they are not completely understood, a better example would be to provide the system with a tilt angle, which has shown to significantly impact dust accumulation (Cano et al., 2014).

Another interesting possibility is the mechanical removal of dust by brushing, blowing, vibration or ultrasonic driving. The Automated, Robotic Dry-Cleaning of Solar Panels (Parrott et al., 2018) purposed solution uses a silicone rubber foam as brush material, which has proven to be effective due to the increased frequency of the proven events. However, an inherent problem to these cleaning mechanisms is that they require a high level of maintenance.

The most promising solution for the case of Martian solar power is the electrostatic removal of dust. The Transparent Self-Cleaning Dust Shield for Solar Panels (Sims et al., 2007) contains a clear panel with embedded parallel electrodes connected to a single-phase AC supply that produces an electromagnetic wave. The produced electromagnetic field prevents deposition of charged particles. Non charged particles will deposit momentarily but are then subjected to an in-homogenous electric field, and move across the panel. This motion causes them to become triboelectrically charged and they are ejected.

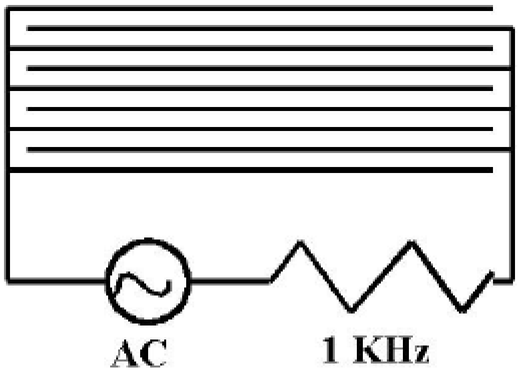

Figure 14: Schematics used for the electrodynamic screen (Sims et al., 2007)

Voltage was found to have the most important effect upon the cleaning of deposited powder particles. Different powders were studied, obtaining the cleaning factors (percentage of powder that has been removed from the screen) shown at Figure 15.

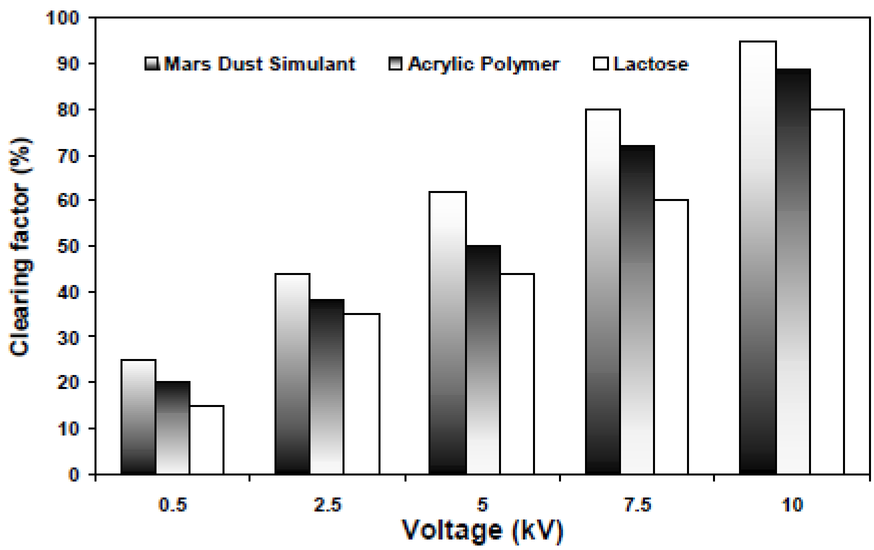

Figure 15: Cleaning factor for different powders at various voltages (Sims et al., 2007)

Mars dust simulant was the powder easiest to be cleaned from the shields, both in terms of voltage required and quickness of removal.

As this system does not require any moving mechanism, the need for maintenance is way lower than in mechanical systems. To be considered is the power required to activate the shield. It would be pointless to provide the system with a shielding mechanism that consumes more power than the expected losses, so a power trade study must be performed in order to define the activation frequency of the shield.

Soiling has a minimal effect on FSPS. Dust can indeed deposit to the surfaces of the radiator, but the decrease in emissivity is so low that is not considered to significantly affect the operation.

3.1.3.2. Dust storms

It is well known that there are regional and global dust storms on Mars that can dramatically reduce the amount of sunlight reaching the surface. This is perhaps the greatest threat to solar power generation, as the power output can be reduced down to 15 % of the pre-storm capability. These storms may last for 1 to 2 months, so the power system must provide minimal survival power for this time. This could be achieved by the combination of extra solar array area and additional fuel cell capacity. To deal with this scenario, the crew would need to deploy an additional thin-film solar array of approximately 4,300 m^2 according to DRA 5.0, with an estimated mass of about 7,800 kg.

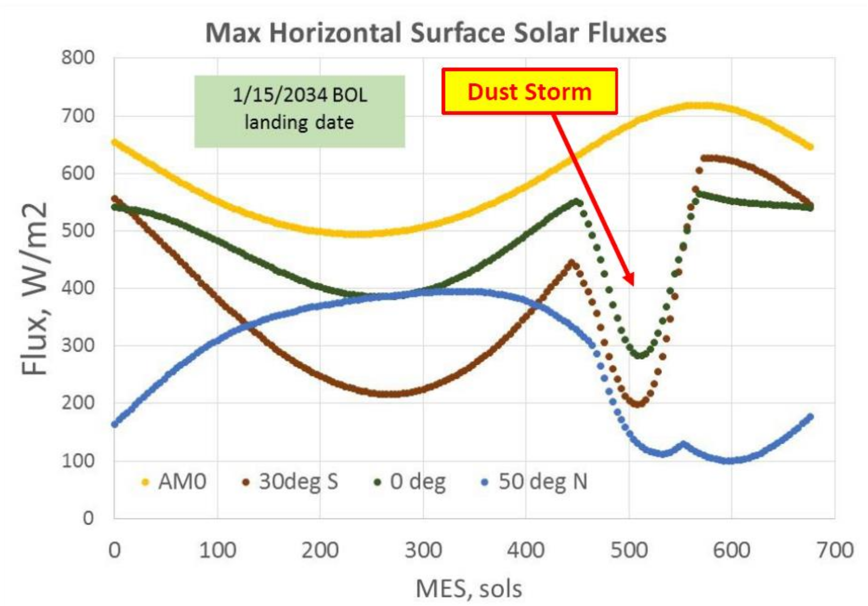

Figure 16: Dust Storms' Impact on Martian Surface Irradiance (Pappa, 2017)

Nuclear FSPS is not affected by dust storm conditions.

3.1.3.3. Deployment

Autonomous deployment of power systems represents an equal challenge for both alternatives. Large solar array wings deployment has been a challenge in the past and crew intervention has been required to solve the problem in the ISS. FSPS will require deployment of its large radiators with the extra difficulty of the jointed fluid lines that they contain as well as transport to its emplacement site and cable deployment during the traverse.

3.1.3.4. Latitude constraints

Another limitation for solar power is the variability of surface irradiance with latitude. In fact, a distinguishing feature of FSPS is its ability to operate at any latitude. Applicability of solar power is considered to be best between latitudes of 15ºS and 30ºN, which automatically discards a lot of interesting landing sites. This applicability land and the landing sites included are displayed in Figure 17.

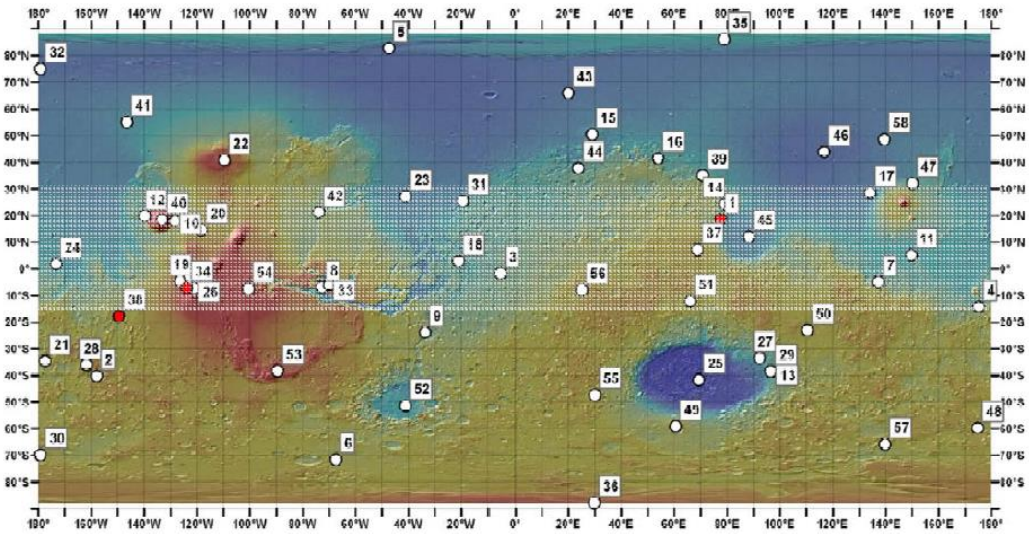

Figure 17: Latitude band of effective solar power applicability (Drake, 2009)

3.1.3.5. Operational restrictions

On the other hand, once installed, solar panels present no operational restrictions. This is not the case for FSPS, as radiation shielding implementation will determine the freedom of operations. Although the use of sharped shielding facilitates an acceptable dose rate at the base, it also results in a restriction area which must be avoided, as shown in Figure 18.

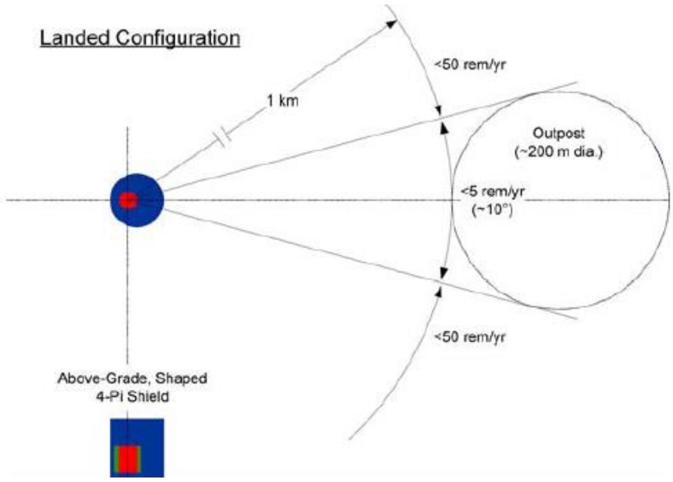

Figure 18: FSPS radiation protection zone (Drake, 2009)

3.1.4. New power system concepts

Several possibilities exist that can be applied to the Mars exploration architectures for main power as well as for backup mobility power. The conceptual main contenders have not changed much since DRA 5.0, but improvements on efficiency and power to mass ratios of the considered technologies need to be considered for an updated discussion.

3.1.4.1. Solar power system concepts

It is becoming a tendency on NASA to outsource certain aspects of the technological development to external participants. To do so, contenders will present their ideas in a contest. The best ideas will be awarded with a contract by NASA to keep developing these technologies. One of these contests was offered in 2017, leading to interesting purposes.

One of them is the so-called Mars Autonomous and Foldable Solar Array (MAFSA), developed by the University of Colorado. This is a low mass, autonomously deployable solar array which includes dust deposition and storm mitigation. An illustration of the fully deployed array is shown in Figure 19.

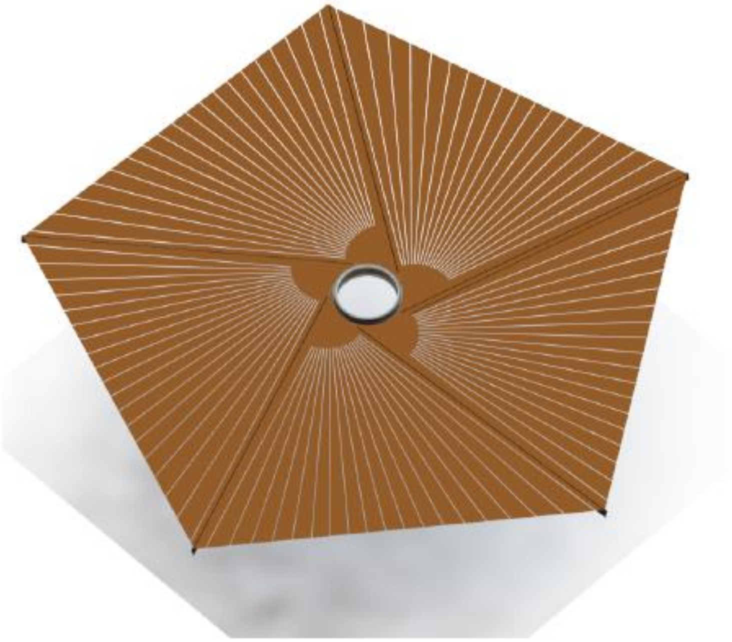

Figure 19: Fully deployed MAFSA (Glascock et al., 2018)

MAFSA is made up from already existing technologies: the deployable boom is a scaled up version of Triangular Rollable and Collapsible (TRAC) booms developed by Roccor and invented by the Air Force Research laboratory that are being used in CubeSat applications; the retraction and deployment motors are two 3-phase, 4-pole induction electric motors used in the Tesla Roster; the bearings are Kaydon NG series bearings scaled up to an outside diameter of 4 m (from 1 m); photovoltaics are XTJ Prime triple junction thin film solar cells from Spectrolab with an area mass density of 500 g/m^2 and EOL efficiency of 26.7%; and the solar cell substrate is a Dupont Kapton PV9100 Series polymide that provides protection to the thin film cells.

The deployed solar arrays are a single unit that forms a pentagon of 1,060 m^2. Each fifth is composed by 80 evenly spaced segments extending radially, each one containing 928 solar cells.

The system has a total mass of 1,463.2 kg and a volume of 1.73 m^3 before deployment and is capable of generating 15 kWe to 30 kWe of equivalent continuous power over a Martian year at the equator, considering EOL efficiency.

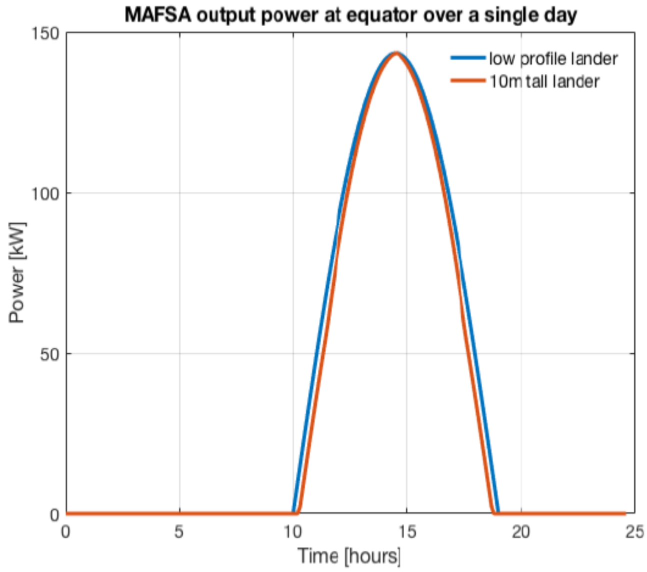

Figure 20: Daily power output with ideal solar profile accounting for lander shadow (Glascock et al., 2018)

MAFSA's dust removal from the array will be accomplished by retracting the array to an angle of 45º once per 21 nights and returning to the fully deployed state before sunrise. This is considered to be enough to keep the loses due to dust deposition below 5% consistently.

Considering that the array cannot be in a stowed state for every storm event because power is still required, the structure has been designed to resist flawlessly winds up to 50 m/s that can happen during Martian dust storms. However, nothing can be done in regards to the loss of power expected during these events.

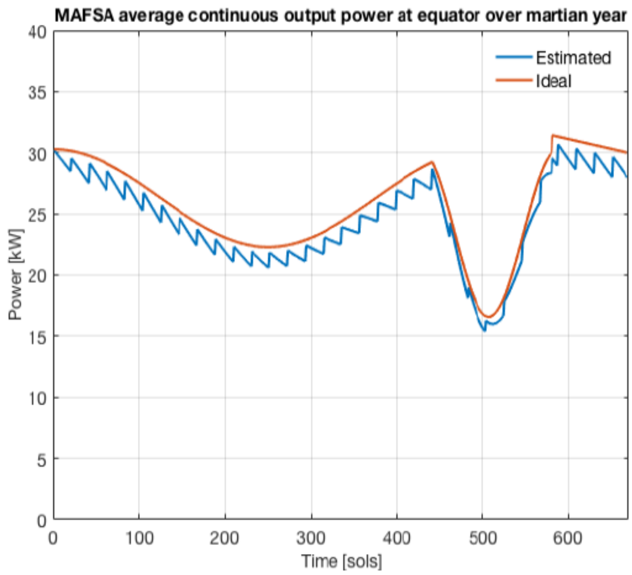

Figure 21: Annual equivalent continuous power output with dust storm event shown at 450 sols (Glascock et al., 2018)

Another promising project is the Norwich Inflatable Mars Solar Array (NIMSA). NIMSA trusts in the new inflatable technologies to provide a structure designed to be strong that uses in-situ Mars atmosphere for installation with a specialized pump and can be compacted into a small volume for transport and autonomously deploy to its operating state. It is also based in state-of-the-art technology and proven methods. The deployed structure is shown in Figure 22.

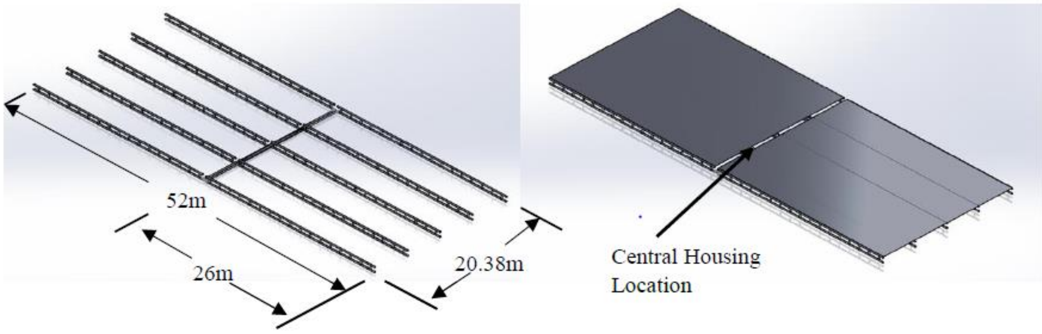

Figure 22: NIMSA's inflatable structure with and without PV cells (Azure et al., 2018)

The central housing located at the middle of the array is a rectangular frame made of carbon fibre, the inflatable structure consists of ten double-chambered air channels made of Vectran, a material used on MER and Pathfinder, connected to the central housing with Vaisala BAROCAP pressure sensors, used on Curiosity Rover, to monitor and evaluate the uniformity of inflation. NIMSA's photovoltaics are flexible NeXt Triple Junction Cells with a solar efficiency of 30.7% and an area mass density of 500 g/m^2. The inflation system is composed of twenty MOXIE CO2 Compressors by Air Squared, Inc. inside the central housing, designed for NASA Mars 2020 mission.

The system will provide similar output levels to MAFSA, with a total mass around 700 kg and a volume of 3.61 m^3 in launch configuration.

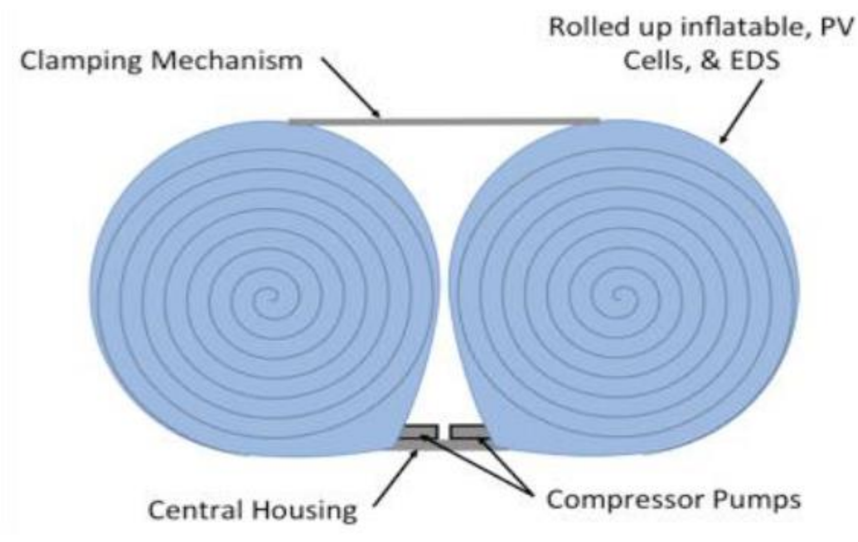

Figure 23: NIMSA configuration for launch (Azure et al., 2018)

NIMSA's dust mitigation strategy relies on an Electrodynamic Dust Shield made of Polyethylene Terephthalate (PET) film that has a conductive Indium Tin Oxide (ITO) coating on one side and will be wired together into a circuit, combined with the concavity of XTJ PV cells and the natural vibration of the system to shake dust particles off.

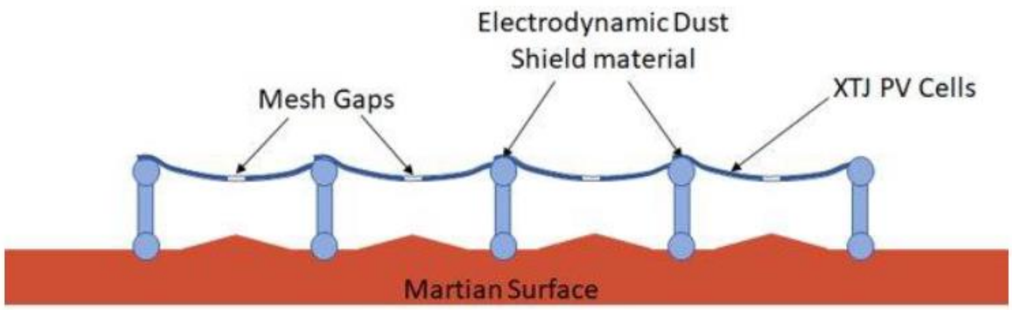

Figure 24: Side view of NIMSA demonstrating structure and dust removal gaps in PV cells (Azure et al., 2018)

The structure will be anchored directly to the lander, using its weight and stability instead of the soft layer of Martian regolith on the surface. The array can adapt to different orientations caused by strong winds and will be able to correct itself by reversing the direction of the compressor pumps, retracting and re-inflating.

Even though these systems are very immature and on a different scale compared to DRA 5.0. They are both very promising and provide an idea of the improvements in terms of both mass and volume, and other problems like dust deposition and storm protection.

3.1.4.2. *Fission surface power system*

The most promising technological development in this area is NASA's Kilopower fission reactor (Gibson et al., 2017). The Kilopower reactors are designed to provide 1-10 kWe. Nuclear powered missions are usually excluded from NASA's plans because of the lack of radioisotope fuel needed when using RTG for electrical generation, and the absence of a flight qualified fission system. In short, mission directorates will not include a fission power system in their solicitation until it is flight qualified, but scientist will not propose new missions that require more power than what is currently available. Since 2015, Kilopower Reactor Using Stirling TechnologY (KRUSTY) has been under development with the intend to become a viable alternative in such cases, including surface power for a Mars mission.

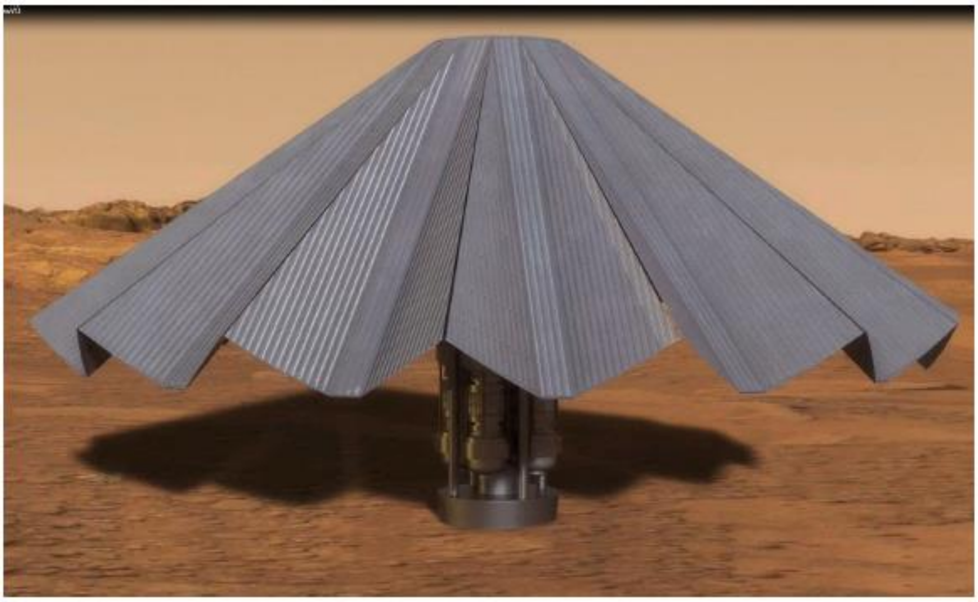

Figure 25: NASA's Kilopower reactor's illustration (NASA, 2018)

Testing was performed during March 2018, with very good results. The most impressing test was a full power run that achieved the operating temperature of the reactor (around 800ºC) that was run for 28 hours. The profile of the experiment can be seen in Figure 26.

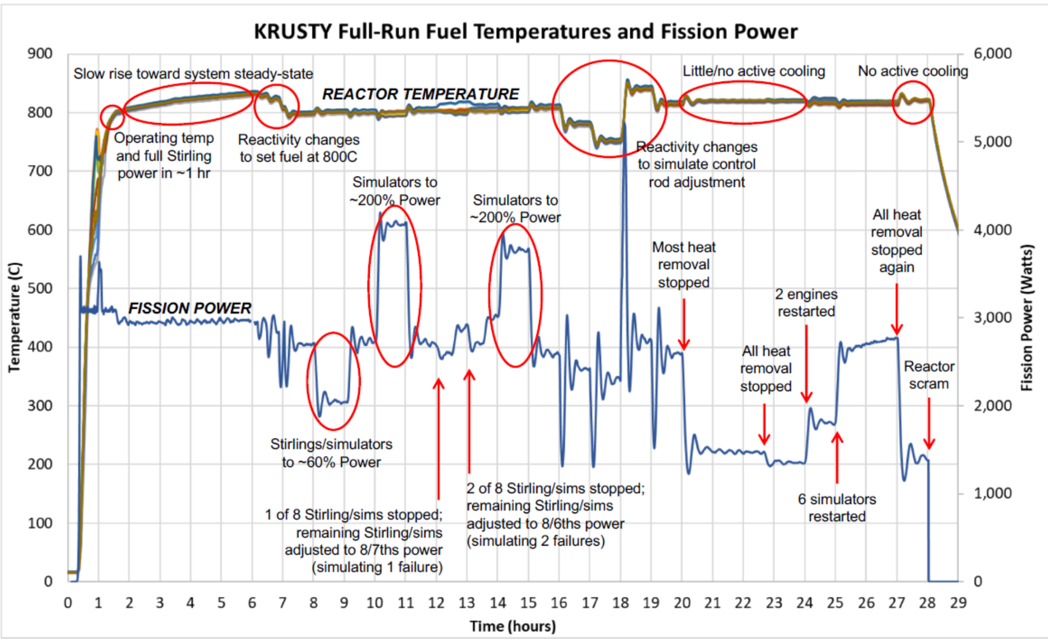

Figure 26: Actual test data from Kilopower nuclear test (NASA, 2018)

The test begun with the insertion of the fuel, that was then bumped in regular intervals until the desired operating temperature was achieved. Then the reactor was allowed to go steady for several hours. After 7 hours, the Stirling power removal was cut around 60% and brought back to maximum power, allowing the reactor to compensate and load follow back to the original power level. After another several hours steady state 1 of the Stirling engines was eliminated, simulating a failed heat pipe or full engine. That was followed by the simulation of 2 simultaneous engines. Finally, all cooling to the reactor was cut to simulate a full loss of cooling event. As expected, the temperature rose to compensate and drop power at level being dissipated by thermal radiation to the vacuum chamber walls.

Using KRUSTY, a 50 kWe fission system including 4+1 spare 10 kWe Kilopower units can be delivered to mars and provide energy for more several expeditions, as the design life is estimated to be 12 years. The performance of this reactors is not changed based on location or dust storms and it could be attached to a lander or offloaded for strategic arrangement. The total mass estimation for the system is 9,154 kg, which shows that DRA 5.0 was accurate on its estimates. When compared with solar systems studied for two different locations, the fission system for crewed expeditions is roughly half the mass.

Kilopower reactor can reduce several risks associated with the Martian environment using the advantages of nuclear surface power, however, it would result in operational restrictions such as the implementation of astronaut keep out zones and radiation safety protocols. Both ISRU and crew phases of the early Mars missions can easily be achieved with several 10 kWe Kilopower reactors. KRUSTY based systems win the mass and power trades for the crewed missions by a factor or two even at solar favourable sites.

3.1.4.3. Radioisotope Generators

The last viable source of energy that could be employed at Mars are radioisotope generators. These devices have been extremely important in the exploration of the outer solar system, as they provide a small power output for long durations when no solar energy is available.

Radioisotope generators convert the heat produced by a decaying radioisotope to generate power. The criteria for selecting the radioisotope is as follows:

- Its half-life must be long enough to release energy at a relatively constant rate.
- The larger the amount of power per mass and volume the better.
- Radiation must be easily absorbed and transformed into thermal radiation, preferably alpha radiation. In any case, penetrating radiations must be avoided.

According to these preferences, plutonium isotope ^{238}Pu is the preferred option. However, this isotope is a very scarce resource on the Earth, it is basically the product of certain nuclear fission reactions. Due to its advantages regarding space exploration, its production has been enhanced globally, however, according to recent estimates, the USA only have enough of it to fuel 5 of their Multi-Mission

RTGs (MMRTG), or 40 of their General-Purpose Heat Sources (GPHS). ESA is exploring the possibility of using ^{241}Am instead, which has longer half-life, smaller power generation, and requires more shielding but is abundant.

NASA's approach is to package ^{238}Pu into modules known as general-purpose heat source (GPHS). Each module contains 1.44 kg of the radioisotope and delivers 250 Wt at the time of manufacture. The alpha radiation they emit is blocked by their own cladding, so they require no further radiation shielding.

Depending on the conversion mechanism from thermal energy to electrical energy, a radioisotope generator can be a Radioisotope Thermoelectrical Generator (RTG) or a Stirling Radioisotope Generator (SRG).

The MMRTG has been widely used by NASA. They are powered by 8 GPHS modules that generate up to 2 kWt. Its thermoelectric couple allows for the production of 125 We at the start of the mission and 100 We after 14 years, which accounts for an efficiency of 6.25% to 5%. The total mass of the unit is 45 kg, containing 11.52 kg of ^{238}Pu, and it provides about 2.8 W/kg at BOL. In order to provide the 5 kWe stated at DRA 5.0, 50 of these units would be required. The system would have a total mass of 2,250 kg, containing 400 GPHSs (576 kg of ^{238}Pu), which is 10 times the amount of ^{238}Pu currently available. In fact, even the 54 GPHS stated to be needed in the DRA 5.0 are greater than the existing 40 units. This discrepancy occurs because, for some reason, DRA 5.0 study considered a thermal to electric conversion efficiency of 37%. Such efficiencies are not possible with MMRTGs, even though its 5% efficiency at EOL could improve with the inclusion of thermophotovoltaic cells, which has proven a 20% tested efficiency with electric heaters.

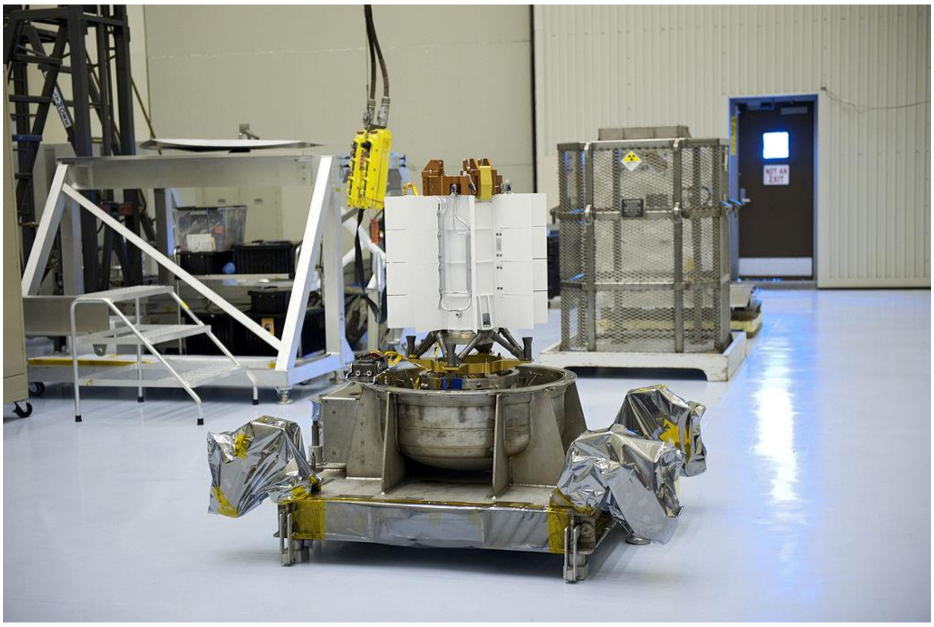

Figure 27: NASA's MMRTG of the Mars Science Laboratory.

SRGs are based on a Stirling engine powered by two GPHS. This system can provide 100-120 We from the 500 Wt generated by the GPHS, which accounts for a 20% efficiency at EOL. 50 of these units would be required for a human outpost at Mars, the same number as MMRTGs, but they would require 100 GPHS (144 kg of ^{238}Pu) instead of 400.

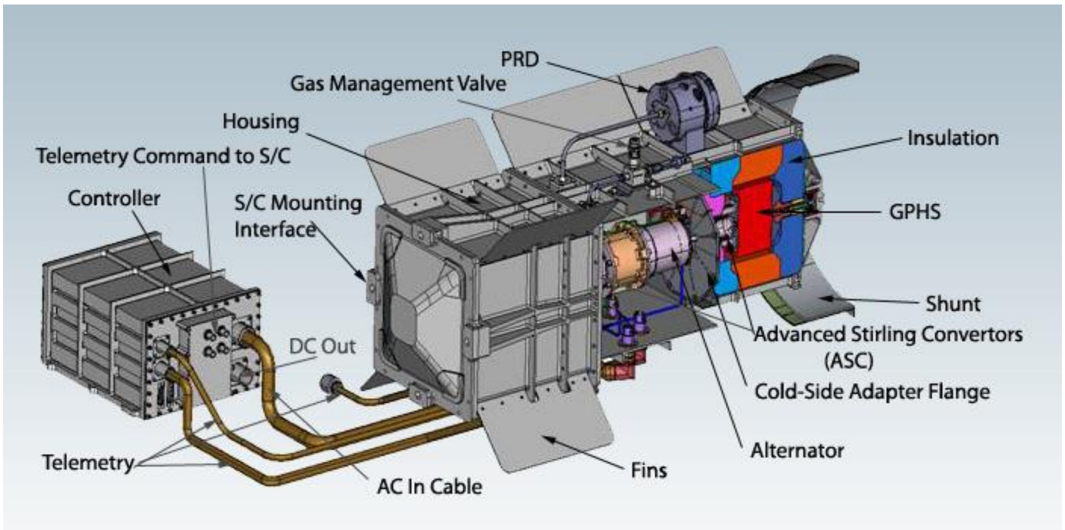

Figure 28: Cutaway diagram of the advanced Stirling radioisotope generator.

SRGs development was stopped by NASA back in 2013 for budgetary reasons and the agency currently relies on MMRTGs, but due to the huge power demands of human exploration, it is clear that two measures need to be applied. First, ^{238}Pu production needs to be enhanced and secondly, SRGs or other alternatives with higher efficiencies than MMRTGs must be developed.

3.2. Objectives of the sustainability study

In view of the previous studies and the state of the art, two things are clear:

- Sustainability regarding outer space activities has not been defined below LEO.
- There are plenty of initiatives studying power system concepts to extend human presence to the surface of Mars.

Therefore, a need arises to carry out sustainability studies related to the permanent human presence in other planets, and in particular, Mars.

With this premise in mind, the objectives of this project are:

1. To provide a framework to perform a complete sustainability study of a human permanent Martian outpost.
2. To make a quantitative evaluation of the impact of the outpost's power system choice on the Earth, Outer Space, and Mars.
3. To elaborate a flexible methodology that can adapt to changes in our perception on what sustainability means, and where to apply it.

4. Methodology

In the first chapters of this project we have explored sustainability related concepts such as sustainable development, resiliency, carrying capacity, impact and circularity. We have also reviewed some of the most important sustainability initiatives regarding space exploration and noticed that there is plenty of work to do. Finally, we have acknowledged how human Martian surface exploration has been assessed in terms of power systems.

In order to perform a sustainability study of a Martian outpost, both comprehension on what sustainability means and knowledge about possible mission architectures are needed.

The challenge is now to link these two concepts. To provide a methodology that allows to study not only the viability and functionality of the chosen architecture but also considers its sustainability, making use of the concepts stated above.

It is extremely important to recall that it is not the objective of this study to focus on a particular well-defined mission in order to study its sustainability. Our goal is to provide a solid rating system that can be applied to different outpost architecture in order to evaluate their sustainability. This should, in the end, allow to compare the sustainability of different possibilities and evaluate the influence of changes in the architecture to the 'sustainability score' of the mission.

A complete sustainability study of a permanent Martian outpost can be structured as follows.

Table 6: Main areas of the Martian Outpost sustainability study.

Location	***Mission***	***Resources and waste***
Carrying capacity Resiliency	Impact on the Earth Impact on Outer Space Impact on Mars	ISRU Circularity

First of all, the carrying capacity needs to be studied as it varies depending on the location of the outpost. This will depend mainly in the availability of resources present in the environment and potential energy sources.

Secondly, the details of each mission will have to be considered. This study will be focused on the influence of power systems in the impact of the mission on Earth, on Outer Space and on Mars, but other areas such as planetary protection, interplanetary transportation and surface systems can also be studied within this frame.

Finally, In Situ Resource Utilization technologies available and circularity should be included to the study as they have a great influence in terms of sustainability.

4.1. Martian Location Environment Evaluation

In previous chapters, it has been stated that Martian Carrying Capacity (MCC) is 0. This seems rather unfair as, compared to Outer Space or even other planets in the Solar System, Mars has great potential to hold life in the future and even could have held it in the past.

With some amount of technological equipment, it is possible to use certain features of a given location and create a closed environment, the outpost, that can withstand human life and activities. Factors that can affect to the carrying capacity of a given location are:

Table 7: Factors that affect the carrying capacity of a given location at Mars.

Atmospheric characteristics	Temperature is dependent on the latitude and the season and have great influence when dimensioning thermal and environmental control systems. Its composition is common at all latitudes. Atmosphere processing can have very positive impacts on the mission.
Water availability	Water is a common resource on Mars but its availability depends on the latitude.
Caves and lava tubes	Caves and lava tubes are present at certain locations and can be an aid, providing isolation from environmental conditions and radiation.
Solar irradiance	Solar irradiance is lighter at Mars than on the Earth but it presents the same behaviour in regards of its variability with latitude.

Note that all of these factors except for the presence of caves and lava tubes have a direct dependence on latitude. This means that latitude is the governing factor when studying the carrying capacity of a certain latitude. Its influence will be studied in more detail in the following pages.

4.1.1. Atmospheric characteristics

The influence of parameters such as temperature and pressure in terms of habitability is clear, the more extreme (usually the lowest) these parameters are, the more will be required from the environmental and thermal control. This means that temperature and pressure directly impact the power required to keep the outpost habitable.

Weather forecasting at Mars is an ongoing area of study. The evolution of temperature is rather similar to the Earth, it depends basically on the time of the year and the latitude. However, these complex influences are difficult to account in a preliminary sustainability study and their quantitative influence on the power requirement is unclear.

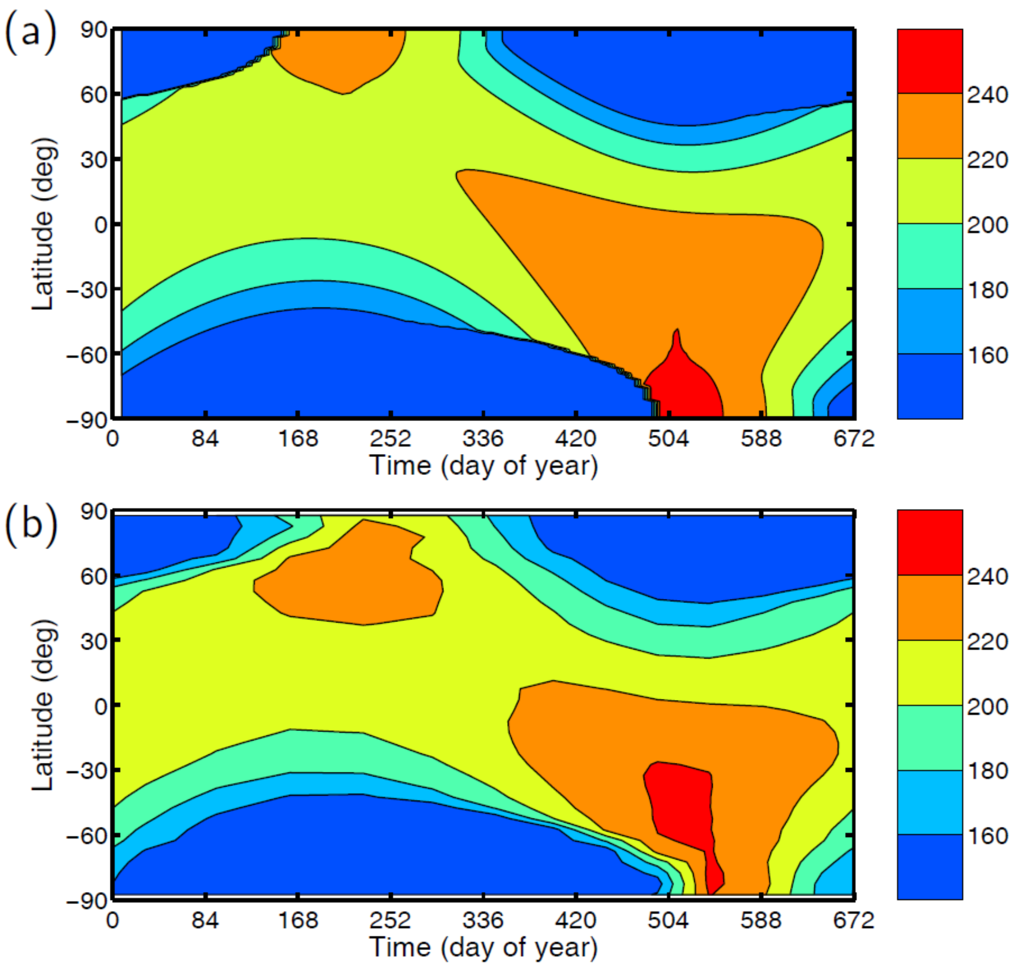

Figure 29: (a) Estimated daily mean surface temperature with a LIT scheme. (b) Mars Climate Database mean surface temperature.

Figure 29 shows the variability of the mean temperature at a given latitude for a given day of the year. Both latitude dependence and seasonality are clearly displayed. Although seasonality plays an extremely important role in temperature variability, when considering a permanent human outpost, we are assuming that such infrastructure will stay indefinitely on the Martian surface and it needs to be ready to operate no matter the conditions. This is important to take into account when designing the outpost but it is irrelevant for this analysis, as any outpost will need to withstand such conditions. In other words, no changes can be applied to the mission design of a permanent outpost to eliminate such variability. In the same way, day-night variations, that can be seen at Figure 30 will not be considered.

However, latitude can be consciously chosen when designing the mission. Thus, the dependence of atmospheric temperature with this parameter is worthy to assess.

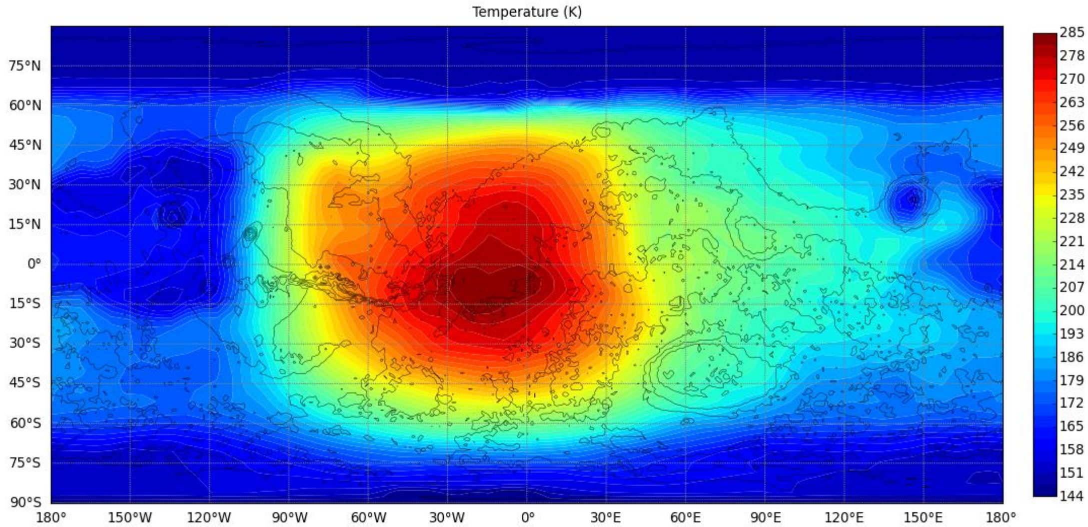

Figure 30: Mars' temperature distribution at April 1st 2019, 14:00 (GMT +0) from Mars Climate Database.

Evaluation of temperatures for a given location can be done using the data from Mars Climate Database

Pressure is more dependent on seasonal variations and remains almost constant with the latitude. Its seasonal variation is originated by the sublimation of part of the carbon dioxide of the polar caps into the atmosphere. Even though it is a fascinating phenomenon, as it is a seasonal effect, it will not be considered in the analysis.

Atmospheric composition remains constant at any latitude of the planet, but it is still a very important factor, as it can be processed to obtain a breathable air or propellant.

Table 8: Mars' atmospheric composition.

Component	CO_2	N_2	Ar	O_2	CO	H_2O
%	95.32	2.7	1.6	0.13	0.08	0.03

Carbon dioxide, nitrogen, and argon can are used to produced breathable air. Oxygen is obtained through different chemical reactions from carbon dioxide and nitrogen and argon are good buffer gases. Additional oxygen to use as propellant could be obtained directly from the atmosphere and, when including water processing, methane could be obtained as well. This dramatically decreases the need of resupply from Earth and greatly reduces mission mass requirements but it also greatly increases the power consumption due to the addition of the atmosphere processing system.

Thus, the chemical composition of the Martian atmosphere provides some carrying capacity and is worth mentioning. However, as the global distribution is considered constant, it does not make a difference between different locations.

The fact that lower temperatures benefit the efficiency of solar cells is also worth mentioning, however, this benefit is considered to be much smaller and thus negligible in comparison with the increased demand on the power system.

4.1.2. Water availability

The presence of water on Mars can represent a huge benefit for the sustainability of a permanent outpost, as it is one of the most important consumption goods that humans need to survive. Its uses extend way beyond human consumption, as it could be used as well to produce oxygen (both for breathable air and propellant) and, when combined with carbon dioxide from the Martian atmosphere, to produce methane as well. Such purposes would have a great influence in the sustainability of the mission by reducing mass requirements and resupply need. On the other hand, extraction and processing of water will suppose a great increase in the power consumption.

Water is present in multiple forms in Mars.

Table 9: Water sources on Mars

Atmosphere	Present, but too scarce to be worth the effort of extracting it.
Hydrated Soil	Water hydration in minerals. 2 to 13% by mass presence at equator and lower latitudes at or near the surface.
Permafrost	Subsurface ice within the top 5 meters in the mid latitudes, it may exist at a deeper level at lower latitudes.
Icy Soil	Nearly pure ice in newly formed craters in mid-upper latitudes exposed by fresh impacts. From 0.3 to 2.0 meters depth. Dirty ice at polar locations with expected water content of 90-100%. Mixed with dust from global dust storms.
Recurring Slope Lineae	Briny water that causes RSL located at equator- facing sunward-facing slides of craters of craters/ridges in the 30º to 50º latitude range. Not globally available.
Aquifers	Suspected to be >1km below the surface.

Of all the possible sources, atmospheric water is considered too scarce to be worth processing it, recurring slope lineae are not globally available and aquifers are too deep into the crust to be extracted in the foreseeable future. This means that the only available options are permafrost, icy soils and hydrated soils. When accounting for their concentration in the upper layer of the Martian crust, water distribution in the red planet looks like Figure 31.

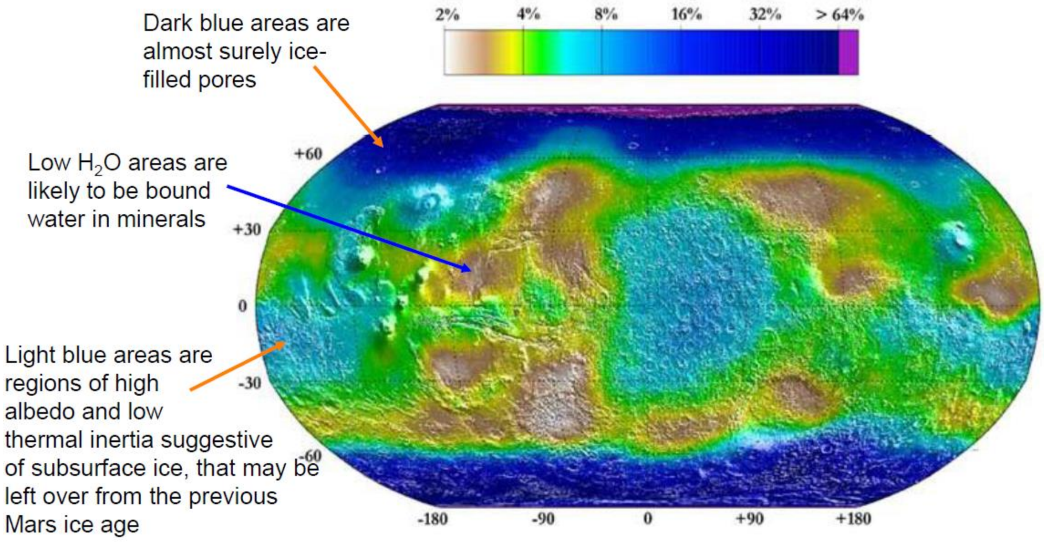

Figure 31: Water distribution in the surface of Mars (Jsc and Mueller, 2015).

Water extraction and processing technologies are currently under development by several organisations. They are not considered viable for the first human missions to the red planet but will, for sure, play a critical role in the development of a self-sustained Martian outpost. Figure 31 shows how water content is very dependent on the selected location so, again, site selection will play a huge role in terms of sustainability.

Another benefit of water presence in the outpost is that it is an extremely interesting asset from the scientific perspective, as the search for ancient life revolves around it.

4.1.3. Caves and lava tubes

Caves and lava tubes are a great way to reduce the impact of environmental factors on the power needed for regulating the habitat. A challenge for ECLSS and thermal control is the extreme variability of temperatures between the Martian day and night. Inside the quasi-isolated environment of a cave or a lava tube, mean temperature might be lower, but it is far more stable and thus it is way less power demanding. A habitat inside a lava tube would be protected from solar radiation, micrometeorites, winds, and regolith dust storms as well. This, in the end, supposes a reduction on the necessary systems and thus the landed payload mass is reduced as well.

These geographic features are also interesting from a scientific point of view, as the benefits listed below could have protected life on Mars. Precisely for these reasons, planetary protection policies must be stricter if the outpost is placed inside a lava tube, as microorganisms unavoidably brought with the astronaut crews could successfully transfer to this new environment.

Although they look very promising and are worth mentioning, their presence has not yet been confirmed on Mars, so they will not be considered in this analysis.

4.1.4. Solar irradiance

Solar irradiance is especially important for the choice of the power system. It rules the power generated by solar arrays and it is primarily influenced by latitude and the optical depth, which is a measure of the dust present in the atmosphere at a given moment. Of course, it also depends on the season and the day-night cycles.

In fact, solar power options are considered not viable outside the 15º S, 30 ºN latitude band. Solar irradiance at the Martian surface has been subject to many studies, for example '*Solar Radiation Incident on Mars and the Outer Planets: Latitudinal, Seasonal, and Atmospheric Effects*' (Levine et al., 1977).

Table 10: Mean annual solar radiation incident at top of the atmosphere and at the surface of Mars (Levine et al., 1977).

Lat.	Top of atmosphere	Surface (τ = 0.1)	Surface (τ = 0.35)	Surface (τ = 2.0)
85	0.167×10^3	0.118×10^3	0.559×10^2	0.877
80	0.170×10^3	0.121×10^3	0.599×10^2	0.143×10^1
75	0.176×10^3	0.128×10^3	0.666×10^2	0.232×10^1
70	0.185×10^3	0.137×10^3	0.759×10^2	0.352×10^1
65	0.198×10^3	0.150×10^3	0.871×10^2	0.501×10^1
60	0.217×10^3	0.167×10^3	0.997×10^2	0.677×10^1
55	0.238×10^3	0.186×10^3	0.114×10^3	0.874×10^1
50	0.259×10^3	0.206×10^3	0.129×10^3	0.109×10^2
45	0.279×10^3	0.225×10^3	0.144×10^3	0.132×10^2
40	0.297×10^3	0.243×10^3	0.158×10^3	0.156×10^2
35	0.315×10^3	0.260×10^3	0.172×10^3	0.180×10^2
30	0.330×10^3	0.275×10^3	0.185×10^3	0.204×10^2
25	0.344×10^3	0.288×10^3	0.196×10^3	0.227×10^2
20	0.355×10^3	0.299×10^3	0.206×10^3	0.247×10^2
15	0.364×10^3	0.308×10^3	0.213×10^3	0.264×10^2
10	0.370×10^3	0.314×10^3	0.219×10^3	0.277×10^2
5	0.374×10^3	0.318×10^3	0.222×10^3	0.285×10^2
0	0.375×10^3	0.319×10^3	0.223×10^3	0.288×10^2

[a] For τ = 0.1, 0.35, and 2.0 [in cal cm^{-2} (Mars day)$^{-1}$].

4.1.5. Qualitative evaluation

Providing a quantitative evaluation of the resiliency and carrying capacity of a particular Martian location is out of the scope of this project. However, the influencing factors have been identified and characterized in order to provide a framework for future studies to develop from.

High latitudes locations present high availability of water resources (icy soils), both in terms of quantity and easiness of extraction. However, temperatures are lower, which increases the demand on the ECLSS, and solar irradiance is prohibitive for solar power options.

Intermediate latitudes present promising quantities of water in the form of hydrated soils and permafrost and solar irradiance may enable the implementation of solar powered outpost at some locations.

Low latitudes are favourable in terms of temperatures and solar irradiance, which provides relevance to the solar vs nuclear debate studied in the following chapters. Water resources are scarcer in this region, which leads to bigger extraction and processing systems.

The presence of caves and lava tubes, if confirmed, will have a tremendous impact on the carrying capacity that will have to be studied for every location considered.

4.2. Mission evaluation

Missions to Mars can and will change greatly in the future. The technology will continue developing and systems will be more efficient, allowing to increase their capabilities and functionalities and thus widening the scientific possibilities and growth. Also, the debate robotic/human makes it very hard to analyse a particular mission as the requirements are completely different. One of the systems that has the greatest impact on the sustainability of the mission is the power system, evaluated in the next pages, but a similar methodology can apply to planetary protection, surface systems or transportation systems.

We have already studied some of the possibilities regarding energy generation in the State of the Art, now it is the moment to link the different characteristics of power generation system to quantifiable and measurable sustainability-related parameters.

Recalling the definition of impact:

$$I = P \cdot A \cdot T \tag{2}$$

The PAT formula illustrates the relationship between the three components of impact: population numbers (P); levels of consumption, or affluence (A), and impact per unit of resource use, or technology (T).

This same concept can be directly applied to this study with small changes to the definition of the variables.

What this expression is doing is simply multiplying the global consumption of resources of a system by the impact per unit of resource used. If we consider power to be a resource, the resource consumption can be easily computed, as we can know the exact performance characteristics of the systems. Impact per unit of resource requires further evaluation.

Redefining the previous expression for power systems:

$$I_i = p_i \cdot n_i \cdot T_i \tag{3}$$

Where p stands for the power generated by each module of the system, n the number of modules, and T for impact per module.

Power per module and number of modules can be easily obtained from the specifications of the system and the power requirements. However, impact needs to be quantified and it is related and changes depending on not only the energy source, but the technology employed. Remember that the power required for the solar system is between 2 and 3 times greater than for the nuclear system, depending on the day-night cycle considered, so the impact per module of the solar system should be smaller than the nuclear to compensate this fact.

The next step for the analysis is to quantitatively assess the value of T, technology, or impact per module. Impact will not have specific units and it will consider economic and environmental consequences of the different characteristics of the solar power system's modules.

4.2.1. Technology estimation

We will take power system analysis of DRA 5.0 as the starting point.

Base Power Supply (Commuter and Telecommuter Options)

Solar Power	Figure of Merit	Fission Power
22.5	Total landed mass (mt)	7.8 (w/propellant ISRU)
High	Autonomous Deployment complexity	Moderate
Variable with dust settling and atmospheric obscuration	Power level stability	Continuous
High	Sensitivity to dust storms	Low
High	Reliability	High
Moderate	Ability to repair	Low
None	Increase in crew radiation exposure	Small (5 rem/year)
Mass increase with latitude	Latitude flexibility	No restrictions
Linear with power	Scalability	Relatively moderate increase with power in ranges of interest
Moderate	Development Complexity	High
Moderate	Similarity to lunar system	High
None	Surface access exclusion zone	Small areas of forbidden access, moderate areas of limited access
Disadvantage	Cost Through First Mission	Advantage (assuming lunar dev.)
Disadvantage	Cost Through Third Mission	Advantage (assuming lunar dev.)

Figure 32: Power system's FOM summary (Drake, 2009)

Figures of Merit (FOMs) stated in this table, however, are analysed with the objective of making a recommendation for the first human campaign to Mars. Such arguments may be valid or not when we considering a permanent outpost. For example, aspects regarding technology readiness or cost through the first mission may not be very relevant for the analysis, while reliability, scalability and others may become more important for an extended presence on the surface. Each FOM is analysed below, including some new figures of merit specifically selected for the permanent outpost scenario:

- *Total landed mass*

There is a big mass difference between solar and nuclear power systems. This comes from the fact that solar systems need to generate more power than nuclear systems. Solar mass requirement is 2 to 3 times greater than nuclear depending on the architecture considered, but this mass difference is already accounted in equation (3). However, this does not account for the extra IMLEO required. This extra mass must be considered, and it is very important as it is directly related to the number of launches required.

- *Autonomous deployment complexity*

Even though this FOM is extremely important when considering the first missions to Mars, it becomes secondary when considering a permanent outpost. Autonomous deployment will only be strictly necessary at the first mission, after that, although this is not ideal, astronauts at the outpost could help in the deployment of new components if needed.

- *Power level stability*

Again, power level stability is especially critical in the first missions, when the number of solar panels that can be deployed is very restricted. However, as it happens in the Evolvable Mars Campaign, following missions would allow to deploy extra array area to compensate for the loss of power during a dust storm. So, in the long term, power level stability is not a big concern.

- *Reliability*

Both systems are considered to have high reliability. So, even though this parameter becomes more important as the duration of the campaign increases, no clear advantages can be identified for either system.

- *Ability to repair*

This is one of the FOMs that becomes more important when considering a permanent outpost. Although considered power systems have very high reliability, the possibility of failure becomes greater with the duration of the mission. Reparations can be necessary and, in this case, the ease of accessibility and reparation will play an important role, especially as the system grows.

- *Increase in crew radiation exposure*

This will depend on the operation of the outpost. If there is a rotation of the crew with every launch opportunity and the stay durations keeps being around 500 sols, then crew exposure will not be increased. However, if 'permanent settlers' are considered, this FOM will become more important.

- *Latitude flexibility*

This remains the biggest disadvantage of solar power. Power requirements do not change, however, surface of solar arrays (and mass) required to provide that power grows in inverse proportionality with solar irradiance. This can be accounted similarly to total landed mass.

- *Scalability*

It is reasonable to assume that the capabilities of the outpost will grow with subsequent missions to Mars. Maybe water processing and extraction will be included, EVA will be enhanced, rovers, scientific equipment, habitat extensions, food processing plants… These are all viable possibilities for the future of the outpost. Power generation will consequently need to grow. Thus, scalability becomes important when considering a permanent outpost.

- *Development Complexity*

This is another FOM that made much more sense for the first missions to Mars, especially given the immaturity of some of the solutions considered in the DRA 5.0 at that time. However, it is less relevant for extended surface presence.

- *Similarity to lunar system*

Again, this is related to the first mission to Mars and becomes less and less important with every subsequent mission on the planet.

- *Surface access exclusion zone*

Surface access exclusion zone is associated to radiation exposure in the areas that are poorly shielded. This supposes a wide extension of the planet that becomes virtually occupied, and no permanent activities can be performed there, so it can be considered as the amount of surface necessary for nuclear fission to occur. With this idea in mind, solar power systems also define access exclusion zones, defined by the surface occupied by the arrays. Of course, access to these zones does not pose any danger for the health of the settlers, however, no permanent activities can be performed there (besides maintenance of the solar arrays). What is more, as scalability of solar power systems require more solar arrays, this zone will grow as the outpost does, while nuclear access exclusion zone can be controlled, and even reduced if additional shielding is installed.

- *Recurring costs*

This is a new figure of merit that takes into consideration the costs of keeping a power supply working permanently. It includes maintenance, refuelling and decommissioning, which vary depending on the energy source considered.

- *Design life*

This FOM will consider the frequency with which refuelling or decommissioning is needed, and it is complementary to recurring costs.

Relevant FOMs from the point of view of the sustainability of a permanent outpost are summarised in the following table.

Table 11: Martian permanent outpost's power system FOMs from a sustainability point of view.

FOM	***Solar***	***Nuclear***	***Comment***
Total landed mass	(2,3)·$m_{nuclear}$	$m_{nuclear}$	Reference values, mass of the solar system is very dependent on the latitude.
Ability to repair	Moderate	Low	None.
Scalability	Linear	Non linear	For nuclear, scalability depends on the size of the reactor. It is moderate until a new reactor is needed.
Surface access restriction zone	Due to solar arrays.	Due to radioactivity	Related to the size of the power system.
Recurring costs	Maintenance, replacing and decommissioning	Refuelling and decommissioning	
Design life	25 years	Several decades	Efficiency at the EOL for solar arrays is around 80% of the BOL value. Certain fission systems (Kilopower) can extend their design life if refuelled for several decades.
Increase in crew radiation exposure	It exists	It does not apply	This is an optional parameter that only has to be considered when groups of people are staying indefinitely in the outpost.

Out of these figures of merits, numerical parameters must be defined:

Table 12: Numerical parameters obtained from the figures of merit analysis.

FOM	***Parameter***
Total landed mass	TLM
Ability to repair	AR
Scalability	S
Surface access restriction zone	SRZ
Recurring costs	RC
Design life	DL
Increase in crew radiation exposure	CRE

These parameters will be de base of the numerical study, along the characteristics of the power systems considered.

4.2.2. Sustainability on Earth, Outer Space and Mars

The three levels of sustainability regarding activities on Mars where defined in the introductory chapter. Sustainability on Earth considers the impact space activities have on the Earth environment; sustainability regarding Outer Space, refers to the contamination of space resources, mainly congestion of LEO; sustainability regarding other Bodies, in this case Mars, need to account for the impact of a considered factor in the outpost's overall sustainability.

The way to account for these levels on the analysis is to actually split the parameters presented in Table 12 depending on their influence regarding this particular aspect.

Table 13: Parameter's influence distribution.

Parameter	***Impact on Earth***	***Impact on OS***	***Impact on Mars***
TLM	TLM_E	TLM_{OS}	-
AR	-	-	AR_M
S	S_E	S_{OS}	S_M
SRZ	-	-	SRZ_M
RC	-	-	RC_M
DL	DL_E	DL_{OS}	DL_M
CRE	-	-	CRE_M

Parameters that influence the impact on Earth account for an increase in the resources that need to be extracted from our home planet. Parameters that influence the impact on outer space refer to the congestion of LEO, that is mainly influenced by the number of launches required. Parameters that influence the impact on Mars can refer to the time spent on procedures like installation, maintenance, refuelling or decommissioning, that translate into cost; to space restrictions, due to either radioactivity or material presence; and to radioactivity effects on the crew.

4.2.3. Power systems considered

Theoretically, the analysis could be applied to any modular power system. However, the objective is to understand the relevance of the parameters in the calculated sustainability. Characteristics such as power, mass, and surface per module are dependent on the power system choice alone. The assessment of the impact is a subjective matter. What makes this study interesting is that, by studying the influence of impact evaluation methodologies and parameter influence, it will provide a flexible methodology to evaluate the sustainability of the system that adapts to the sustainability concept defined by the evaluator, whoever he or she may be.

With this objective in mind, the issue can be addressed considering only the power systems that has been stated in the State of the Art, that have very clear specifications. In some cases, these specifications need to be readapted to fit a common criterion of evaluation.

- DRA 5.0 solar concept

Solar modules of the DRA 5.0 provide 5kWe of continuous power when combined with regenerative power cells. The mass of each array and the subsequent fuel cell is 1,980 k, and the surface 290 m^2.

- DRA 5.0 FSPS

A single reactor capable of producing 30 kWe of power weights 7,800 kg according the DRA 5.0.

- Kilopower

Five Kilopower units (4 plus 1 contingency) would add for a total mass of 9,154 kg. This means that each unit is 1,830.8 kg. Even though they are 10 kWe units, in the configuration purposed, they would be providing 8,75 each with four units working and one for contingency, which means that the system is easily scalable.

- EMC Solar at Jezero Crater

Power demand at Jezero Crater is around 35 kWe and if solar arrays were used, each lander on expedition 1 would require four 12-m diameter array (one module), for a total of 16 arrays (four modules), this means that the power for module is 8.75 kWe. The following expedition would add 12 arrays (three modules) more to the system, for a total mass of 17,815 kg, which leads to a mass per array (considering complementary systems) of 2,545 kg. At that point, 61.25 kWe would be generated in standard conditions, which is enough to operate with dust storms with little operative restrictions. If only the arrays were considered, the mass per module would be 2,034 kg.

- MAFSA

This system has a total mass of 1,463.2 kg and the manufacturer claims an annual average of 25 kWe production. The total area of the system is 1,060 m^2.

- NIMSA

The total mass for NIMSA is around 700 kg. The power of the array depends on the latitude, of course. Under the most favourable conditions, at the equator and without dust storm, it provides 73.82 kWh per sol. Considering 12 hours of operation, that leads to an average power of 6.15 kWe.

- MMRTG

MMRTGs can also be considered as an additional source of power for backup and surface mobility. A single unit provides up to 120 We at the BOL, and 100 We at EOL, which is considered the design point. The total mass is 45 kg.

- SRG

SRGs are an alternative to MMRTGs as backup and surface mobility power. A single unit provides around 100 We at the EOL and the total mass is 32 kg.

Results from these power systems' specifications calculations are summarized in Table 14. Where power and mass are displayed for each system and surface is considered only in the solar power scenarios. Nuclear power related surface limitations also exist, but it will be considered later.

Table 14: State of the art's power systems specifications.

Module	***Power***	***Mass***	***Surface***	***Operation time***
DRA 5.0 solar concept	5 kWe	1,980 kg	290 m^2	8 h/day
DRA 5.0 FSPS	30 kWe	7,800 kg	-	Continuous
Kilopower	8.75 kWe	1,830.8 kg	-	Continuous
EMC Solar at Jezero Crater	8.75 kWe	2,545 kg	450 m^2	12 h/day
MAFSA at equator	25 kWe	1,463.2 kg	1,060 m^2	12 h/day
NIMSA at equator	6.15 kWe	700 kg	1,000 m^2	12 h/day
MMRTG	0,1 kWe	45 kg	-	Continuous
SRG	0,1 kWe	32 kg	-	Continuous

4.2.4. Excluding factors

Even more important than the parameters pointed out at the technologies estimation chapter, are the excluding factors that some of these systems exhibit. An excluding factor is a circumstance that directly discards a possibility without need of further analysis.

For solar power, latitude restrictions are an excluding factor. Solar is not considered viable for the moment outside the 30º N to 15º S region, so the alternative is directly dismissed for missions at higher latitudes and fission power must be the choice for the primary source of power, at least for now.

Radioisotope generators also present an excluding factor, fuel availability. Both MMRTG and SRG utilize ^{238}Pu as fuel, an extremely scarce resource on Earth. Its production has been enhanced recently at a global scale, so the reservoirs are expected to grow, however, due to its extremely low efficiency, MMRTGs would require around 10 times the amount of ^{238}Pu currently available to provide backup power to a human outpost. SRGs would require 2,5 times the amount of ^{238}Pu due to its higher efficiency. Still, neither of them can be considered sustainable as a full-scale backup power option and alternatives need to be found.

4.2.5. Power requirement and number of modules

For a given continuous power requirement, that will depend on the mission objectives and is an input for this study, the number of modules needed of a particular system required for the mission can be found. That will allow to compute the mass of the system, which is a very important factor.

$$n_i = \frac{P_r}{P_i} \tag{4}$$

4.2.6. Parameter analysis

In order to give a quantitative value to the parameters indicated, a methodology is purposed that computes a first approximation. All the quantitative results are subjective comparisons that rely on the provided data and circumstances considered. Their purpose is not to serve a precise comparison between the systems regarding the particular topic, but to provide a score for each of the systems in each of the fields. The study will later focus on analysing the sensitivity of the sustainability global score of each system depending on a given criterion with a weighting methodology.

4.2.6.1. *Total landed mass*

As stated above, this parameter attains to compute the mass associated not to the power system itself, but to all the necessary extra fuel resulting for the IMLEO increase. This will impact sustainability on Earth because more resources will be needed, and it will also affect the sustainability on the outer space, particularly on LEO, as the number of launches can increase with the TLM.

This is ruled by Tsiolkovsky rocket equation, that relates the delta-v, which is fixed for a mission to mars, with the effective exhaust velocity, which is determined by the rocket and does not apply to this study, and the initial and final mass of the rocket, which is associated to the propellant mass fraction. This, in the end, can give a measure of the proportionality of the parameters. A propellant mass fraction of 85% is a reasonable value for modern LEO rockets. This means that for every kilogram that needs to go to LEO, around 17 kg of fuel need to be added (considering a 5% payload fraction). The energy cost to get from the surface of Earth to LEO is 8 km/s, and the energy to get from LEO to the surface of Mars is another 8 km/s, this means that the same principle must be applied, so for every kilogram of payload from LEO to Mars, 17 kg of fuel are needed. But these 17 kg need to be carried to LEO as well, and that requires 17 kg for each, for a total of 289 kg.

$$mf_{Surface\ to\ Mars} = x \cdot mf_{surface\ to\ LEO} \cdot (1 + mf_{LEO\ to\ Mars}) \qquad (5)$$

So, the fuel necessary to get x kilograms to Mars can be roughly approximated as the fuel necessary to get a kilogram to LEO and the fuel necessary to get the fuel necessary to get that kilogram from LEO to the Martian surface to LEO. This is around 306 kg of fuel.

This calculation illustrates two things. (1) A huge amount of resources is necessary to put payload in the surface of Mars, and (2) this relation is linear if a orbiting refuelling strategy is followed, which is why almost all architectures require some kind of orbit assembly or refuelling of the Mars transportation vehicle.

The applicability to this study is that direct proportionality can be applied between the total mass of the power system, so:

$$TLM_{E,i} = \frac{n_i m_i}{\min(n_i m_i)} \qquad (6)$$

This means that all power system masses will inevitably affect the impact on Earth and that the greater score, 1, will be given to the maximum mass, and the others will be proportionately lower.

Surface power is around 8% in mass of the payload at IMLEO, being the most significative load the aeroshell (40%), followed by the wet descent stage (20%). This is actually a considerable contribution, considering that DRA 5.0 takes 12 Earth launches, this means that power system can take 1 or 2 launches to be put in orbit depending on its mass. Considering a total IMLEO mass of 213,500 kg, consistent with DRA 5.0 estimates, systems that weight more than 17,800 kg will require 2 launches, while the others will require only 1.

$$TLM_{OS,i} = \left\lfloor \frac{n_i m_i}{17{,}800} \right\rfloor \quad (7)$$

4.2.6.2. *Ability to repair*

This assessment is highly qualitative. It is understood that solar concepts have an advantage in this area, as reparation of active nuclear reactors is a delicate issue. In accordance with DRA 5.0, solar architectures will receive a smaller impact than nuclear, even though the ability to repair solar power systems is moderate:

$$AM_{M,i} = \begin{cases} 0.5, if solar \\ 1, if\ nuclear \end{cases} \quad (8)$$

4.2.6.3. *Scalability*

Scalability refers to the ability of the power system to grow as the outpost's needs do. It is mainly referred to the extra mass that needs to be provided. This is usually better for nuclear energy, as the power output can be regulated by the configuration of the reactor. For example, Kilopower operates at 8.75 kWe in the study but it can grow up to 10 kWe. Power generated by solar power is fixed by solar irradiance and array area and it is, thus, less flexible.

$$S_{M,i} = S_{E,i} = S_{OS,i} = \begin{cases} 1, if solar \\ 0{,}5, if\ nuclear \end{cases} \quad (9)$$

4.2.6.4. *Surface restriction zones*

This is associated to two factors, radiation in the case of nuclear power, and the presence of the solar arrays in the case of solar power. The objective of this topic is to determine the amount of surface each equipment really needs. According to DRA 5.0, the area where radiation is greater than 50 rem/year is more than 3 km^2, while the total area of solar arrays varies with the system but is in the order of thousands of m^2. This means that surface requirements are more than a thousand times greater for nuclear energy than for solar, so the impact of solar energy is negligible in terms of surface.

$$SRZ_M = \begin{cases} 0, if solar \\ 1, if\ nuclear \end{cases} \tag{10}$$

4.2.6.5. Recurring costs

Recurring costs depend on the operations required to keep the power system working. This includes maintenance, frequency of reparations expected, refuelling when applicable and decommissioning at the EOL.

For solar, maintenance is the biggest factor, as issues related with dust deposition require constant monitoring. Even though there are dust mitigation strategies, some amount of work effort is expected to happen in that regard. Maintenance also increase by the expected bigger complexity of the grid, requiring more auxiliary systems as well. Refuelling is not a factor to consider but decommissioning will, for sure need some amount of work. Non-functional solar arrays will need to be replaced with new ones.

For nuclear, maintenance related issues are way smaller than for solar, both because of the structure of the system, and the complexity of the required grid. However, refuelling and decommissioning are important considerations. Refuelling a nuclear reactor is not an easy task and the products will need to be properly isolated and stored, probably requiring large amounts of shielding.

It is too early to create a precise estimation of these costs, but maintenance related topics for solar energy have already been treated, while decommissioning and refuelling of nuclear power systems at the surface of other planets remains an unexplored topic.

$$RC_M = \begin{cases} 0{,}5, if solar \\ 1, if\ nuclear \end{cases} \tag{11}$$

4.2.6.6. Design life

This is a complementary parameter to the recurring costs, as it will directly impact aspects related to decommissioning and refuelling. It has impact on Earth and LEO because when a component of the power system because, without advanced In Situ Manufacturing (ISM) techniques, that are out of the scope for this study, a replacement is needed to be brought from Earth, with the subsequent resource utilization and increased number of launches.

This is, in fact, a very important source of impact, as it affects in the same way the three levels of sustainability. The design life of the considered systems is considered to be around 15 years, which is enough to provide energy to the 3 expeditions considered in NASA's studies. However, it is stated that, with refuelling, Kilopower could extend its design life for 'several decades'. No further information is provided, so the design life of the Kilopower is assumed to be around 45 years (two refuelling operations). Modern solar arrays can operate for 25 years in the surface of the Earth, so that can be a future objective, but for the systems considered at the study, 15 years of operation design life for solar systems is assumed.

Module	***Design life***
DRA 5.0 solar concept	15 years
DRA 5.0 FSPS	15 years
Kilopower	45 years
EMC Solar at Jezero Crater	15 years
MAFSA at equator	10 years
NIMSA at equator	10 years

$$DL_{M,i} = DL_{E,i} = DL_{OS,i} = \frac{\max(dl_i)}{dl_i} \tag{12}$$

4.2.6.7. Increase in crew radiation exposure

The assessment of this parameter is clear. Nuclear power sources will produce an increase in crew radiation exposure while solar will not.

$$CRE_M = \begin{cases} 0, if solar \\ 1, if\ nuclear \end{cases} \tag{13}$$

4.2.7. Parameter weighting

Each of the parameters has been independently calculated and set into a range of values from 0 to 1. This normalization allows to compute each factor independently and to make their influence comparable. However, it is clear that, depending on the mission needs, sustainability scenario considered, or particular interest, one may have greater relevance in the study than another.

To address this fact, a weighting model that defines the importance of each parameter can be created and studied. This 'sustainability criterion' will modify the results of the sustainability study and will be addressed in the discussion.

4.2.7.1. Equity criterion

The first possibility is to consider all the parameters with the same importance. This is a direct implementation of the analysis

Table 15: Parameter's weighting according to the equity criterion.

Parameter	***Weight***
TLM	1
AR	1
S	1
SRZ	1
RC	1
DL	1
CRE	1

4.2.7.2. Growth criterion

The growth criterion maximizes the influence of all the parameters related to the growth of the power requirements, such as ability to repair and scalability. Parameters like surface restriction zones, recurring costs, and crew radiation exposure are less important.

Table 16: Parameters' weighting according to growth criterion

Parameter	***Weight***
TLM	1
AR	1.5
S	2
SRZ	0.5
RC	0.5
DL	1
CRE	0.5

4.2.7.3. Mass reduction criterion

This criterion is focused on the reduction of the mass of the system, which is arguably the major diver of costs. Parameters like total landed mass and design life are maximized, while ability to repair, surface restriction zones, recurring costs and crew radiation exposure are less impactful.

Table 17: Parameters' weighting according to mass reduction criterion

Parameter	***Weight***
TLM	2
AR	0.5
S	1
SRZ	0.5
RC	0.5
DL	2
CRE	0.5

4.2.7.4. Radioactivity reduction criterion

Another criterion consists on minimizing the negative effects of radioactivity both on the environment and on the population of the outpost. This criterion maximizes parameters like surface restriction zone or crew radiation exposure, while scalability, recurring costs, and design life are minimized.

Table 18: Parameters' weighting following radioactivity reduction criterion

Parameter	***Weight***
TLM	1
AR	1
S	0.5
SRZ	1.5
RC	0.5
DL	0.5
CRE	2

4.2.7.5. Operations optimization criterion

If the point of focus is to maximize scientific exploration and crew performance, an operations optimization criterion will maximize the recurring costs and surface restriction zones impact, giving less importance to total landed mass, scalability, ability to repair, and design life.

Table 19: Parameters' weighting according to operations optimization criterion.

Parameter	***Weight***
TLM	0.5
AR	0.5
S	0.5
SRZ	2

RC	2
DL	0.5
CRE	1

4.3. Resources and waste

After evaluating the carrying capacity of a certain location and estimating the impact of the different systems that compose the outpost, resource handling closes the loop and allows to evaluate the outpost globally. This item includes ISRU and ECLSS circularity.

ISRU refers to the production of consumables and fuel from the resources available at the studied location, while ECLSS refers to the system that provides an habitable environment to the crew using consumables both from feedstock and ISRU products. The differences between the two systems are summarized in Table 20.

Table 20: Difference between Mars ISRU & Life support (Sanders, 2016)

ISRU	Life Support
Resource Feedstock	
Potentially unlimited (except for Trash)	Controlled feedstock as function of number of crew
<100% collection efficiency acceptable	Maximize collection efficiency
Feedstock input ratios function of resource availability	Feedstock input rations function of crew waste products
Processing Systems	
External to habitable volumes	Internal to habitable volumes
Pressures and temperatures are a function of optimizing chemical reaction and system mass/power	Pressures based on cabin pressure; temperatures minimized for thermal control and touch
Carbon dioxide/Carbon monoxide (CO_2/CO) processing reactors run hydrogen rich with H_2 recycling to maximize CO_2/CO conversion	CO_2 processing reactors run hydrogen poor to mitigate H_2 leakage concerns
Production and venting of CO allowed	Production of CO avoided due to toxicity risk
System Design	
CO_2 Acquisition, CO_2 Processing, & H_2O Processing highly integrated (esp. thermally)	Subsystems for ISS were designed and built seperately
Subsystems designed to operate all at the same time. Separate subsystem operation or batch process a function of available power or CO_2 collection approach.	Subsystems for ISS operate at same or different times
Small amount of leakage acceptable	Leakage not acceptable because of habitable volume concerns
Oxygen Storage	
Storage pressure optimized for system performance and liquefaction energy	Storage pressure for EVA portable life support system recharge
Oxygen purity based on end user (propulsion, fuel cell, or life support	Oxygen purity based on crew
Operation	
Operate continuously while power is available (sunlight or nuclear); minimize start-up/shutdown operations	Operate on as needed basis. Continuous if possible
ISRU systems must be designed for minimum/no maintanace since operations often occur before crew arrives	Crew maintanance acceptable

ISRU production of consumables and fuel for the ascent vehicle can be mission enabling and has a huge impact on the mission, especially regarding the power system dimensioning. In fact, power systems studied assume ISRU production of oxygen for use as propellant. More information about ISRU systems available and current studies on the topic can be found in Annex I, In Situ Resource Utilization.

ECLSS need to be studied separately, evaluating their efficiency in handling and recycling waste and their compatibility with ISRU in order to minimize feedstock needs.

5. Discussion

5.1. Equity criterion

Equity criterion gives equal importance to all the parameters stated. In this scenario, DRA 5.0 Nuclear power system has the highest impact for a high-power requirement, followed by DRA 5.0 Solar, EMC Solar and NIMSA. These two options are very similar one to another and the preference varies depending on the level of power required. The same happens with Kilopower and MAFSA, the less impactful systems according to this criterion. This can be seen in Figure 33.

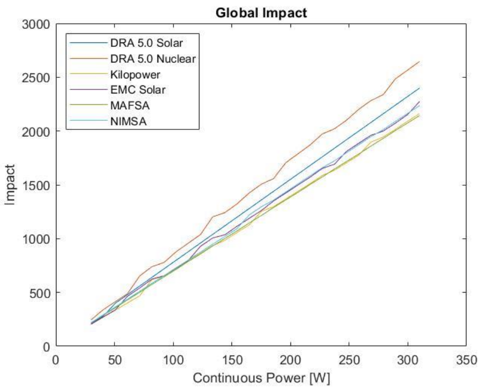

Figure 33: Global impact according to the equity criterion.

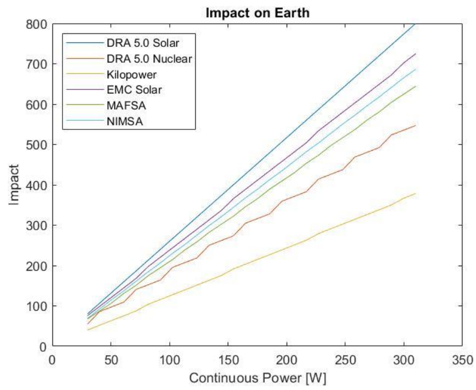

Figure 34: Impact on Earth according to the equity criterion.

As shown in Figure 34 and Figure 36, nuclear systems are superior in terms of sustainability regarding the Earth and Outer Space. This is because these two are ruled by mass related parameters. However, sustainability on Mars is deeply affected by issues related to surface restriction and radioactivity, so solar energy presents an advantage.

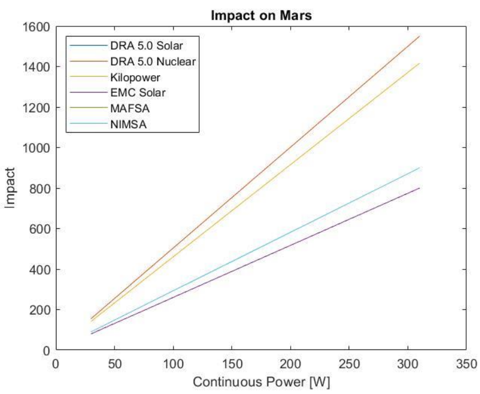

Figure 35: Impact on Mars according to the equity criterion.

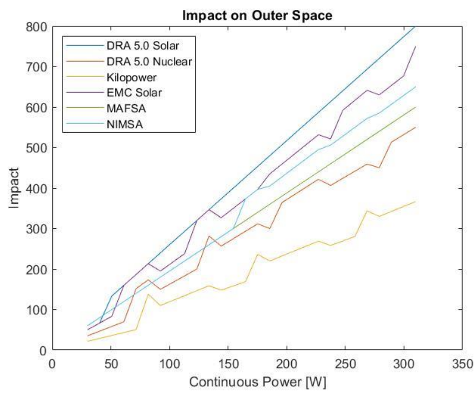

Figure 36: Impact on Outer Space according to the equity criterion.

The equity criterion is a neutral form of evaluation that shows that the study is useful to compare the architectures, as no clear difference can be appreciated between the systems when the importance of the parameters is even.

5.2. Growth criterion

When maximizing the relevance of scalability and ability to repair, both related to Martian operativity, the analysis is favourable to Kilopower and other nuclear power concepts, as seen in Figure 37.

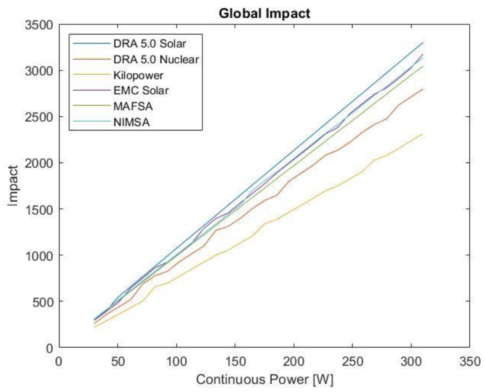

Figure 37: Global impact according to the growth criterion.

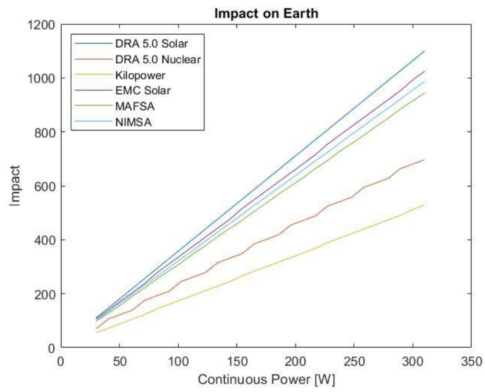

Figure 38: Impact on Earth according to the growth criterion.

Impact on Earth and Outer space remain favourable to nuclear, as the mass contribution parameter, TLM, is not affected by this scenario. However, the reduced importance of radiation related issues and restriction zones, combined with the emphasis on scalability, makes the impact on Mars (Figure 39), although still favourable to solar concepts, more balanced.

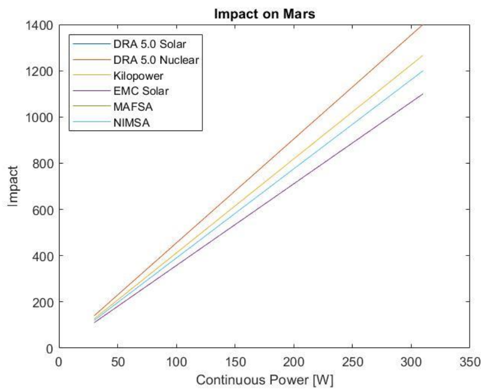

Figure 39: Impact on Mars according to the growth criterion.

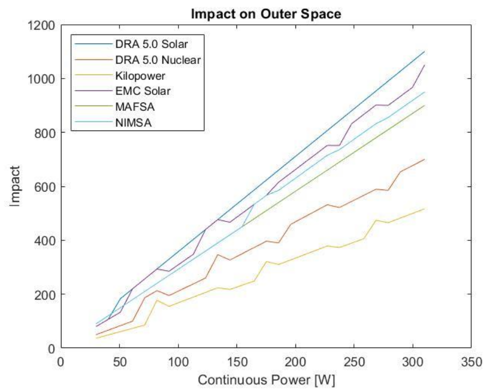

Figure 40: Impact on Outer Space according to the growth criterion.

When scalability becomes important, nuclear concepts, and in particular Kilopower, present a better sustainability score.

5.3. Mass reduction criterion

If the interest is around reducing the mass to be put on Mars, Kilopower wins the trade by even a larger margin (

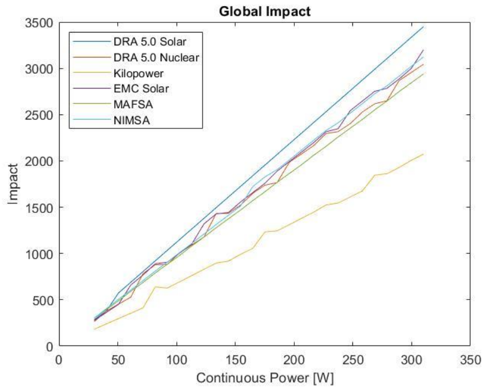

Figure 41: Global impact according to the mass reduction criterion.

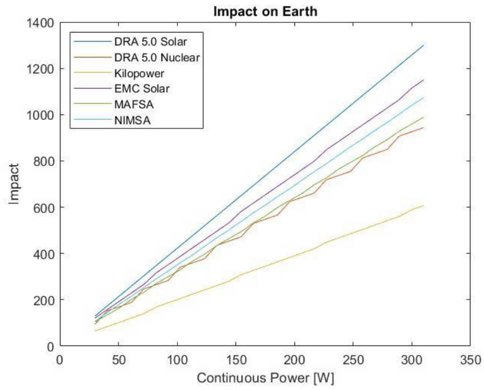

Figure 42: Impact on Earth according to the mass reduction criterion.

However, MAFSA and DRA 5.0 FSPS can be chosen as a secondary option depending on the power requirement.

This occurs because the weight of a MAFSA module is way lower than the nuclear reactor required in the DRA 5.0 nuclear power system. There are certain power requirements that would lead to the inclusion of excessive power if nuclear DRA 5.0 was chosen, in those cases, MAFSA wins the trade. Figure 44 is perfect to visualize the effect just presented.

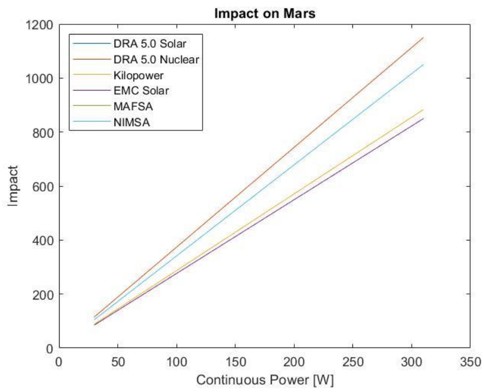

Figure 43: Impact on Mars according to the mass reduction criterion.

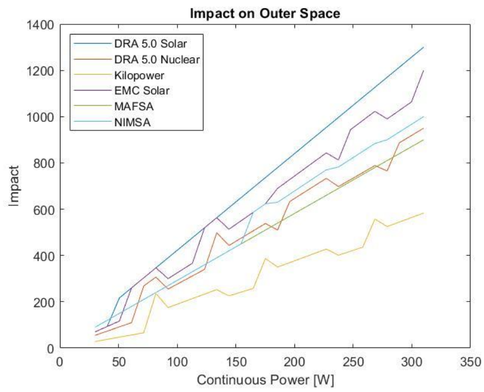

Figure 44: Impact on Outer Space according to the mass reduction criterion.

The impact on Mars, represented in Figure 43, is different from previous scenarios. In this case, as ability to repair, surface restrictions and crew radiation exposure are considered less important, the study is also favourable to Kilopower, which explains the great margin on the global impact for this system.

5.4. Radioactivity reduction criterion

A different approach considers on focusing in the effects of radioactivity. Figure 45 shows how this scenario favours solar concepts.

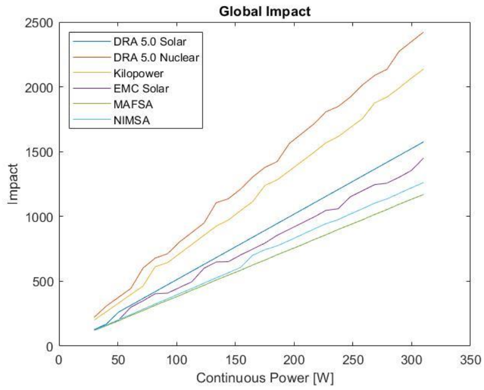

Figure 45: Global impact according to the radioactivity reduction criterion.

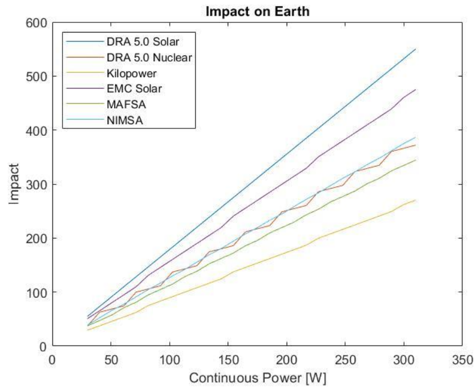

Figure 46: Impact on Earth according to the radioactivity reduction criterion.

Impact on Earth and on Outer Space still favour Kilopower, as seen in Figure 46 and Figure 48, as total landed mass is not affected by this criterion. However, differences in the impact on Mars (Figure 47), are considerable.

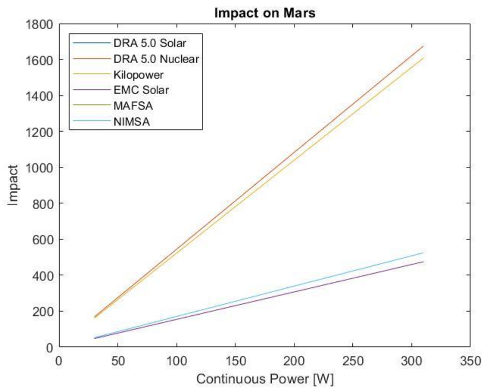

Figure 47: Impact on Mars according to the radioactivity reduction criterion.

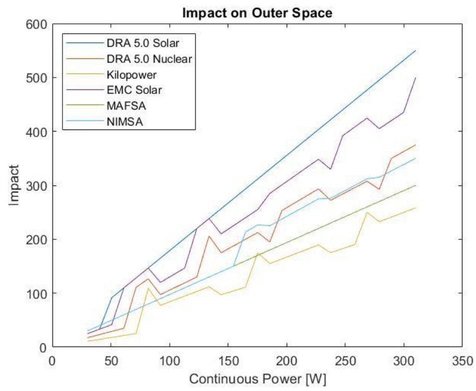

Figure 48: Impact on Outer Space according to the radioactivity reduction criterion.

It is interesting to notice that the EMC solar concept has a smaller impact on Mars than MAFSA and NIMSA alternatives, this is because of the longer design life of this system.

5.5. Operations optimization criterion

The last possibility studied focus on the optimization of operations. When parameters like surface restriction zones and recurring costs are emphasized, solar concepts still win the trade (Figure 49), even though recurring costs is a favourable parameter to nuclear concepts.

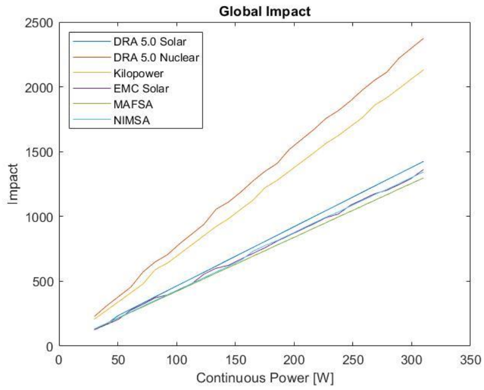

Figure 49: Global impact according to the operations optimization criterion.

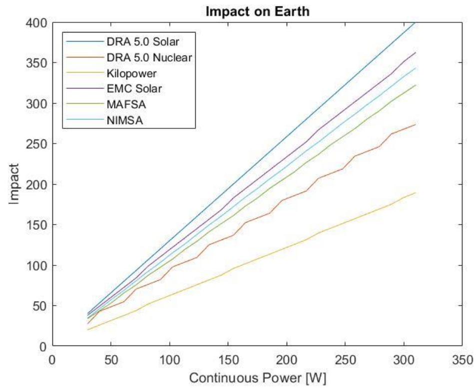

Figure 50: Impact on Earth according to the operations optimization criterion.

Impact on Earth and Outer space is still dominated by the low mass requirements of the Kilopower system. However, all the factors favourable to nuclear applicable to the impact on Mars are minimized except for recurring costs, which ends up in a big advantage of solar options, as seen in Figure 51.

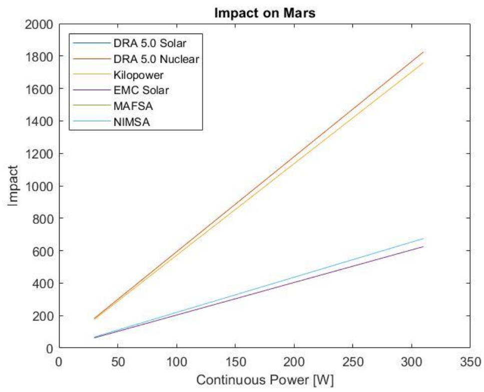

Figure 51: Impact on Mars according to the operations optimization criterion.

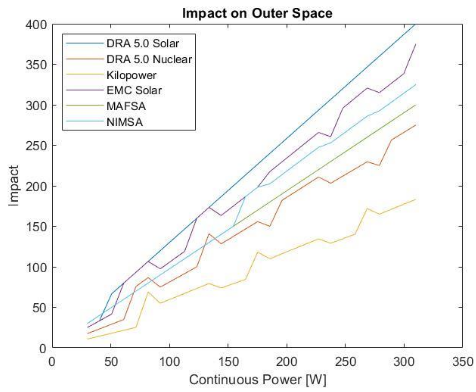

Figure 52: Impact on Outer Space according to the operations optimization criterion.

6. Conclusions and future work

6.1. Conclusions

The concept of sustainability has been studied from the origins of the term and adapted to the explorations of outer space and Mars in particular. Concepts like carrying capacity, resiliency, impact and circularity have been reframed for a permanent human Martian outpost.

Current initiatives regarding power system selection for human missions to Mars have been reviewed and summarized. DRA 5.0 has been taken as the base for the analysis and complemented with more recent studies like EMC, Kilopower, NIMSA and MAFSA. Even though the available documentation provides valuable data and estimations for the systems studied, no analysis of their sustainability has been proposed. The most similar initiative is DRA 5.0's figures of merit analysis for the nuclear vs solar concepts for the first human expeditions to Mars.

A methodology to globally evaluate the sustainability of a permanent Martian outpost has been proposed. The analysis is structured in three parts: location, where carrying capacity and resiliency of the environment is evaluated; mission, where the impact regarding Earth, Outer Space, and Mars is assessed; and resources and waste, where concepts like ISRU and ECLSS circularity are evaluated.

This project has provided qualitative guidance on location and resources and waste according to bibliographic search and has developed a quantitative model to study the impact of the power system concept chosen, solar or nuclear. DRA 5.0's figures of merit have been considered and some of them has been included in the study, along with new parameters such as recurring costs and design life.

Radioisotope Generators have been excluded from the analysis due to the extreme scarcity of their fuel, ^{238}Pu, and solar alternatives are considered not viable for latitudes between 15º S and 30º N.

The methodology proposed is flexible to different definitions and tendencies of sustainability and results are split between impact on Earth, Outer Space, and Mars, which also allows to prioritize one environment over the other depending on the needs of the moment.

Kilopower has shown great promise in terms of sustainability regarding the Earth and the Outer Space when compared to the other systems. The lower mass requirements are dominant in these areas and the high modularity of the system allows for flexible strategies that minimize the number of launches. It has been the best option in terms of global impact considering an equity criterion, a growth criterion, and a mass optimization criterion.

Solar concepts reduce the impact of the mission on Mars, mainly because they do not produce radioactivity, which can affect the crew and also requires the definition of extensive surface restriction zones. It has been observed that small modules produce less impact regarding both Outer Space and the Earth, which makes the NIMSA option very competitive, being the preferred choice according to the radioactivity reduction criterion and the operations optimization criterion.

It is important to mention that, while most impactful features of the Kilopower are related to radioactivity, which can be mitigated with extra shielding mass, solar alternatives have an intrinsic problem in the mass requirement. This is influenced by the relatively low efficiencies of the solar panels still up to date and by the higher power requirements associated to a lower operational time. In fact, interruptions in the power generation require storage systems such as regenerative fuel cells or batteries, which adds to the mass of the solar panels alone.

The sustainability study proposed has allowed to compare the available candidates for levels of power and has been able to identify the best suited option depending on the evaluation criterion selected. Evaluation of the parameters is still very immature, as no emphasis has been given previously to accurately define the required specifications. However, the methodology has proven to be viable and it will improve as more precise and concrete data related to the topics studied is collected. Additional parameters are also easily included in the analysis.

6.2. Future Work

In order to complete the sustainability study and make it a valuable comparative tool for different architectures, several lines of work can be taken.

Regarding the first part of the study, location:

- Inclusion of a location database which allows to apply the study to the most interesting candidates for Mars surface exploration.
- Accurate weather forecasting for the selected locations in order to determine the environmental conditions.
- Precise mapping of water availability for the locations database.
- Geographical assessment of the locations identifying promising features like caves or lava tubes.
- Precise global irradiance modelling for the locations database.
- Develop a methodology to link all these environmental factors with the carrying capacity of a certain location and its resiliency.

Regarding the second part of the study, mission:

- Include a parametrical evaluation of other aspects of the mission such as mission type, cargo deployment, orbit capture method, planetary protection, surface systems, mission operations, and transportation systems.

Regarding the power system sustainability study:

- Explore additional parameters related to Earth sustainability such as manufacturing, raw materials or logistics.
- Explore additional parameters related to Mars sustainability.
- Refine the definition of parameters such as ability to repair, scalability, surface restriction zones, recurring costs and crew radiation exposure to make them dependable on the characteristics of the system, mission, or architecture.

Regarding the third part of the study, resources and waste:

- Develop an in-depth analysis of the ISRU alternatives available and their influence on the mission impact and carrying capacity of the environment.
- Evaluate the interaction between the ISRU systems, the location, the power system and other mission elements, and the ECLSS.
- Develop an in-depth analysis of ECLSS systems with focus on efficiency and interaction with ISRU alternatives.
- Study the quantitative integration of these systems to the global sustainability study.

On the other hand, nuclear and solar power systems for a human scale mission to Mars are still not fully develop and require of precursor missions in order to study their real implementation. In order to provide valuable data for sustainability studies, future missions in preparation for human exploration should include and consider:

- ISRU demonstrators in order to prove the processability of the Martian atmosphere and the compatibility of the required systems with ECLSS and power systems. MOXIE is the first example of these kind of missions, but the possibilities for atmosphere processing are wider.

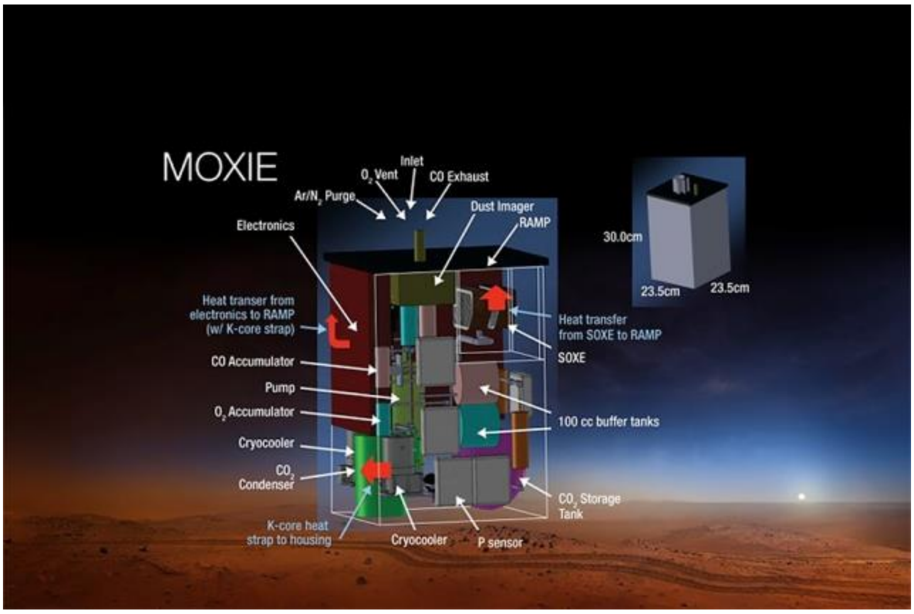

Figure 53: Subsystems of the MOXIE instrument (NASA)

- Water extraction and processing demonstrator in order to evaluate the viability of the concept. Regolith Advanced Surface Systems Operations Robot (RASSOR), an instrument of Kennedy Space Centre, is an example of such technologies.

Figure 54: RASSOR demonstration of resource utilization (Kennedy Space Centre)

- Include the mentioned technologies in combination of power systems alternatives like Kilopower or EMC solar systems in a long-stay ISRU demonstrator mission in order to evaluate the compatibility of the systems and the performance of power concepts in the surface of the planet. The mission should have a target ISRU production for a certain amount of years and then be extended indefinitely in order to understand how Martian environmental conditions affects to the design life, reliability and recurring costs of the power systems studied.

6.3. Journey to Mars

We are entering an exciting epoch for space exploration. Private companies are pushing the pace of governmental agencies for the first time in history, threatening to go to Mars by their own means with revolutionary advances on reusable rockets. NASA, far from being defensive, is enhancing private-public partnerships and is outsourcing most of its secondary development program, focusing on developing the strategy to go to the Moon first, and later to Mars.

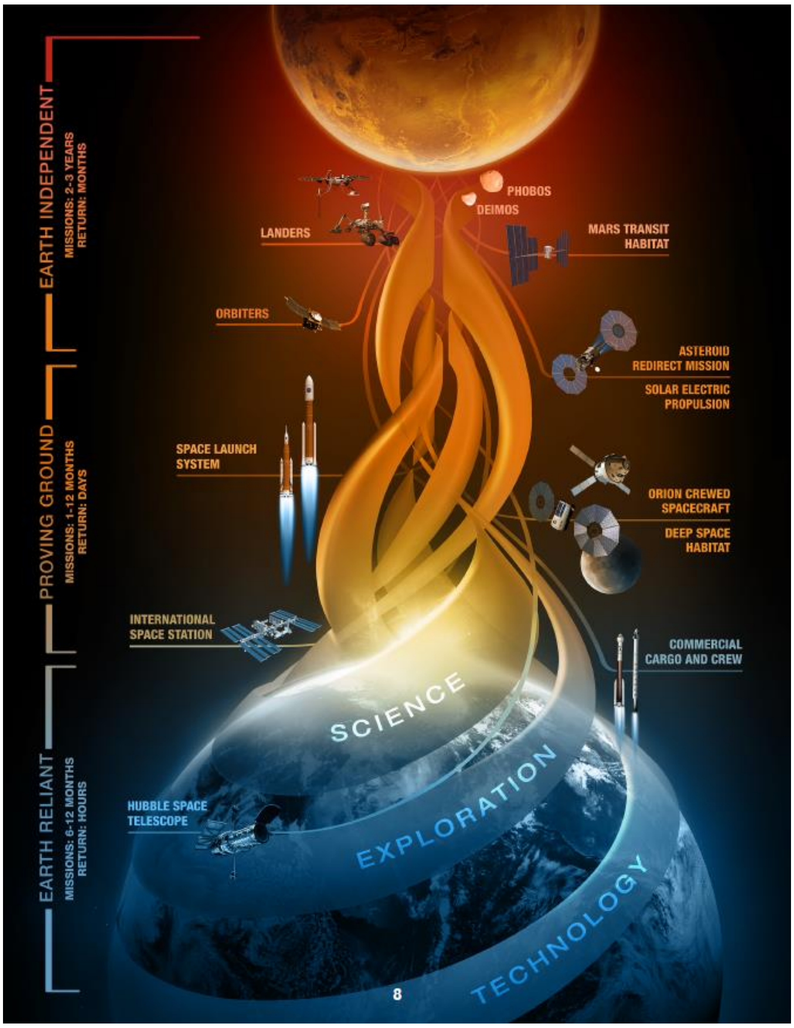

Figure 55: NASA's Journey to Mars (NASA, 2015)

The Journey to Mars has three steps: the Earth Reliant phase, the Proving Ground, and the Earth Independent phase.

The Earth reliant phase is the beginning of the transition beyond LEO. Private and public investments are sustaining the economic activity in LEO, allowing public agencies to focus on further destinations. The ISS has been key for the long-term testing of new life support and crew health systems, advanced habitat modules, and other technologies needed to decrease reliance on Earth. It will continue to demonstrate and experiment with long-duration life support for Mars missions, advanced fire safety equipment, next-generation spacesuit technologies, large deployable solar arrays, in-space additive manufacturing, advanced exercise and medical equipment, radiation monitoring and shielding, human-robotic operations, and autonomous crew operations. All of these are key areas of knowledge for a sustainable human presence in another planet.

The Proving Ground objectives are summarized in Table 21.

Table 21: Proving Ground objectives (NASA, 2015).

Proving Ground Objectives		
Category	**Title**	**Objective**
Transportation	Crew Transportation	Provide ability to transport at least four crew to cislunar space.
Transportation	Heavy Launch Capability	Provide beyond LEO launch capabilities to include crew, co-manifested payloads, and large cargo.
Transportation	In-Space Propulsion	Provide in-space propulsion capabilities to send crew and cargo on Mars-class mission durations and distances.
Transportation	Deep Space Navigation and Communication	Provide and validate cislunar and Mars system navigation and communication.
Working in Space	Science	Enable science community objectives.
Working in Space	Deep Space Operations	Provide deep-space operations capabilities: • Extravehicular activity (EVA) • Staging • Logistics • Human-robotic integration • Autonomous operations
Working in Space	*In-Situ* Resource Utilization	Understand the nature and distribution of volatiles and extraction techniques, and decide on their potential use in the human exploration architecture.
Staying Healthy	Deep Space Habitation	Provide beyond LEO habitation systems sufficient to support at least four crew on Mars-class mission durations and dormancy.
Staying Healthy	Crew Health	Validate crew health, performance, and mitigation protocols for Mars-class missions.

This stage establishes a permanent presence in orbit around the Moon from where NASA will get ready to the next steps on the exploration, testing the key features summarized above. Solar Electric Propulsion (SEP) enables near-term missions while proving capabilities for a reusable deep space transportation system that could reduce estimated cost in previous human Mars mission studies following a split mission strategy. Deep-Space habitats will have to be designed to provide highly reliable habitation systems during missions that last up to 1,100 days, evolving ISS habitation systems to meet future deep-space mission needs.

The Proving ground will also allow to validate Mars habitat concepts and systems, including exercise systems, environmental monitoring, long-duration consumables storage, fire safety in high-oxygen environments, radiation shielding, and high-reliability avionics with long periods of dormancy.

In order to become Earth Independent, ISRU technologies to transform local resources into water, fuel, air, and building materials are a must. Surface mobility, permanent surface habitats, and crew transfer vehicles such as the MAV will enable an integrated a sustainable campaign.

Robotic explorers investigate and map destinations prior to human missions, collect surface samples and characterize potential landing sites, testing new technologies as well. They will continue to do so in the next decade, being Insight and Mars 2020 the most recent example, but also ESA's orbiter and lander Exo Mars. Future robotic missions will identify resources and areas of scientific interest, understand the effects of space radiation, validating EDL techniques and study regolith mechanics and dust.

The Journey to Mars has already begun, it is now our responsibility to take a sustainable approach as mankind extends his presence to another planet for the first time.

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