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A Hybrid Power System for a Permanent Colony on Mars

Daniel Vázquez Pombo [1,2]

[1]*Technical University of Denmark (DTU), Risø, Denmark*
[2]*Vattenfall Vindkraft, Kolding, Denmark*

Correspondence should be addressed to Daniel Vázquez Pombo; dvapo@elektro.dtu.dk

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Since the dawn of humanity, people have contemplated the sky exploring the firmament. However, it was not until the twentieth century that humans were able to leave Earth and visit other celestial objects. In fact, nowadays, rovers roam Mars on a daily basis pushing the limits of science in a seemingly routine fashion. It is just a matter of time before humanity sets foot on the red planet with the aim of establishing a permanent colony. Such a complex endeavour demands continuous research, simulation, and planning. Consequently, this paper is aimed at starting a proper discussion about the configuration and design of a suitable power system for said Martian outpost. An initial literature review leads to the definition of a reference colony and its growing stages, which is followed by a revision of available energy-related technologies leading to a concrete design of a suitable electrical network. Lastly, the proposed hybrid power system is evaluated in terms of its reliability during the long-term operation under the extreme environmental conditions of Mars. The reference colony starts as an unmanned mission, as robots will prepare the selected location for the first human inhabitants. Later, it suffers several upgrades in size reaching a permanent population of 100 people. Therefore, a holistic approach is needed when designing the power system in order to ensure the continuous supply of the colony. Finally, the selected topology of the colony's power system is presented.

1. Introduction

Exploration is deeply attached to the very meaning of being human. Historically, people have always wanted to go where no man has gone before. The twentieth century opened a new horizon for science and technology with the space race which culminated with the first human setting foot on the Moon. Then, funding was drastically reduced [1], even despite the fact that the first manned mission to Mars was envisioned as soon as 2006 [2]. Later, the arrival date would be deleted altogether [3], even despite the NASA Authorization Act of 2005 which specifically stated that reaching Mars represented a key objective [4]. Now, SpaceX, a private company claims that they will deliver the first crew by 2024 [5].

Many are the reasons behind establishing a colony in Mars such as the possibility of discovering extraterrestrial life, ensuring the survival of our species after a massive extinction event, and improving quality of life, etc. However, there are only a few scientific publications regarding Mars colonisation. The few existing focus mostly on spacecraft concepts and design, at the expense of hardly mentioning or even neglecting basic day-to-day critical infrastructures like the power system. In fact, the relevant previous work starts mostly on the 70s, later in the 90s and 2000s; a couple of very high-level publications appear that mainly update some of the base assumptions due to the discoveries obtained by different unmanned missions sent to the red planet. In any case, establishing a permanent outpost in Mars requires a flexible, scalable, reliable, and safe power system. Therefore, this paper is aimed at analysing power sources, transmission/coupling possibilities, topology, etc. for a near-future Mars colony. This is addressed by reviewing all the excellent work developed since the 50s until the early 2000s and then updating it with present methods and technologies. Culminating with a proposal of a power system suitable for the task at hand, serious dialogues must start among the scientific community as it is its duty to serve humankind's development [1–5].

There has not been much development specifically about the power system. Early documents like [6] proposed either a purely nuclear system or a combination with solar photovoltaic (PV) [7]; some others [8] suggested radioisotope but with a back-up role. However, most of the available work is superficial and undetailed. Recent development in energy

technology obtained as a result of the energy transition demands a revision of the sources and storage system that might be used in the power systems of surface space missions. In addition, no document has proposed a balance of plant, a proper topology, or addressed the transmission system for the colony to name a few, not to mention how to address the particular effects of the Martian environment on electrical equipment [9]. Thus, studies focusing solely on the Martian environment and requirements are needed. Thus, this paper is aimed at reviewing the available technologies that will conform the power system of a near-future Martian colony and propose a suitable topology. This is done by reviewing the different proposed mission designs, concluding in a reasonable evolutionary scenario for the colony and its balance of plant suitable to satisfy its power and energy needs.

Then, the structure of the paper is as follows: Section 2 reviews the history of the most important documents published targeting manned missions to Mars, the interest behind establishing a permanent outpost, and it subsequently defines a dynamic architecture for the outpost. Thereafter, different power sources are analysed on Section 3 in order to choose a suitable combination conforming the Martian hybrid power system (HyPS). Then, whether the coupling should be in AC, DC, or mixed is discussed in Section 4. Afterwards, the resulting topology of the HyPS is presented and evaluated in Sections 5 and 6, respectively. Finally, the conclusions of this work are presented in Section 7, while also pointing out research paths that might continue this work.

2. Background, Motivation, and Mission Requirements

This section reviews the most important studies targeting Mars exploration in chronological order. This is aimed at illustrating the evolving concepts in certain areas while the stagnation in others such as power systems, while also helping to define the targeted mission. Despite the intention of providing an overview of all the developed science, there is a strong focus on NASA achievements until the 2000s, since Roscosmos public documents are written in Russian, a language sadly falling out of the knowledge base of the author.

The first formal approach to reach Mars was published in 1953 [10], where the flight systems and spacecraft are envisioned. A crew of 70 would be the first humans seeing the planet up-close as the arrival date was 1965 and precursor robotic missions were not considered. However, it was not until 1988 where a space agency such as NASA published a study with a similar aim [2], followed shortly by series of studies of human and robotic exploration beyond Low Earth Orbit and the Moon, Mars, Phobos, etc. [11, 12]. Then, [13] concludes that enough technological readiness would be achieved by 2000, starting the operations shortly afterwards; envisioning crews of 4 people, doubling two years after the first arrival and, also, suggesting several schedules ranging from 2011 to 2018 for the first mission and 2014 to 2027 to inaugurate the first permanent settlement.

In any case, [13] satisfies the power needs of the missions by means of SP-100, a nuclear fission reactor designed in 1989 for lunar missions easily adaptable for Mars [6]. It is worth mentioning that all the previous publications dismiss the possibility of using any locally available resources since there was no data available until the discoveries obtained by both Viking landers. Subsequently, in 1991, [14] further elaborates about a surface operating reactor, while [15] takes an extra step by coupling it with an in situ resource utilisation (ISRU) unit. A device capable of using local water, ice, and atmospheric CO_2 as raw materials for fuel, air, water, plastics food, and other supplies. However, this concept will fall into oblivion for more than 10 years [16–18]. Afterwards, [19] points out the need for further research about the Martian environment before they could design landers, space suits, and other surface systems. After 1997, the approach taken by the studies changes trying to acquire a more holistic perspective, since previous attempts like [20] ended up focusing mostly or solely into flight and trajectory designs. Then, [9, 21] represent the most complete analyses until then, aiming to be used to drive R&D plans, understand mission requirements, open discussions, establish a baseline for future proposals, and stimulate further thought by also demanding improvement in certain aspects like the power system. A crew of 6 is envisioned in [9], no attention to surface power system is paid, and no ISRU is considered despite [15] being published 6 years prior.

After entering the new millennia, a high-level review of the Mars mission is published [3] stating that human arrival to Mars is so certain that a second revision will be necessary between 2015 and 2020 to account for the actual arrival. The book reviews concepts such as [10, 19] which never envisioned the role of robotic exploration. These unmanned missions helped discover unknown phenomena that would have ruined any manned mission developed with that time's technology. It also points to the arrival delay caused by these discoveries as the reason for funding reduction in benefit of robotic exploration. The more was discovered, the least money available for a manned mission was available. Then, [16, 17] present concepts for self-sustaining Mars colonies by means of implementing ISRU. In [16], the 500 people colony site is selected in the North polar cap due to the water/ice available, while [17] focuses on obtaining water from the atmosphere, to avoid site dependency, envisioning a modular architecture capable of either 100, 1000, or 10000 crew scenarios. Following this trend, [18] is aimed at implementing an ISRU system to support propulsion and power systems for ground and flight vehicles in two scenarios, an Antarctica-inspired 100 people scenario and another terraforming scenario with a crew of 10000.

The first document from the European Space Agency (ESA) about a Mars mission is published in 2006 [22], which presents plans to study the Martian environment by using rovers. Then, [23] revives the interest of manned missions in three different sites, discussing mobility possibilities both on the surface and underground; the arrival is estimated between 2030 and 2040. Subsequently, in 2009, [7] suggests a framework aiming to facilitate reaching Mars as a multiagency effort. The document describes the systems and operations of a robotic precursor and the first three manned missions of 6 people each in different locations. This document stands out as the first time that the power system and

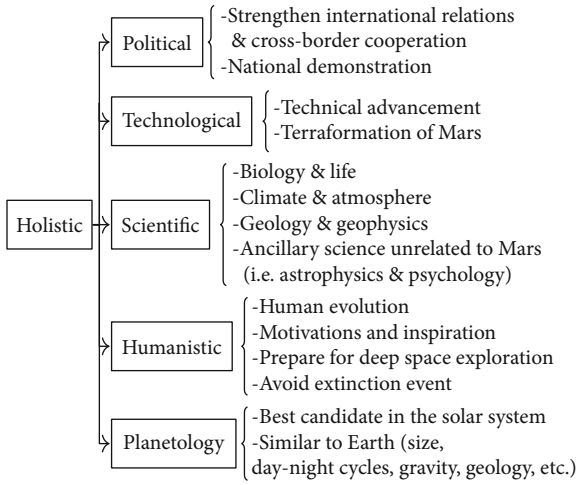

Figure 1: Reasons to go to Mars.

energy management are highlighted as a key improvement needed. Subsequently, [24], a more completed version of [7], builds upon some of the aforementioned documents like [11–14, 21, 22] and others like [25, 26]. Among the conclusions of [24], the higher importance of robot-human partnership should be mentioned. Additionally, the selected crew of 6 must land prior to 2030; otherwise, a technology reassessment will be needed. Lastly, [24] contains the first proper section about the power system, which is envisioned as a combination of nuclear and PV for the main power while radioisotope power systems (RPSs) for backup needs. Thereafter, in 2014, [27] updates [7] with the latest developments, increasing again the role of robots and identifying solar power generation, nuclear fission, and active thermal control among the critical technologies. On the other hand, ESA and Roscosmos have a shared exploration agenda; however, no manned missions are foreseen [28, 29]. India and Japan have expressed that their targets do not include Martian exploration whatsoever, while China do it independently, targeting manned missions to the Moon in 2030 in collaboration with Russia as a prior step [30, 31]. Then, the Evolvable Mars Campaign is the current NASA mission seeking to enable crewed Mars missions in the mid-2030s timeframe [32]. Lastly, SpaceX is targeting the first manned mission to Mars in 2024 as preparation for a permanent settlement to be started shortly afterwards [5]. Nevertheless, why should we keep pursuing the dream of reaching Mars?

Many publications like [7–9, 33, 34] have reviewed the numerous reasons and objectives behind reaching Mars, which can be divided into 5 categories: planetology, humanistic, scientific, technological, and political. Ultimately, the goal is the integration of all the prior and acquired knowledge, which is referred in this work as holistic. This unification of knowledge will transcend any objectives established for the Mars colonisation and will push humanity forward. A summary of the possible reasons and objectives behind the conquest of Mars is presented in Figure 1. Nevertheless, the questions risen due to this endeavour might be even more valuable than the answers we hope to find [23].

Once the reasons behind getting humans into the red planet have been stated, the importance of establishing a permanent settlement instead of a temporary visit should be highlighted. The most important reason backing a sustained human presence in Mars is the increased cost-effectiveness of the mission. Research potential and discoveries escalate during sustained missions, while the cost does not increase significantly [23]. However, even disregarding the difficulty of reaching the planet safely, the particularities of engineering a robust system capable of operating under the Martian conditions will unequivocally translate in technological advancement for the general humanity. Examples of this process can be [35] where cross-disciplinary research is undertaken making use of the ISRU to propel an ascent vehicle in Mars, or [36] where a prototype for a greenhouse suitable for the Martian environment is presented, or [37] which is aimed at expanding the applications of ISRU units. Additionally, since one of the objectives is to avoid a massive extinction event, establishing permanent human settlements in other celestial bodies is a key. Then, terraformation of Mars, which consists of warming up the planet, in order to thicken its atmosphere, ultimately obtaining liquid water surface oceans on Mars [34], would only be interesting to achieve if there is a sustained human presence on the planet [38]. Lastly, Mars is not considered the end of the space exploration, but rather a step in it. Future missions aimed at more distant celestial objects will require longer stays before returning or continuing; thus, Mars represents a great training outpost.

At the end of the day, there are a variety of different envisioned manned missions, with crews ranging from 4 to 10000 depending on the length of stay and the ultimate exploration objectives. Barely no attention has been paid to the configuration and actual implementation of the power and energy management system (PEMS). Manned missions might still be decades down the road; however, complex robotic missions rather than individual rovers might be closer than ever due to latest developments in the field [39, 40]. Whatever the case, manned or unmanned, all the infrastructures depend on having a functional power system. Therefore, a reference architecture for the colony must be defined prior to sizing the necessary PEMS as it is needed in order to estimate the mission's power and energy needs.

2.1. Architecture of the Colony. Even though there is no certainty as of this moment about the exact outlook of the colony, there are several strong candidates that can provide a rough approximation to be used as a starting point. Additionally, one of the self-imposed conditions of this work is that all systems must use current or near-future technology (technology readiness level of at least 6); no breakthrough technologies are assumed as following the recommendations of [22, 41]. Then, depending on the objective, any Mars surface mission can follow one of the coming strategies [7]:

(i) Mobile home: all the structures are packed in a mobile, rover-based colony whose objective is long-duration exploration at great distances in a nomadic way

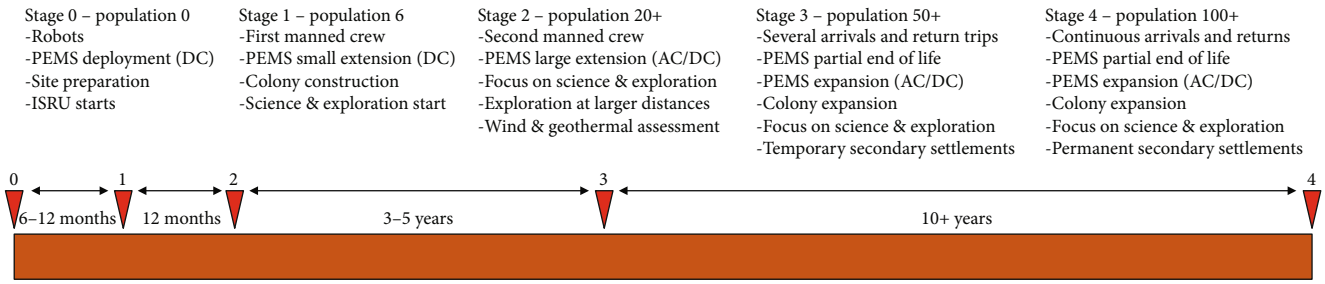

Figure 2: Timeline of the Martian colony.

(ii) Commuter: fixed, stable site for the colony with inclusion of both un- and pressurised rovers for mobility and science. The focus is on human exploration

(iii) Telecommuter: similar to commuter, although most of the exploration is based on teleoperation of small robotic system from the local habitat

The focus of this work is on the commuter scenario as is the one that has received more attention and, also, it is the one best serving the purpose of a complex, permanent colony. One of the main reasons is the expected cost reduction of future missions by making use of the ISRU units and local manufacturing. While its concrete economic implications are tough to estimate and fall beyond the scope of this work, it is simple to understand how having a base in Mars will greatly reduce future mission costs. This is due basically to two reasons: launching satellites or other robotic missions manufactured directly on site and the possibility of providing support or maintenance [23].

In the commuter architecture, any planetary structure can be divided into 8 categories: habitats, laboratories, bioregenerative life support, ISRU, surface mobility (rovers), extravehicular mobility (eva suits), power system, and launch and landing area. All of them contain similar equipment such as windows, hatches, docking mechanisms, power distribution systems, life support, environmental control, safety features, stowage, waste management, communications, airlocks, and egress routes [9, 13, 17]. It is worth mentioning that rovers in this scenario are assumed to have a range of 100 km before needed resupply [7]; however, there is already available technology to get significantly larger ranges [42]. Disregarding the mobility range and the number of rovers, the habitats are always expected to keep a minimum of occupation due to safety measures [24]. Then, with an increasing population and expected duration of the colony, the number and purpose of the habitats change dramatically; if for a 6 people colony, habitats only include the bare minimum survival needs [7, 9]; a 100 people colony demands the existence of recreation facilities such as shops, open community spaces, parks, and public transportation [17].

2.2. Growing Stages of the Colony. After identifying the colony architecture as a commuter, the most influencing parameter affecting the power and energy demand is the foreseen population as it affects the required resources, habitats, etc. Since the aim of this work is to establish a permanent self-sustaining colony, its deployment is approached in stages.

Given the recent development in the field of robotics, it is reasonable to assume that the settlement will be founded by robots, which will select and prepare the terrain for the arrival of the first crew. Later, an initial crew of 6 will arrive, continuing the expansion of the colony and starting the scientific work. The next arrivals are expected shortly afterwards once the technology and structures have been tested, thus ramping the population in steps to 20, 50, and 100. This chain of arrivals and colony development is consistent with published work as [7, 10, 13, 17, 32, 41]; however, the robotic role has been considered, in general, higher. Then, even though there are already scenarios envisioning colonies up to 10000 people [16, 17], the author considers that scenario to be far enough in the future to require a technology and method reassessment specially including the lessons learned from the first years of the Martian colony.

Following the example of [16, 17], in this paper, it is assumed that the mission target is to reach a population of 100 humans. This is carried out in 5 development stages summarised in Figure 2. The high-level definition of such stages is used in this section to estimate the power and energy needs of the colony. This is later used to design the topology of the PEMS. According to [16, 17], a population of 100 should be possible to achieve within 8 to 10 years since the arrival of the first manned crews. That is considered the end of this analysis as any subsequent analysis of what could be done is pure speculation, which would require further analysis including new technological developments and lessons learned from the day-to-day activities of the colony.

Stage 0: in this stage, robots and autonomous vehicles are the only inhabitants of the colony. They have a well-defined set of tasks aimed at preparing the outpost for the arrival of the first manned mission, which is expected several months later. Since the settlement operates unsupervised, simplicity and reliability are a key

The first task of the settlement is to deploy the HyPS and basic structures relatively close to the landing spot. Secondly, the robots should clean and prepare the landing area for the crew and find a suitable location for the habitats. In addition, they should also start drilling and mining operations. There is a general acceptance related to the possibility of using caves to set up inflatable habitats, as this protects from the tough meteorological conditions of Mars. Additionally, this allows to start collecting data related to geothermal activity. Lastly, the ISRU unit must start accumulating enough fuel, oxygen,

and water as to allow the crew to take off and initiate the return trip as soon as they land. This is of course not the objective, but a fail-safe in case catastrophic problems are detected while on route. Thus, fulfilling security constrains defined in [9, 43].

Stage 1: the arrival of the first manned crew establishes the start of the next stage with a total human population of 6. This is expected to happen between 6 and 12 months after the robots. Assuming that no emergency return is necessary, the objective of the mission is to build the main structures of the colony: habitats, laboratories, etc. The newly landed ship will also deploy PV arrays and energy storage. These units should easily connect to the already existing HyPS of the colony. Now, the collaboration between humans and robots allows to undergo much complex tasks. The first scientific experiments start in this stage

Stage 2: the beginning of this stage is marked by the arrival of a second manned group which rises the population to 20 people. This is expected 1 year after the first crew arrives. As the main structures were built during stages 0 and 1, the main focus of this crew is science and exploration. Apart from the population increase, on-site manufacturing of different components and tools, along with newer processes and research activities raises the power needs of the colony. Since the settlement is older than 2 years now, the colony is well-established and relatively safe. Not only several arrivals are expected but also part of the colonists will return to Earth, thus, slowing down the population growth rate, which ultimately makes the duration of stage 2 significantly longer than for the previous

Stage 3: once the population reaches 50 settlers, the colony starts stage 3. This is expected between 3 and 5 years after stage 2 begins. It should be noted that some of the original equipment has reached the end of its life expectancy. In addition, new structures are needed to host the rising population. Therefore, at this stage, there must be a reassessment about how to cover the power and energy needs of the colony. The life rhythm of the colony at this point is well known. Science is still the main occupation of the settlers, along with increased exploration at further distances from the original landing site. It is possible to start new temporary settlements at other locations in order to extend the operational area of the colony

Stage 4: this stage is reached once the population reaches 100. Some authors suggest that this will take over 10 years after reaching 20 due to population renewal. However, it is tough to say due to an almost unlimited number of uncertainties, from funding availability, to psychological or biological limitations. Therefore, the chronology is stopped at this point in time

2.3. Expected Power and Energy Needs. The expected power needs per person stay fairly constant with a growing population at around 24 or 25 kW/person for missions ranging from 4 to 500 people [16, 17]. However, there are discrepancies regarding the distribution of said power needs as some authors divide them evenly between habitats, science, and life support [7, 41], while others prioritise some over the others [43]. In any case, an agreement point is that the ISRU represents the highest consumption of the colony ranging from 30 to 50 kWe for missions from 4 up to, at least, 50 people [35].

Table 1: Expected power needs for a growing colony.

Stage	Population	kWe per person	Generic	ISRU (kWe)	Total
0	0	25	140	50	190
1	6	25	140	30	320
2	20-49	23	460	50	970-1735
3	50-99	20	1200	100	2300-3775
4	100+	17	2500	200	4400-7700

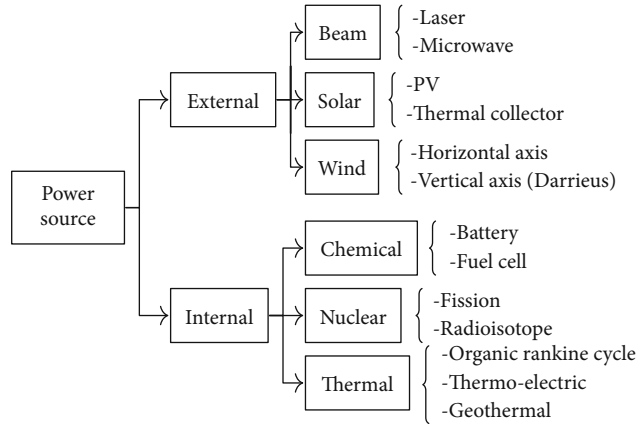

Figure 3: Considered energy sources in Mars.

A summary of the colony's power needs for a growing scenario is presented in Table 1. These values are consistent with prior estimations [9, 44]. As aforementioned, the population is considered fixed in the first 2 stages, but increasing over the next. Therefore, two values are shown for population and the corresponding total power, one for the minimum and another for the maximum population level. Although, this assumes a constant power production, if intermittent production (i.e., standalone PV dealing with day/night cycles) is selected, the power needs result 2-4 times higher, approximately, even though the energy demand remains unaltered [24]. In any case, it should be noted how the necessary energy per person remains fairly constant. On the other hand, ISRU initially represents the largest load, reducing its influence over the overall needs with population growth.

3. Sources of Energy and Power

The available power and energy resources were originally analysed in 1986 [43] focusing on nuclear, solar, radioisotope, fuel cells, and batteries. Subsequent studies as modern as 2009 [7] tend to repeat the same dogmas, without much thought, simply updating specific parameters like efficiencies, power capabilities, and technology readiness level of a given resource. On the other hand, in this paper, a methodical approach is applied to resource selection. Then, Figure 3 presents a summary of the evaluated technologies.

3.1. Solar. Solar power in the PV form was originally developed for space applications [45]. It is a more than proven technology, relatively easy to deploy and maintain, with a long expected lifetime [45]. However, its generation capacity is not only location and season dependent but also subject to day-night cycles [45]. In general, the available solar radiation on Mars surface ranges from 36 to 52% of that of Earth with an average of 43 [46]; on the other hand, as PV perform better, the colder they are, the reduction in production is less dramatic [47]. Additionally, dust deposition is a major issue since it slowly deposits on top of the panel reducing the production until stopping it completely [18]. In fact, some studies claim that this decline is as dramatic as 77% in a two-year operation [48] or 0.2% per Martian day (sol) [24]. Thus, dust removal technologies were identified as a major technology deficit given the seasonally expected dust storms [18]. This has led to the development of solutions such as electrostatic dust repulsion [49]. Nevertheless, with enough storage, a 20% overinstallation seems to be sufficient up to 2 months long dust storm as according to [7]. In any case, there is evidence that wind will periodically blow away part of the deposited dust improving the situation as it already happened to several rovers [24]. On the other hand, in the alternative solar technology, thermal collectors has been implemented in combination with thermoelectric generators [7], but, for a Martian permanent outpost, a concentrated solar power (CSP) might be more interesting since it could allow to overcome the day-night cycle without chemical storage and has a long-life expectancy [50]. Once the colony grows from the initial stages, PV does not present an interesting mass payload when compared to other options such as nuclear [6]; however, it becomes interesting again when long missions or a population larger than 1000 is targeted [51].

3.2. Beam. Power beaming by microwave from space to Earth was first suggested in 1968 [52]. The idea is to generate power at a satellite in stationary orbit (usually by means of solar or nuclear power) and then transmit the said power to the surface [53]. This transmission can be done by using a laser beam or microwaves. It has been tested in the Earth orbit; however, it is difficult to scale up to hundreds of kW, due to the large distances between the satellite and the surface energy collector [43]. It is indeed feasible for small celestial bodies like Phobos, Mar's satellite, but not for planets even with lower orbits and reduced atmospheric density such as Mars [43]. Its current efficiency is around 0.4%, and some authors suggest that it will not be practical until it reaches 40% [53].

3.3. Wind. Barely any publication evaluates wind power deployment in Mars; however, it might prove itself useful. Wind power has experimented huge development since the 90s, and it is reaching now full maturity [54]. Mars' atmosphere density represents 1% of Earth's which means an equivalent reduction for the produced power as it is directly proportional [45]. However, long periods with strong winds, which cause dust storms are expected. These storms are seasonal and expected to last up to two consecutive months [7], which is extremely challenging for solar power [18]. In that case, [55] concluded that Darrieus turbines could be deployed to provide power not only during night periods (expected to be more windy [54]) but also during said emergency periods caused by the dust storms as wind power is not severely affected by those particles [56]. Lastly, there is a project lead by ESA aimed at developing a wind power generator specifically for the Martian environment starting in 2021. The concept is based on triboelectric harvesting, which presents a lot of potential given the particular electrostatic conditions of the Martian atmosphere [57]. Nevertheless, wind power has a lower technology readiness level than 6 as of 2020, and it is therefore excluded from the analysis.

3.4. Chemical. Both batteries and fuel cells belong into this category whose function is to provide energy storage [43]. Historically, fuel cells have been preferred due to their reduced mass/power relationship [9], even despite their relatively low efficiency of 27% [7]. Thus, fuel cells are a better proven technology in space applications; however, the latest advancements on battery performance, energy management, and lifetime extension [58] might tilt the balance towards including batteries due to their better regulated power and higher efficiency (around 80%) [53]. The inclusion of either batteries or fuel cells allows time constant production for a purely solar station to function [13] apart from providing protection against low or none production periods due to dust storms [51]. If combined with a dispatchable resource such as nuclear, either batteries or fuel cells can be used to up/downregulate the system, while nuclear provides bulk generation. In this way, the generator can keep a steady operation which has proven to extend its lifetime.

3.5. Nuclear. Reactors based on either fission or radioisotopes are proven technologies with recognised capabilities for ground operations [7]. Fission power can be used for bulk generation in combination with other resources [7] or even in standalone operation [16] while radioisotope power ranges only allow them to be part of the back-up system [8, 9] or to power small systems like rovers [9, 59]. On the first hand, the advantages of fission are capability of providing constant power disregarding meteorological conditions, scalable up to 100 kWe per reactor, proven technology on Earth [9]. On the other hand, the main disadvantages are limited life expectancy requiring an exclusion zone to be delimited in order to avoid excessive radiation contamination, and there is political and social opposition against launching nuclear material since a failed launch will cause radioactive contamination on Earth [60]. Once operational on the surface, shielding is needed in order to protect people and structures from the radiation; [27] concludes that burying 2 meters is the best way for long-time missions. Regarding the technology readiness level of the reactors; in 1989, NASA started the development of the SP-100, a 825 kWe fission reactor, but the project was terminated in 1994 [6]. A maximum lifetime of 7 years at full capacity 24/7 was expected; however, if a lower working rate was selected by for example by having several of this generators working together that could be increased [6]. Later in 2004, a 111 kWe scalable reactor concept known as SAIRS was conceptualised and

built concluding that there were no major improvements needed to deploy such technology [61]. Then, in 2014, [27] complains about the lack of progress in this surface reactors although it considers them ready for deployment. Subsequently, in 2015, [60] presents a small fission power system for the 1-10 kWe range acknowledging that the most important obstacles for this technology were political and financial. Finally, it is worth mentioning that, so far, the designed fission reactors had an expected lifetime ranging from 4 to 7 years, which presents a major drawback when compared to others like PV which, with proper maintenance provided, can endure decades [24].

3.6. Thermal. Some publications have concerns regarding heat dissipation from nuclear waste heat [61]. Even though it is considered a residue, it could be recovered with an organic Rankine cycle, which uses refrigerants as fluid conductor to recover part of that energy [62]. This approach might be interesting for relatively big colonies over a 100 population since extreme amounts of excess heat are expected [16]. The technology is proven and commercialised on Earth [63], but it has never been implemented in space applications. Lastly, thermoelectric generation is nowadays employed as part of radioisotope systems to power rovers and spacecrafts as the Cassini [7]; however, it presents low efficiencies, and their mass/power range only makes them suitable for small and back-up generation [7]. Lastly, even though Mars' volcanic activity has ceased [64], there is a huge potential of finding areas with residual warm suitable for geothermal exploitation [65]. Combined with current available technology for penetrating Mars' surface up to 300 meters [23], it possesses potential for further enlargements of the colony and therefore should be considered.

Even though there is still much to learn about Mar's climate and metheorology, a few hints can be stated since part of the analysed resources are weather dependent. On the first hand, solar irradiance is subject to high seasonal variations caused by the planet's orbital eccentricity (high when compared to Earth). The maximum and minimum available radiances are 717 and 493 W/m^2 corresponding to the perihelion and aphelion, respectively, at the equator [48]. Summarising, 2.25 times as much solar energy collectors as for the same application on Earth are needed [9]. Then, the day/night cycle is specially important while the settlement holds less than 50 people since it requires to install between 2 and 4 times more solar than nuclear in order to ensure ISRU production [7]; however, that rate reduces as the installed power increases [51]. Additionally, it should be mentioned that solar power mass increase as landing sites are selected further from the equator, making landing site selection a key driver in the final power system decision [51]. On the other hand, winds are predicted to have velocities ranging from 25 to 33 m/s at 25 meters above the surface that are also affected by topography, i.e., craters facilitate higher speeds than nearby areas. Lastly, the air density corresponds to approximately 1/75 of the Earth's; thus, a Martian wind speed of 35 m/s contains roughly the same energy as 8.25 m/s on Earth, which would require using turbines targeting very high speeds but with reduced energy yield [48].

The practical totality of the studies propose HyPS for any kind of manned Mars surface mission due to the required redundancies; catastrophic failure of one of the technologies would be independent of the rest of the system [9, 43]. Some use PV during the deployment due to simplicity, adding nuclear power in later stages, leaving PV for back-up and redundancy [6, 7, 17]. Others like [24, 41] target to use just one main power source and either chemical storage or radioisotope as back-up concluding to use nuclear as main due to the weight of the solar for large arrays. However, its size may be reduced with a better energy management, different storage, power saving modes, and other different improvements on efficiency based on recent microgrid research [66].

Then, in 2016, the most complete study comparing PV with nuclear for a Martian colony was published. Four analysis are performed: (1) PV operating only during the day at a higher rate, (2) PV with minimum storage (only able to keep vital functions at night), (3) PV with enough storage to operate normally during the night, and (4) nuclear reactors without storage. It concluded that a solar-powered mission is certainly possible without further development; nuclear would still require investments for implementation and research. Solar is more expensive in mass but more reliable than nuclear if combined with storage. In the long run, meaning several missions or longer time in same site, PV is more desirable. Then, regarding storage technology states that fuel cells were been outperformed by batteries [51].

In conclusion, there are a lot of strong candidates to power a near-future Martian colony. However, there is no silver bullet foreseeable; the system will be based in a combination of the aforementioned resources. In fact, the Martian energy mix is expected to grow in complexity as the population and structures increase. According to the previously exposed, PV with some kind of chemical storage is expected during the robotic deployment stage. Later, once the first humans arrive, a nuclear fission reactor will most likely be added. However, given the reduce life expectancy of the reactors, the bulk generation will not be provided by nuclear power in the long run. In that case, there will be possibilities of exploring installation of wind turbines, geothermal, or CSP. Since the outpost is expected to eventually become self-sustaining, it is assumed that it will be possible to manufacture complex devices in Mars that will avoid material transportation from Earth, facilitating options that are now unfeasible due to mass constraints. Lastly, it should be mentioned that since the ISRU unit will create fuel (among other products), this can be used as an emergency energy source in critical situations.

4. Transmission and Coupling

In this section, electrical coupling and transmission are discussed based on the conclusions from the previous sections. As the population grows, the energy mix will gain complexity. In early stages, only PV and storage are expected; thus, a DC bus is sufficient to satisfy the needs of the colony. Then, DC/DC converters can be used to have different voltage levels throughout the system. Higher voltages are needed to operate large machinery such as drills, while lower ones are

Table 2: AC vs. DC coupling comparison.

DC		AC	
Advantages	Disadvantages	Advantages	Disadvantages
Simpler to control small networks	Low efficiency for large loads	Directly couple large units	Most small loads operate in DC
Directly couple PVs and storage	Heavier machines for same power/torque ratings than AC	High efficiency for large loads	Complex control in small systems
Modularity		Lighter machines for same power/torque ratings than AC	

useful to day-to-day devices, e.g., lights and computers. On the other hand, nuclear reactors, CSP, or geothermal units are expected to operate as 3-phase 4 wires at 400 Hz AC [67, 68]. Additionally, some of the colony's activities present higher efficiencies by using AC motors, as they are, in general, smaller and lighter than DC motors of the same power range and torque, which greatly improves the payload of the mission [69]. Therefore, AC buses present clear advantages, while one of the main traditional drawbacks is the need for transformers, which add large amounts of mass to the PEMS. However, this might be solved by using cycloconverters which can be configured to output arbitrary voltage and frequency configurations while representing as well less mass than transformers. Subsequently, in [70], a hybrid AC/DC distribution system is presented which employs static synchronous compensators (STATCOM) as interface between the AC and DC areas. In this way, it proposes a double ring structure with generation sources located in both subsystems. The bulk generation will be connected to the AC while the secondary and back-up will be on the DC side. Due to the STATCOM inclusion, cross-strapping is allowed for additional reliability. Additionally, the double ring structure allows for isolation of specific segments for fault clearing without causing a general blackout. A brief comparison of AC- vs. DC-coupled networks is presented in Table 2; the selected hybrid configuration is aimed at combining the advantages and minimizing the disadvantages.

There has not been much discussion about general power system specifications for a Martian outpost like voltage levels, buried vs. over-head-lines, grounding methods, cathodic shielding, protection selection, and coordination. However, a few statements can be included; in [9], a 500 V effective voltage limit is presented due to Paschen breakdown associated with Mars' atmospheric pressure. In short, conductors at an electrical potential greater than 500 V are expected experience unacceptably large power drains due to atmospheric discharges. Then, [27] proposes AC and DC generation at 400 V and 120 V, respectively, with transmission at 2 kV AC using transformers. The distribution will again be at 400 V AC, no DC bus is expected, since the immediate rectification of the waveforms after generation is envisioned. Lastly, in [70], 102 and 50 kV AC and DC, respectively, are proposed for transmission.

Due to the evolving nature of the envisioned colony, in this work, a DC-coupled PEMS is selected for the first stages of the colony. Then, after the arrival of the second manned crew, when additional generation is needed, the inclusion of an AC grid is assumed due to the connection of bulk generation such as a nuclear fission reactor. Thus, a hybrid AC/DC grid similar to the one proposed in [70] is expected for most life of the colony since it presents advantages in energy efficiency, safety, and reliability. Technicalities regarding the electrical installations in Mars such as specific voltage levels, frequency, shielding, and protection schemes are purposely left out for a future revision, given the focus of this paper on PEMS and the clear research gap regarding safety limits of such parameters. A future publication will in fact focus on addressing the problem of electrical safety practices on installations in both the Moon and Mars.

5. Topology of the Hybrid System

The principles followed in the design of the HyPS for a near-future Mars colony are stability, reliability, service continuity, storage, protection, fault tolerance, emergency power, weight, safety, technology maturity, maintenance requirement, cost, environmental immunity, and power quality [67]. The layout of the HyPS covers the needs defined in Table 1, and it is presented according to the selected energy sources and coupling for each colony growing stage:

Stage 0: PV plus storage as a combination of regenerative fuel cells and batteries is selected for this stage, as it is the most reliable and tested configuration with a decent payload. In addition, its deployment is simple which facilitates to do it using solely robots. After the deployment of the HyPS, the energy needs are focused on the ISRU and minor robotic activities as reconnaissance. Briefly, the selected topology is 380 kW of PVs, 125 kW of batteries, and 125 of regenerative fuel cells. This accounts solely for the dedicated power system components; thus, storage directly powering rovers or robots is not included in these values. The overinstallation accounts for different safety margins, for example, ensuring sufficient generation from PVs despite the effect of dust accumulation [51]

Stage 1: the first crew brings additional equipment to increase the size of the already existing HyPS upon arrival by adding 420, 125, and 125 kW to PV, battery, and fuel cell installations, respectively. Some authors declare the use of nuclear reactors as mandatory at this stage. However, given the recent developments of microgrid technology, this can be avoided by ensuring a 50% of storage and doubling the installed power over the nominal requirements. Even though fuel cells are less weight-efficient than batteries, they are included due to their higher maturity in space applications. From the HyPS perspective, the search for geothermal potential must be prioritised in this stage, as this would allow to

reduce the deployment of nuclear reactors in subsequent stages. Shortly before the arrival of the following crew, a suitable location for a nuclear reactor is prepared. As presented in [27], a buried enclosure of 2 meters allows to shield the whole colony from radiation, with a minimal, nearly nonexistent, exclusion zone

Stage 2: the first task of the second crew is to reinforce the HyPS. This is done by adding 200, 1000, 400, and 100 kW of PV, nuclear, batteries, and fuel cells, respectively. The objective is to provide a constant base load with the reactor while still carrying most of the activities on PV plus storage. This is done in order to extend the operational life of the nuclear unit. As aforementioned, the reactor is expected to operate in high-frequency AC. Therefore, in this stage, the coupling of the colony becomes hybrid AC/DC, as explained in Section 4. As the colony gains maturity, there should be sufficient meteorological and geological data to consider the inclusion of wind and/or geothermal generators. If possible, the first prototypes are added before the end of this stage. Nevertheless, as this stage is expected to last a minimum of 3 years, that is around twice the time since it started. During this time additional 1500, 800, and 100 kW of PV, battery, and fuel cells are installed, respectively.

Stage 3: at the beginning of this stage, the nuclear reactor and part of the storage reach their design's life limit. Thus, it is necessary to perform several substitutions. In addition, 1000 and 100 kW of nuclear/geothermal and fuel cells, respectively, are installed. In this stage, the first temporary settlements are deployed. Therefore, the system's modularity must allow to disconnect small parts of the HyPS in order to transport them to new locations back and forward. Given the long duration of this stage, parts of the HyPS must be replaced several times due to their relatively short life expediencies, although it falls within reason to think that it will be possible to extend this parameter as more is learnt from the field deployment. In any case, by the end of this stage, it is necessary to install 1500, 1000, and 600 kW of PV, nuclear/-geothermal, and batteries, respectively, in order to accommodate the increasing population

Stage 4: if the whole mission is carried out in the shortest deadlines, this stage will start more than 13 years after the robot-based landing. Thus, it is very tough to envision, how the architecture of the colony will look by then. Therefore, the same growth rate as for the previous stages is assumed. This implies the installation of 1000 kW of nuclear/geothermal at the beginning. Then, it is also necessary to replace most of the already existing HyPS due to reaching the end-of-life. As the population keeps growing, it will be necessary to add 3000, 2000, and 500 kW of PVs, nuclear/geothermal, and batteries

The topology of the HyPS is summarised in Table 3. Note how from stage 2 there are two numbers in some cells; this indicates the initial and final installed capacity for a given stage. That notation accounts for the population growth over time. Also, N/G stands for either nuclear or geothermal, although geothermal could only be included during the last periods of stage 2 onward. As aforementioned, wind power and CSP are considered not ready for extraterrestrial applications due to its low technology readiness level. Thus, they cannot be included as of this moment, although it will be important to reassess it in the future along with ORC that can be used as part of a CSP or as a heat recovery method. On the other hand, there are two considerations that must be stated about the sizing criteria. First, given the current redundancy levels required in critical systems, it is necessary to size the system for twice the existing load; although from stage 3 onward, this requirement is relaxed. The duplicity is certainly needed when the system is small, but results less relevant once the settlement is more established, and there is more knowledge about the equipment's behaviour. In the same way, storage represents around 50% of the installed capacity until stage 3; then, it is again relaxed. This is due to recent advances in microgrids and isolated power systems, which allow to reduce this requirement. Also, since there is an increasing installation of sources that do not depend on weather (nuclear and geothermal), the role of storage moves from power smothering towards grid support, thus requiring less available power and energy.

Table 3: Installed capacity of the energy mix in MW.

Stage	PV	N/G	Battery	Fuel cell	Total	
					Gen	Storage
0	0.38	0	0.125	0.125	0.38	0.25
1	0.8	0	0.25	0.25	0.8	0.5
2	1-2.5	1	0.6-1.4	0.3–0.4	2-3.5	1-1.9
3	2.5-4	2-3	1.4-2	0.5	4.5-7	2-2.6
4	4-7	4-6	2-2.5	0.5	8-13	2.6-3.1

This smooth relaxation can also be observed in Figure 4, where the colony's HyPS evolution is presented. Then, Figure 5 presents the conceptual configuration of an advanced colony with the classic microgrid layout. AC and DC coupling is marked with black and blue, respectively; interconnections of both systems are marked in their respective colours. Note how part of the loads are expected to operate with DC while others (large motors) are expected with AC. On the other hand, Figure 6 presents a more detailed description of the overall distribution system. This picture also illustrates the growing stages from the electrical network perspective. Note that the number of units drawn on each stage corresponds to the size of their first inclusion in the HyPS, that is, each PV block corresponds to approximately 380 kW while for nuclear is of 1 MW, as stated in Table 3. Again on Figure 6, there are two different voltage levels in DC, two distribution rings, and power electronic converters that couple them. This allows to operate different loads more efficiently as the conversion is performed as a bulk instead of on each individual component. In that sense, low DC (light blue) feeds lighting, consumer electronics (computers, screens, etc.) and other equipment with low power requirements. Then, high DC (purple) not only feeds larger consumption, like medium-size motors, heaters, and chargers but also couples all the generators and energy storage systems. Lastly, the fission reactors and largest loads of the colony are powered with a single level high-frequency AC (around 400 Hz) in order to reduce the weight payload of the

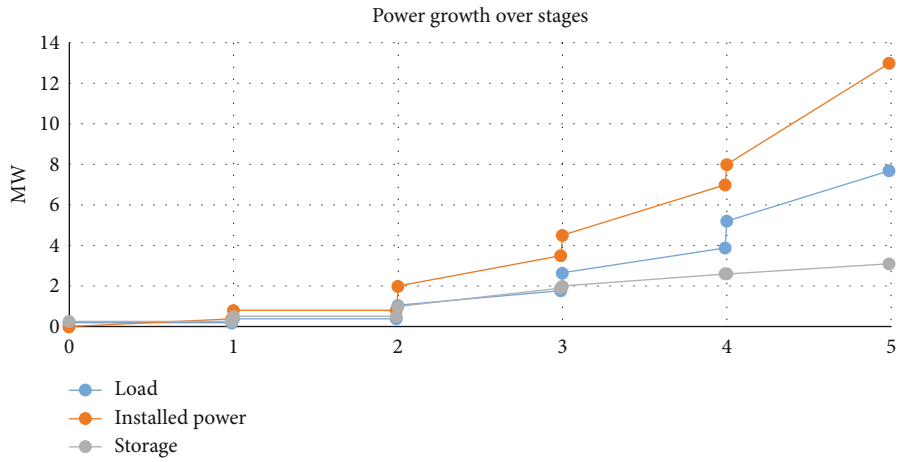

Figure 4: Evolution of the HyPS's installed power capacity.

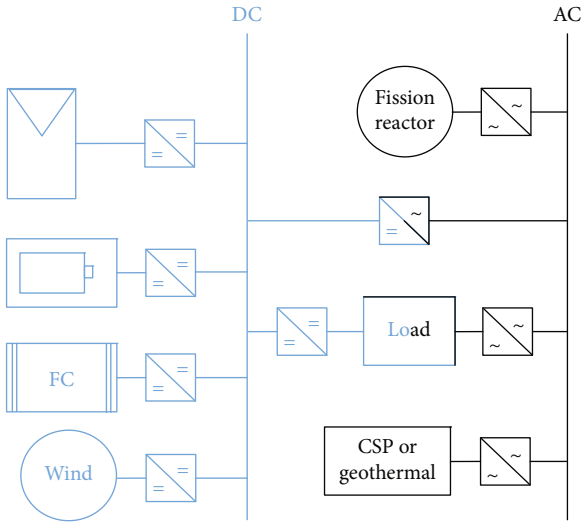

Figure 5: Conceptual configuration for the HyPS.

mission. It should also be noted how this configuration avoids the use of transformers which are not weight efficient from the perspective of interplanetary travel. If AC/AC adaptations were needed, cycloconverters can be used for both voltage and frequency. Lastly, the ISRU unit is initially part of the high DC system; however, as the colony grows and the initial ISRU reaches end of life, its substitute is likely to be powered in AC as this again improves the overall weight payload.

6. Proposal Evaluation

In this section, a number of scenarios are evaluated in order to evaluate the proposed HyPS. The focus is on stages 0, 1, and 2 as these are the most challenging ones due to the novelty of the installation. First, the scenarios are defined, then the simulations are performed, and lastly, the results are discussed. In all of them, the PEMS satisfies the constant critical load, then battery charging, subsequently the ISRU or science-related load, and finally, the rest of the demand. The battery is prioritised over the regular loads since its function is to keep critical functions alive.

6.1. Scenario Definition. The three scenarios (A, B, and C) is aimed at analyzing the regular operation, reliability against nearly catastrophic contingencies and operational flexibility, respectively.

Scenario A: this scenario takes place during stage 0. The performance of the HyPS is evaluated by checking whether the generated energy is sufficient to fulfill the mission requirements, that is, allow the ISRU units to produce enough oxygen, water, and fuel for a return flight to Earth. This requirement is established in case there is a fatal error in the manned ship as to require an emergency return. This implies a total of 26 or 80 kWh/day during 300 sol for 24- and 8-hour operations, respectively, depending whether the ISRU is continuously supplied or it has to deal with day-night start/stop cycles [7]. This is tested considering a generation loss of 0.2%/sol which is the maximum historically measured without applying any cleaning or antidust procedures [24]. Also, a value of 36% of the equivalent solar radiation is assumed [46].

Scenario B: it takes place during stage 1. This scenario evaluates whether the manned mission will be able to prosper if the robotic mission suffers a catastrophic collapse. It is assumed that the crew it is already on route when the failure occurs and that no equipment can be retrieved from the robotic mission. Thus, the objective would be to establish the colony without the robot help and hold the position until the next manned mission arrives. This is done by exploring the mission's energy profile assuming an activity reduction. In this case, the energy needs of the colony are divided into survival, science, and operation, whose priority follows the same order. Survival refers to the minimum necessary to keep the crew alive, along with minor critical loads. Science implies that certain experiments can be conducted, while operation relates mostly to exploration and mining activities

Scenario C: it takes place during stage 2. Here, the performance of the HyPS is evaluated during a 24-hour cycle, thus

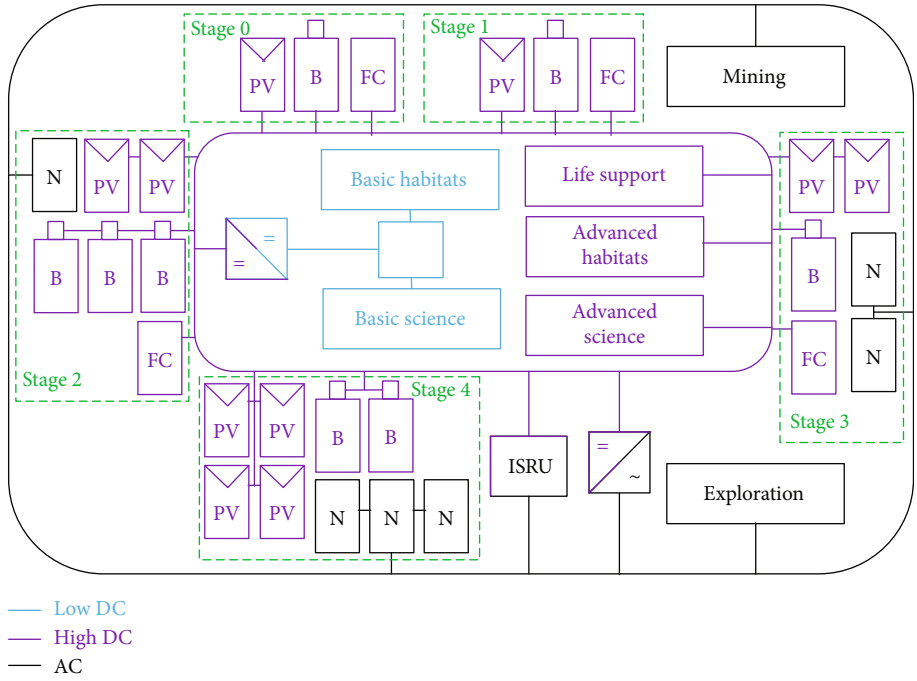

Figure 6: Transformer-free topology for the HyPS.

Table 4: Summary of scenario's targets.

Sc	St	Loads (MWh/sol) Critical	ISRU/science	Other
A	0	0.288	0.12-1.2	0.07-0.72
B	1	0.48	0.06-0.62	0.4-4
C	2	1.3	0.4-4.4	1.2-12.2

exploring the differences between generation/consumption profiles. A regular day and a sand storm day are chosen for the comparison.

A summary of each scenario's targets is presented in Table 4. It should be noted how the last two columns present a range of minimum and maximum loads as they are used to balance the system.

6.2. Results

6.2.1. Scenario A. Due to the large security margins required in space applications, the proposed architecture excels at satisfying the targets. The simulation is run for 300 sol. In Figure 7(a), the production decay of the PV plant is presented, where it is clear how generation capacity reduces to almost half. Then, in Figure 7(b), the SOC evolution for the first 4 days is presented. It follows a cyclic pattern until the ISRU is satisfied; since then, minimum daily SOC increases 5%. On the other hand, Figure 7 presents the ISRU's cumulative demand evolution, where it can be seen how the objective production is reached by day 16. Lastly, Figure 7(d) presents the load distribution during the mission as a daily average. The critical loads are fully satisfied continuously during the scenario. Then, ISRU is covered as fast as possible, which allows the rest of the loads to start operating once it is done.

As an example, Figure 8 presents the power supplied to the three types of loads along with the PV production and the storage's behaviour. Note how the critical loads are always covered, while the ISRU modifies its behaviour according to the available power without ever shutting down. It should also be noted how negative and positive values for the storage's behaviour correspond to periods where the devices are charging and discharging, respectively. The period shown in Figure 8 corresponds to days 15 to 17; thus, the energy shift from ISRU to other loads can be easily spotted.

6.2.2. Scenario B. The simulation ran for 356 sol, which roughly corresponds to 365 Earth days. The PVs are not considered to degrade during this period as the colonist would be able to properly take care of the dust cleaning tasks. A glimpse of the simulation's results is presented in Figures 9(a) and 9(b) which show the three first days of operation. In this scenario, the storage system results insufficient to satisfy the critical loads over night at their nominal rate. Therefore, a rescheduling must be done in order to accommodate part of that load during daylight hours. This is reasonable for thermal loads (heating) due to their high inertia; however, shifting them will almost surely cause a decrease in comfort. In addition, both science and other loads need to be shut down during the nights and be used carefully during the day as to not overload the system. The highest priority is set towards recharging the battery as it is the critical system that will keep alive the colony during the night. If additional generation or storage degradation is included, there would be a need to further curtail the loads. On the

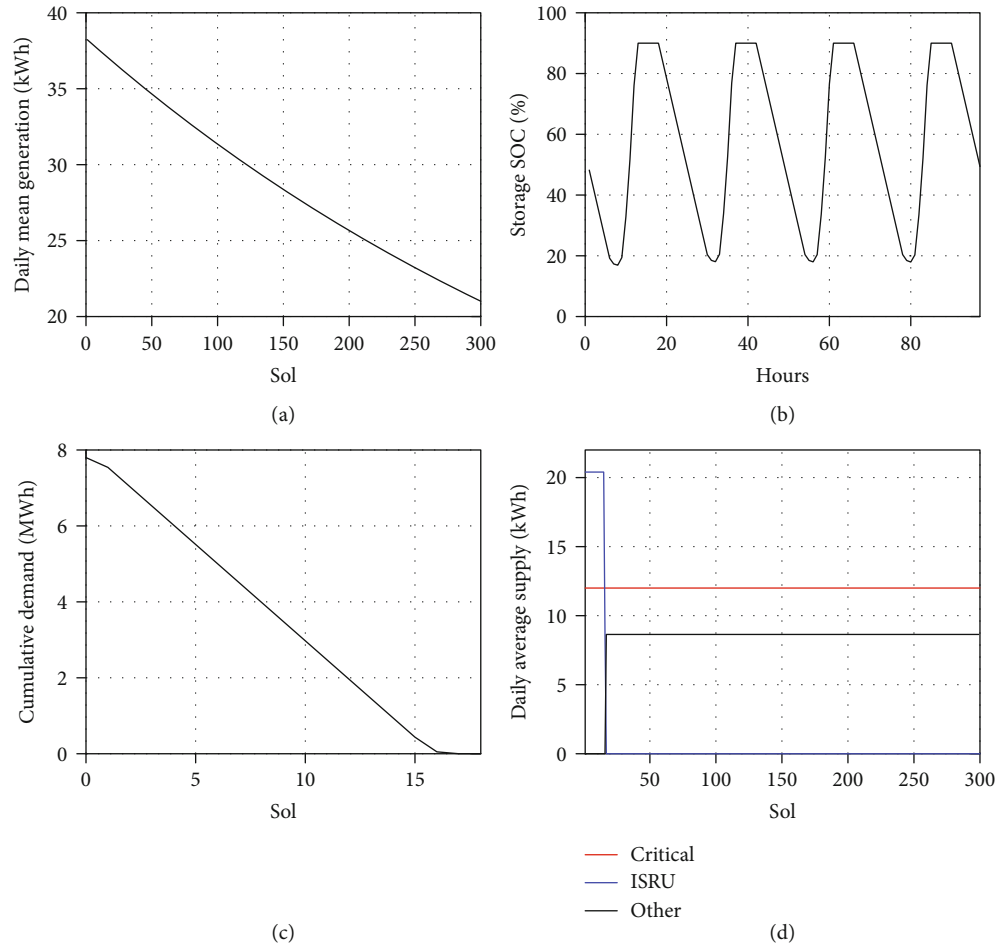

Figure 7: Sc A: (a) daily mean PV generation. (b) Example of SOC evolution for the first 3 Sol. (c) ISRU's cumulative demand evolution. (d) Distribution of the daily average supply.

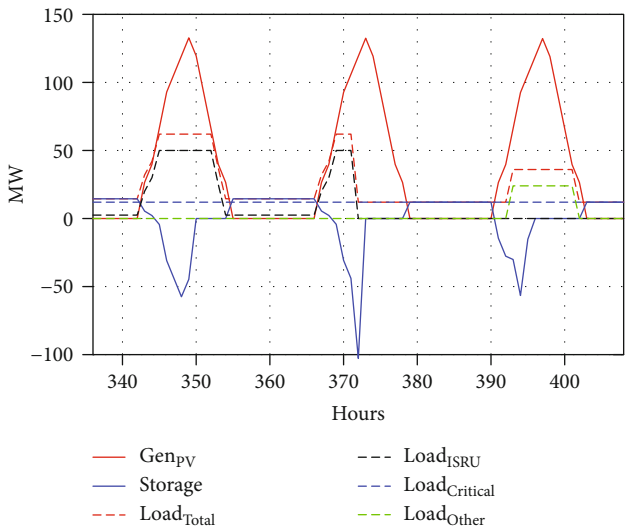

Figure 8: Sc A: generation and load profile for three days.

other hand, the performance of the storage system is consistent during the whole period, whose first three days are presented in Figure 9(b).

6.2.3. Scenario C. The simulation ran in two sets of 300 sol. The generation and consumption profiles are of the three first days are presented in Figure 10 along with the SOC of the storage systems. There, two sets are compared; Figure 10(a) presents a regular day in the fully functional colony, while Figure 10(b) presents the behaviour during a sandstorm. This was undertaken by assuming a PV generation reduction of 50%. In Figure 10(a), it can be seen how all the loads are satisfied without any problem or major control applications applied on it with the exception of charging the battery during day time. This permits the nuclear reactor to run smoothly at low powers which potentially enlarges its life expectancy. On the other hand, in Figure 10(b), it is clear how the loads have been widely curtailed. This allows for the nuclear unit not to be used as regulation, still operating steadily at low requirements. In this case, both science and other loads are shut down overnight in order to protect the critical operating parts of the colony. Lastly in Figure 10(c), the SOC of the storage systems can be observed. It is clear how during normal operation, the SOC follows a cycle from maximum to minimum. While during sandstorms, the storage stays at a relatively high SOC; this is done in order to enlarge the operational safety margins.

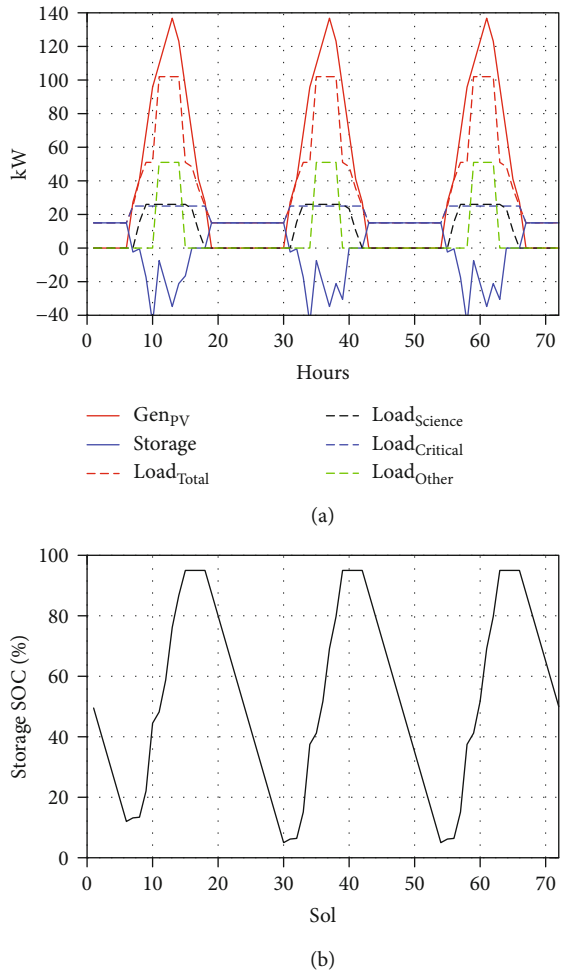

Figure 9: Sc B: three days of (a) storage system's SOC profile. (b) SOC, generation, and consumption profiles.

6.3. Discussion. The presented scenarios cover a range of situations that can potentially harm the mission's success. However, it is clear that the proposed configuration is sufficient to ensure the survivability of the crew while also allowing a variable amount of scientific experiments to take place. The main goal of any proposed HyPS is to ensure crew safety and return capacity at least until another crew is able to rescue them. In scenario A, it is clear that there exists a huge margin for error as the ISRU generates enough resources for the crew in just 16 sols, while it is expected to have 300. The rest of the time can be employed on site preparation and initial robotic exploration. Then, scenario B proofs how, even despite a catastrophic failure of the robotic mission (e.g., an atmospheric disintegration or crash), the crew will be self-sufficient. Their scientific and exploratory capabilities will be affected but not eliminated. Lastly, scenario C presents the flexibility of the discussed topology as it allows to keep the nuclear bulk generation in a very steady and constant operation, while balancing the grid with the battery in normal operation, whereas during sandstorms, load shedding allows to similarly adapt without shifting the nuclear reactor's operation. Lastly, it should also be noted how the SOC of the storage systems

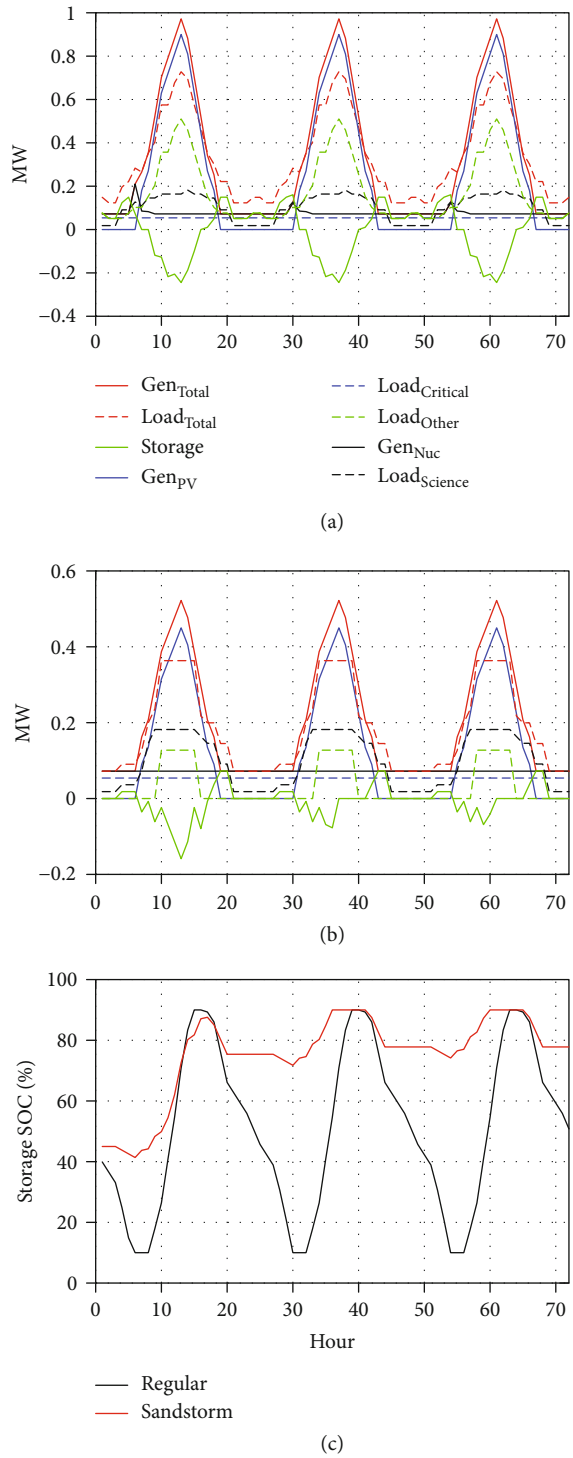

Figure 10: Sc C: generation and consumption profiles for three days. (a) Regular. (b) Sandstorm. (c) Storage system's SOC.

is always kept between 10 and 90%; this is a common practice applied to limit the degradation [71].

A scenario evaluation summary is presented in Table 5. There is one limitation to this assessment as there is no data available regarding the different daily and hourly energy/-power needs of the colony. During periods in which partial load shedding is applied, it is not possible to assess exactly

Table 5: Scenario evaluation summary.

Sc	St	Load covered			Evaluation
		Critical	ISRU/science	Other	
A	0	Fully	Fully	Fully	Very satisfactory
B	1	Barely	Some	Some	Sufficient
C	2	Fully	Fully	Some	Satisfactory

how much of the energy needs are covered. This of course limits the possibility of comparing different scenarios in such terms. It seems reasonable to assume that the largest loads in the system (e.g., mining activities) will only be operated during daytime, and thus, the hourly demands defined by NASA will correspond to peak hours and not averages to be smooth out with different simultaneity coefficients.

Indeed, the ultimate objective is to conduct various scientific experiments, but the economical burden that a mission of this magnitude implies does not leave room for any mistake. Specially, since in space-related applications, failures lead to huge budgetary restrictions that further hinder the capability of continuing space exploration [72]. Lastly, it is worth mentioning how this work could be continued with a dispatch optimization in the shape of a unit commitment problem that could take into account ageing of components, different efficiencies, etc. However, this falls out of the scope of this work.

7. Conclusions

The conquest of Mars has been envisioned for centuries if not more; however, after the Moon landing, interest was fast and steadily lost in making humankind an interplanetary species. With the ultimate aim of restarting scientific dialogue in pursue of our evolutionary imperative, this work proposes an evolvable HyPS for a permanent near-future colony on Mars. In order to do so, a thorough review of all relevant documents published since 1953 until 2019 about establishing manned outposts outside low Earth orbit has been reviewed and challenged. It has been shown how some of the axiomatic assumptions taken during decades had to be discarded several times due to new discoveries and how some other possibilities had never been considered before. Even though it is indeed still unclear the actual architecture of the colony, it is already possible to state the general configuration and growing stages that must suffice in order to become a permanent settlement. Then, its power system will foreseeable be hybrid due not only to the triple level of redundancy needed for life-critical functions but also to the scientific relevance of testing as many different possibilities as possible in that new frontier represented by the red planet.

The proposed final topology evolves from a combination of PV and storage to a complex HyPS including multitude of sources like nuclear or geothermal depending on availability. In addition, other sources such as wind or CSP should also be explored. On the other hand, the HyPS will start fully DC-coupled further evolving into a redundant AC/DC system. Its design is focused on reliability and modularity, while the target is to ensure crew survivability and using available technology with TRL 6 or higher. In addition, the use of transformers has been avoided which improves the weight payload of the mission. On the other hand, disadvantages are the use of nuclear, which might be minimized depending on geothermal resource availability and the lack of an economical assessment, as there could be additional price-related constraints.

Once proven feasible, the proposed HyPS must be challenged and validated trough different iterations in due time prior to the mission planning. This work has just started; computer simulations will be presented in future publications aiming to optimally size energy sources and storage by using the latest developments in micro/mini-grids. Additionally, the proper definition of an energy management system is envisioned for this HyPS. Other potential issues caused by the Martian environment must be acknowledged as the grounding system, cathodic shielding, or protection selection and selectivity. Ultimately, pushing and finding the limits of what is possible and what is not the responsibility of the scientific and engineering community. When Mars is reached, it will be the result of the immense effort of thousands of people worldwide, sharing a fundamental appreciation for international collaboration and open-access research.

Data Availability

The simple models used to evaluate the HyPS topology can be found in [73]. Future work-related isolated hybrid power systems such as the aforementioned optimal dispatch will also be published there.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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