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How do Habitability Factors Impact the Economic Feasibility of A Sustainable Human Colony on Mars?

Swayam Sampoorna

Student, Aditya Birla World Academy

Abstract

The idea of colonising Mars has moved from science fiction to serious scientific discussion in the 21st century. The shortage of resources on Earth in recent decades has led to a bold new concept: colonising other planets. If humanitarian and environmental efforts do not help stabilise Earth, a Plan 'B' is needed for the survival of humanity. This is not our current reality, but it is approaching fast, and we need to understand this issue better. While transportation costs and technological progress often dominate talks on feasibility, the importance of habitability criteria has received less focus. This paper looks at how survival needs like life support systems, environmental protection, and resource availability impact the economic feasibility of creating a sustainable human colony on Mars.

Keywords: Mars, colonisation, human settlement, inter-planetary exploration, civilisation

1. INTRODUCTION

1.1 The Need for Inter-planetary Colonisation

Planet Earth has been facing a major environmental crisis over the past few decades. While efforts are being made to salvage what is left, it is advisable to have a contingency plan and a back-up in case of destruction of the planet due to man-made or natural disasters. Climate change, resource depletion, loss of biodiversity and habitats, and the exponential growth in human population are putting a lot of strain on the planet and have prompted discussions about humanity's long-term survival.

According to recent environmental assessments, Earth faces major challenges: rising global temperatures, increasing sea levels, diminishing freshwater reserves, and declining usable land. While protecting and keeping the planet healthy is the primary objective, the concept of establishing human presence has evolved from being a fictional dream to a possible reality.

With the advent of the 21st century, the idea of colonising Mars has become a topic of interest, especially since it seems to be within reach. Rapid advancements in aerospace technology, declining launch costs, and involvement of private organisations along with national space agencies have made interplanetary colonisation achievable and increasingly feasible. SpaceX's development of reusable rocket systems, NASA's sustained Mars exploration program, and growing international interest signal a shift from purely exploratory missions to settlement-oriented planning.

1.2 The Research Gap

Many of the current studies focus on the transportation and financial aspects of colonising Mars; however, very little focus is given to the habitability factors on Mars which can have a major impact on how a viable colony may be built. Much of the current research and public debate remains focused on the challenges of reaching Mars. Transportation costs, rocket technology, and the engineering of spaceflight dominate discussions of feasibility. These concerns are central to the problem of colonisation, but do not give a complete view of what building a long-term human settlement might need.

The true measure of feasibility extends beyond the act of arrival to the capacity for survival and sustainability on the Martian surface. Previous economic analyses have often treated habitable infrastructure as a fixed cost item without examining how different construction and resource utilisation strategies might dramatically alter feasibility calculations. The interdependencies between habitability factors and their collective impact on economic viability remain underexplored in existing literature.

1.3 Habitability Factors and Economic Implications

Habitability factors that can affect the feasibility of colonising Mars include: life-support systems, energy generation, production of food, breathable air, and water, protection against ultraviolet and cosmic radiations, and utilisation of local resources. Without accounting for these factors while analysing the economic feasibility of colonising Mars, economic assessments may be incomplete or misleading.

Mars poses extreme environmental challenges that do not exist as much on Earth and require separate requirements for infrastructure and associated costs. The planet has a very thin atmosphere that gives almost no protection from space radiation and minimal breathable air. Surface temperatures fluctuate dramatically, averaging around 193 kelvin. Dust storms can engulf the whole planet, which can pose a threat to solar powered systems and mechanical equipment. Water exists primarily in solid form, and it requires extraction and processing infrastructure.

1.4 Research Objectives

This paper examines how habitability factors influence the economic feasibility of building a sustainable human colony on Mars and how we can overcome them. Specifically, this research aims to:

1. Quantify the cost implications of seven critical habitability factors across different mission scales
2. Compare the economic efficiency of Earth-based versus Mars-based construction approaches
3. Identify which habitability factors offer the greatest cost reduction potential through local resource utilisation
4. Assess the overall economic viability of sustainable Mars colonisation given current technological capabilities and projected advancements

1.5 Significance of the study

This analysis contributes to the growing body of literature on Mars colonisation by providing an integrated cost-habitability framework that accounts for both technological requirements and construction strategy alternatives. By examining how in-situ resource utilisation and local manufacturing affect the economics of each habitability factor, this study offers actionable insights for mission planners and policy makers. The findings have implications for technology development priorities, mission architecture selection, and investment decisions in the emerging space economy.

2. Literature Review

2.1 Historical Context and Evolution of Mars Exploration

Mars exploration began in the 1960s with Soviet and American flyby missions, but systematic studies on Mars began when NASA's Viking landed on its surface (Masson, 2005). These missions showed a cold, dry world with a thin carbon dioxide atmosphere and evidence of the existence of ancient water flows. The 1990s brought the Mars Pathfinder and its Sojourner rover, which established remote and mobile surface exploration capabilities. The 21st century has witnessed an intensification of Mars science, with NASA's Spirit, Opportunity, Curiosity, and Perseverance rovers conducting increasingly sophisticated investigations of Martian geology, climate, and potential habitability.

These missions have progressively expanded our knowledge and understanding on Mars as a potential destination for human occupation. The confirmation of subsurface water ice, identification of mineral resources, and characterisation of atmospheric composition have transformed Mars from an object of pure scientific curiosity to a feasible colonisation target. Recent missions explicitly display technological demonstrations of utilising in-situ resources, such as MOXIE (Mars Oxygen ISRU Experiment) aboard the Martian rover Perseverance, which successfully produced oxygen from Martian atmospheric carbon dioxide (NASA, 2023).

2.2 Environmental and Habitability Challenges

Much of the literature agrees that building a human settlement on Mars comes with significant survival challenges. According to MB (2017), the environmental conditions on Mars, such as temperature and atmospheric pressure, are closer to that of Earth compared to any other planet or moon; however, the surface is inhospitable to humans due to lack of oxygen content in the atmosphere. Neukart et al. (2024) state that Mars's atmosphere consists primarily of carbon dioxide and provides minimal protection against cosmic radiation, and that Mars has the gravitational force 38% of Earth. However, it also emphasises that the Martian environment has extreme fluctuating temperatures and reduced atmospheric pressure which contradicts the earlier literature that claims that these factors are similar between the two planets.

2.3 Structural and Habitat Design Solutions

Structural studies by Soureshjani et al. (2023) propose in-situ concrete and shape-optimised habitats as cost-effective alternatives to expensive imports from Earth, potentially reducing construction costs by over 50%. Researchers have investigated "Marscrete" formulations that could be manufactured from Martian regolith using minimal binder materials brought from Earth or synthesised locally. Additive manufacturing technologies, including large-scale 3D printing, offer potential for constructing habitat structures directly from local materials.

Habitat designs span a large range of possibilities. Some concepts use inflatable models like those already tested on the International Space Station (ISS), while others use rigid structures buried beneath layers of Martian soil for protection. Going underground provides a natural shield from radiation and dust-storms, and keeps temperature levels regulated, but it does require heavy machinery and infrastructure. Many practical solutions fall in the mid range between the two designs which use pressurised modules covered with piled regolith to balance protection against construction difficulty.

Maintaining the pressure inside the habitat needs careful designing and structural integrity. Cylinders and spheres handle pressure stress most efficiently, needing less material for a given volume. Rectangular rooms waste some structural mass, but make better use of interior space. There's also a fundamental trade-off in layout: multiple small modules connected by airlocks provide safety redundancy if one loses pressure, but this approach means more walls, more joints, and more complexity overall.

2.4 Resource Utilisation and Economic Viability

Classic advocates like Robert Zubrin argue that Mars is uniquely positioned for colonisation as it possesses almost all the raw materials necessary to support life, unlike any other known body. He highlights its abundance of carbon, nitrogen, hydrogen, and ice, which could support both human survival and agriculture.

His economic vision positions Mars as a centre of innovation and a hub for solar system resource extraction rather than as a source of exportable commodities. He suggests that a Mars colony with a shortage of labour would drive technological innovation and more dependence on automation, with new technologies and intellectual property licensed back to Earth serving as a major economic return.

2.5 Technology Development and In-Situ Resource Utilisation

The development of in-situ resource utilisation technologies represents a critical pathway to economic viability. ISRU can accomplish a range of processes including atmospheric processing to extract oxygen and produce propellant, water extraction from ice or hydrated materials, and manufacturing building materials from regolith. NASA's technology development roadmaps identify ISRU as a high-priority area, with demonstrations like MOXIE providing proof-of-concept for Mars applications.

Life support systems have evolved considerably over the past decades through space station operations. Although it needs frequent consumable resupply and extensive maintenance, the Environmental Control and Life Support System of the International Space Station exhibits closed-loop water recycling with an efficiency of about 90%. Mars applications would need higher reliability and closure ratios to reduce resupply requirements. Advanced systems incorporating bioregenerative components, such as plant growth for food and atmosphere revitalisation, could improve closure while providing psychological benefits, though they add complexity and resource requirements.

Energy systems for Mars can be based on solar and nuclear options. Solar power offers simplicity and proven technology but suffers from reduced irradiance because of Mars's greater distance from the Sun, atmospheric dust absorption, and complete unavailability during dust storms. Nuclear fission reactors provide consistent baseload power independent of environmental conditions but carry higher developmental costs, regulatory challenges, and public acceptance issues.

3. Methodology

3.1 Research Design and Data Collection

This study takes a qualitative and comparative approach. It uses data from peer-reviewed scientific literature, NASA technical reports, and cost projections from private and government space programs. The analysis looks at the connection between habitability factors and its economic impact.

By comparing Earth-dependent models, which rely on imports for resources, to self-sufficient models that use resources existing on Mars, the study assesses the potential for long-term cost reduction. The analytical framework examines seven important areas: life support, which includes atmospheric pressure and temperature; radiation protection; dust protection; food systems; water systems; energy generation; and in-situ resource utilisation. It also estimates how these areas affect the total mission cost.

1. Temperature control: Includes heat recovery from equipment, thermal control fluids, active heating and cooling systems, and insulation for habitats. Mars's extreme temperatures necessitate active thermal management and strong insulation in order to maintain habitable conditions (approximately 18–24°C) against an average external surface temperature of -80°C.
2. Atmospheric Pressure Management: Includes airlocks, pressurised habitat structures, pressure monitoring and control systems, and structural reinforcements to keep Earth-normal or reduced pressure (generally between 50 and 100 kPa) in comparison to Mars' 0.6 kPa outside pressure. Cost and structural mass are greatly influenced by pressure vessel design.
3. Water and Life support systems: Includes Environmental Control and Life Support Systems (ECLSS) for waste processing, water recycling, trace contaminant removal, and atmosphere revitalisation. includes ISRU water purification systems and water extraction from Martian soil or ice. The necessary

resupply mass is directly impacted by the effectiveness of water recycling.

4. Food Production: Includes growth chambers, LED lighting, nutrient delivery, crop management automation, and food processing equipment for hydroponics, aeroponics, and other controlled environment agricultural systems. Although it uses a lot of energy and infrastructure, higher closure lowers resupply.
5. Radiation protection: Includes radiation-hardened electronics, personal dosimetry, storm shelters, passive shielding (polyethylene, water, and regolith), and possibly active electromagnetic shielding ideas. Launch mass can be decreased by using local regolith, but shielding mass requirements drive significant cost.
6. Dust storm and wind mitigation: Includes protective coatings, dust filtration for suitports and airlocks, electrodynamic dust shields for solar panels, structural siting in sheltered areas, and dust removal maintenance procedures. Dust mitigation is technically difficult, but it is comparatively more affordable than other factors.
7. Energy Generation and storage: includes energy storage (batteries, regenerative fuel cells, compressed gas), power distribution, thermal management, and primary power systems (photovoltaic arrays, nuclear reactors). All other systems, especially ISRU and food production, are either enabled or limited by the availability of energy.

3.2 Cost Categories and Calculation

For each habitability factor, costs are broken down into four categories:

1. Labour: The work done by humans in the areas of design, engineering, manufacturing, testing, operations, and training. Earth labour costs are based on the wage rates of the aerospace industry in developed nations. Despite the smaller workforce and possible inefficiencies, Mars labour costs are hypothetical and assume higher productivity for on-site work with shorter communication loops and direct access to assembly locations.
2. Energy: Electrical power and thermal energy required for manufacturing, transportation, deployment, and operations. Earth energy uses terrestrial grid costs. Mars energy reflects the high cost of power generation in the Martian environment and its scarcity during initial phases.
3. Assembly: Integration, testing, quality assurance, and deployment activities. Earth assembly assumes established facilities and supply chains. Mars assembly accounts for constrained facilities, limited tooling, and need for specialised equipment to work in pressure suits or habitats.
4. Transport: Launch mass and mission delivery costs. This represents the dominant cost driver in Earth-based models. Mars-based models minimise transport by manufacturing components locally but still require transport of raw materials, specialised equipment, and items that cannot be manufactured on Mars.

Cost estimates for a starter base supporting approximately 10 people represent the initial settlement phase with minimal infrastructure. Expansion estimates for 100 people reflect scaling challenges and economies of scale.

3.3 Comparative Scenarios

1. Earth-Based Construction: All components are manufactured on Earth using terrestrial industrial capabilities, then launched to Mars. This approach leverages established manufacturing and testing facilities but incurs massive transportation costs. It represents near-term feasibility with current technology but poor long-term economics.

2. Mars-Based Construction: Minimal equipment and feedstock materials are transported from Earth, with assembly and manufacturing occurring on Mars using local resources wherever possible. This requires more capable robotics, ISRU infrastructure, and possibly pre-positioned supplies, but dramatically reduces transportation costs. It represents the pathway to long-term sustainability but requires significant upfront technology development.

3.4 Assumptions and Limitations

Assumptions:

- Technology Readiness: Most assessed technologies are assumed to reach flight readiness within 10-20 years. Some capabilities, particularly advanced ISRU and closed-loop life support, remain aspirational.
- Launch Costs: Transportation costs assume partially reusable launch systems comparable to Falcon 9/Falcon Heavy performance, with costs of $2,000-5,000 per kilogram to Mars. Fully reusable systems like Starship could reduce costs by an order of magnitude but are not yet operational.
- Scale: Analysis focuses on outpost-to-settlement scale (10-100 people). Larger populations would face different constraints and opportunities.
- Mission Duration: Assumes permanent settlement rather than short-term missions, necessitating high reliability and closure.

Limitations: The analysis excludes social, psychological, legal, and governance dimensions. Medical capabilities are addressed only briefly. Cost estimates carry high uncertainty, particularly for unprecedented technologies. Environmental data represents typical conditions but extreme events could exceed design parameters. Supply chain dependencies and failure modes require detailed analysis beyond this study's scope.

4. Results and Analysis

4.1 Martian environmental factors and parameters

The Martian environment is much harsher than that of Earth, so it poses more risk to human survival without proper survival gear. Environmental data was used to determine the physical parameters influencing habitat design and energy expenditure.

Table 1 portrays the summary of the environmental conditions on Mars which majorly affect the feasibility of building a human habitat on its surface.

Table 1					
Variable	**Units**	**Min Value**	**Max Value**	**Description**	**Mean Value**
Temperature	K	141	246	Atmospheric temperature at ~10 m above surface	193.5
Surface Pressure	Pa	82	1200	Pressure at Martian surface (higher in basins, lower on highlands)	641

Pressure (general)	Pa	82	1100	General pressure distribution map, similar to surface pressure	591
Horizontal Wind Speed	m/s	0.1	93.9	Horizontal wind speed at 10 m altitude	47
Distance from the surface of Mars to its core	km	1,500	2,100	-	1,800
Altitude above Areoid (Mars geoid)	m	-7103	19488	Elevation relative to areoid (Mars geoid)	6192.5
Orographic Height (surface altitude above areoid)	m	-7113	19478	Surface altitude above areoid (topography)	6182.5
Altitude above Local Surface	m	0	10	Altitude above local ground reference (~10 m)	5
Dust Optical Depth	-	0.017	0.54	Monthly mean dust column visible optical depth above surface	0.2785
Surface H2O Layer (non-perennial frost)	kg/m^2	0	9.3	Thin seasonal frost or surface water ice layer	4.65
Incident Solar Flux	W/m^2	0	538	Incoming solar flux on horizontal surface	269
Air Heat Capacity (Cp)	$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	670	800	Specific heat capacity of Martian air	735
Temperature RMS Day-to-Day Variation	K	0.1	17.1	Temperature day-to-day RMS variability	8.6

Surface Temperature	K	140	292	Ground temperature (surface)	216
Sun–Mars Distance	AU	1.6	1.6	Distance between Sun and Mars during this season	1.6

As seen in Table 1, the data collected (Mars Climate Database v6.1: The Web Interface, n.d.) shows that there is a huge range between the minimum and maximum value of many environmental factors that can make the construction of a base more difficult, costly, and energy inefficient.

The basic design requirements for Mars habitats are determined by these factors. With an average temperature of 193.5K and extremes as low as 141K (-132°C), habitats have to maintain temperature differentials greater than 100°C compared to the surrounding environment. For surface operations, where some conductive and convective heat transfer occurs through the thin atmosphere and ground contact, multilayer insulation systems similar to spacecraft thermal protection are necessary.

The average surface pressure of 641 Pa is equivalent to approximately 0.6% of the pressure on Earth at sea level. This is below the Armstrong limit (roughly 6,300 Pa), above which bodily fluids would vaporise and cause ebullism in exposed human tissues. As a result, all inhabitable areas need to remain pressurised, with habitats functioning as pressure vessels that can withstand the stress differential. One of the main factors influencing habitat construction costs is pressure management since the structural mass requirements roughly scale with the enclosed volume and pressure differential.

Incident solar flux averages 269 W/m^2 at the surface, compared to approximately 1000 W/m^2 at Earth's sea level. This reduced irradiance means solar panels must be 3.7 times larger to generate equivalent power, assuming same panel efficiency. Dust optical depth, which varies seasonally and during storm events, further reduces solar availability. During global dust storms, which occur roughly every three Martian years, solar irradiance can drop to less than 20% of normal levels for weeks or months.

Dust is a complex problem. Systems for active or passive dust mitigation are necessary because the electrostatically charged particles stick to surfaces. Even though they carry less kinetic force than comparable Earth winds because of the thin atmosphere, maximum wind speeds of almost 94 m/s (210 mph) can mobilise dust and abrasively damage exposed surfaces. Without routine cleaning, dust buildup on solar panels can cut efficiency by 50% or more.

Orbital radar mapping and surface observations showing subsurface ice deposits at mid-to-high latitudes and polar ice caps containing both water and carbon dioxide ice are used to confirm the availability of water. Although extraction would require a large amount of energy for heating and collection, the seasonal surface frost layers, which average 4.65 kg/m2, show that water circulates through the atmosphere. Drilling or excavation to depths of meters or more would be required for most accessible water deposits.

Mars has no liquid water on the surface and an unbreathable atmosphere consisting of 95.3% CO_2, 2.7% N_2, 1.6% Ar, and trace amounts of oxygen. All water must be extracted from ice deposits or recycled from human waste and respiration.

Mars lacks a global magnetic field and has a thin atmosphere, providing minimal protection against galactic cosmic rays and solar particle events. Surface radiation doses measured by Curiosity average approximately 233 mGy per year (or about 0.64 mGy per day), which would deliver roughly 466 mSv effective dose annually. According to the majority of space agency regulations, this is beyond an astronauts' career limits.

4.2 Cost Analysis with habitability factors

Table 2 displays the estimated cost it would take to build infrastructure for a particular environmental factor on Earth and Mars.

Table 2											
		Cost (USD) (in millions)									
Factor	Method	Earth Labour	Earth Energy	Earth Assembly	Earth Transport	Earth Total	Mars Labour	Mars Energy	Mars Assembly	Mars Transport	Mars Total
Temperature	Underground Habitats	5	10	20	150	185	20	30	50	10	110
Atmospheric Pressure	Pressurised cabins	10	15	40	200	265	25	40	60	20	145
Water	ECLS	15	20	50	250	335	30	50	80	30	190
Food	Hydroponics	10	15	30	100	155	30	40	50	20	140
UV Protection	Radiation shielding	20	30	50	300	400	40	60	100	30	230
Dust Storm	EDS + suitports	5	10	20	80	115	15	20	30	15	80
Energy	HyPS	20	40	100	400	560	50	70	120	40	280

4.2.1 Temperature Control Systems

Technical Solutions: Multiple interconnected systems are involved in temperature control. Martian regolith is used as insulation and thermal mass in underground habitats to reduce temperature fluctuations. ETFE (ethylene tetrafluoroethylene) dome structures with multi-layer insulation are used in surface habitats, which have R-values ranging from R-30 to R-50. Heat recovery systems that recover waste heat from electronics and human metabolism, radiant heating panels, HVAC (heating, ventilation, and air conditioning) equipment, and fluid thermal control loops similar to spacecraft systems are examples of active systems.

Factor	Earth-Based Construction Costs	Mars-Based Construction Costs
Labour	\$5M	\$20M
Energy	\$10M	\$30M
Assembly	\$20M	\$50M

Transport	$150M	$10M
Total	$185M	$110M

Cost Reduction: 40.5% through Mars-based approach

Key Finding: Using local resources greatly improves temperature control. With excavation costs significantly lower than launch costs for equivalent shielding mass, regolith shielding provides both thermal insulation and radiation protection. Specialised HVAC equipment that cannot be manufactured locally in the early stages is the main transport requirement that still exists.

Scaling Considerations: Systems for a 10-person starter base could be placed within 2-4 habitat modules with a combined pressurised volume of 200 to 400 m³. It would take about 2000-4000 m³ to accommodate 100 people, possibly spread across 20-40 modules or multiple larger structures. Although costs increase somewhat linearly with volume, as the population grows, economies of scale in shared thermal management infrastructure and HVAC systems result in modest per capita savings.

4.2.2 Atmospheric Pressure

Technical Solutions: Pressurised habitats use spherical or cylindrical geometries for structural efficiency and serve as pressure vessels. Composite materials, aluminium alloys, and inflatable structures with restraint layers are a few such materials. Leaks or pressure irregularities are detected by continuous pressure monitoring systems equipped with redundant sensors. Airlock compartmentalisation, emergency patches, and pressure equalisation valves are examples of backup systems. With special attention to ports, windows, and penetrations that produce stress concentrations, structural reinforcements maximise stress distribution.

Factor	Earth-Based Construction Costs	Mars-Based Construction Costs
Labour	$10M	$25M
Energy	$15M	$40M
Assembly	$40M	$60M
Transport	$200M	$20M
Total	$265M	$145M

Cost Reduction: 45.3% through Mars-based approach

Key Finding: Due to the high launch costs for pressure vessel structures, atmospheric pressure management shows one of the highest cost reduction percentages. The cost of transportation of materials from Earth to mass far exceeds the cost required to transport local materials. Assumptions regarding Mars' manufacturing capacity and quality control procedures have a significant impact on this factor.

Scaling Considerations: Because thicker walls are needed to manage stress in larger structures, pressure vessels scale superlinearly with volume. However, as airlocks and connecting components are reproduced, several smaller modules might end up costing more than a few larger structures. Moderately sized modules (100–200 m³) that strike a balance between redundancy and efficiency are probably part of the ideal architecture.

4.2.3 Protection from radiation

Technical Solutions: Radiation protection utilises a variety of methods. Water walls that provide both radiation shielding and thermal mass, regolith piled 2-3 meters thick over habitats to absorb incoming radiation, or specialised materials like polyethylene that efficiently scatter high-energy particles are all examples of passive shielding. Electronics that have been radiation-hardened are resistant to particle strikes. Crew exposure is constantly tracked by personal dosimeters. During solar particle events, protection is offered by storm shelters with additional shielding. Although they are still experimental and power-intensive, conceptual active shielding systems deflect charged particles using superconducting magnets. Radiation damage may be lessened by biological countermeasures such as antioxidant supplements, radiation protective medications like amifostine and possibly gene therapy.

Factor	Earth-Based Construction Costs	Mars-Based Construction Costs
Labour	$20M	$40M
Energy	$30M	$60M
Assembly	$50M	$100M
Transport	$300M	$30M
Total	$400M	$230M

Cost Reduction: 42.5% through Mars-based approach

Key Finding: The strongest argument for building on Mars is radiation protection. Earth-based methods are almost unaffordable due to the mass requirements for shielding, whereas local regolith is practically free once collection infrastructure is established. This element exemplifies ISRU's core benefit: use cheap, plentiful local resources instead of launching expensive, low-value goods from Earth. The main expenses that remain are labour, excavation energy, and structural reinforcements.

Scaling Considerations: As colony size increases, radiation protection scales favourably. Over time, several habitats can be protected by a single excavation system. Habitats require little additional investment in radiation protection once they are buried or shielded. Economies of scale in the use of excavation equipment are advantageous for larger colonies. For long-term occupancy, underground facilities offer better protection and thermal stability, despite requiring more excavation up front.

4.2.4 Water and life support systems

Technical solutions: Environmental Control and Life Support Systems (ECLSS) process waste, provide edible water, and keep the atmosphere breathable. Advanced filtration for the removal of trace contaminants, silica gel or zeolite beds for humidity control, rapid cycle amine systems that remove CO_2 from the cabin atmosphere, and the Urine Processing Assembly (UPA) for water recovery, which achieves up to 85–90% water reclamation, are important parts. Systems designed specifically for Mars would also include purification systems to eliminate perchlorates and other Martian pollutants, as well as ISRU water extraction from subsurface ice via drilling, heating, and condensation collection.

Factor	Earth-Based Construction Costs	Mars-Based Construction Costs

Labour	$15M	$30M
Energy	$20M	$50M
Assembly	$50M	$80M
Transport	$250M	$30M
Total	$335M	$190M

Cost Reduction: 43.3% through Mars-based approach

Key finding: Although not as much as pressure or temperature systems, ISRU significantly reduces the cost of water systems. The main drawback is that some ECLSS components still need to be imported from Earth, especially the filtration media, sensors, and control systems. Compared to water transport, water extraction infrastructure is more expensive but pays for itself more quickly. Water is essential for agriculture, drinking, radiation shielding (water walls), hygiene, and possibly propellant production, making it a crucial component of sustainability.

Scaling Considerations: With 85–90% recycling and 1-2 tonnes of water in active use, a 10-person base may lose 50–150 kg of water per month due to improper closure. The water requirements of a 100-person settlement would increase approximately linearly, but larger, more advanced systems might be able to increase recycling efficiency. The infrastructure for ISRU water extraction scales well; once operational, a single well could supply several tonnes per month.

4.2.5 Food production

Technical Solutions: On Mars, controlled environment agriculture would use vertical farming systems with stacked growing layers, hydroponics (growing in nutrient-enriched water), or aeroponics (growing in a mist environment with exposed roots). Crop management robotics, automated nutrient delivery systems, water recycling loops, LED lighting optimised for photosynthetic efficiency (mainly red and blue wavelengths), growth chambers with precise environmental control, and food processing equipment are examples of infrastructure. Bioregenerative systems, in which plants not only produce food but also aid in water recycling and atmosphere revitalisation, are incorporated into advanced concepts. Crop varieties that are suited for Martian conditions, such as tolerance to higher CO_2 concentrations or lower pressure environments, could be created through genetic engineering.

Factor	Earth-Based Construction Costs	Mars-Based Construction Costs
Labour	$10M	$30M
Energy	$15M	$40M
Assembly	$30M	$50M
Transport	$100M	$20M
Total	$155M	$140M

Cost Reduction: 9.6% through Mars-based approach

Key Finding: Since the systems are already reasonably light and the essential parts (seeds, specialised electronics, and effective LEDs) cannot be produced on Mars in the early stages, the food production industry stands to gain the least from Mars-based construction. However, because continuous resupply is economically prohibitive, food production is still necessary for long-term sustainability. Food systems must be established regardless of construction strategy, which is why the low construction cost difference should not be interpreted as diminishing the importance of food. The real savings are not from local manufacturing infrastructure, but rather from closing and attaining high crop yields.

Scaling Considerations: The scaling characteristics of food production are difficult. With specialised agricultural facilities, a 100-person settlement may reach 80–90% closure, whereas a 10-person base might reach 50% closure. Nonetheless, the needs for labour, space, and power scale approximately linearly or even superlinearly. A 100-person colony that is completely self-sufficient might require 500–1000 m² of growing space that is always in use, 100–200 kW of power for lighting alone, and energy for climate control.

4.2.6 Dust and Wind Mitigation

Technical Solutions: There are many techniques used for dust mitigation. Alternating electric fields are used by Electrodynamic Dust Shields (EDS) to lift and eliminate dust particles from surfaces, especially solar panels. Limited field testing and laboratory conditions have been used to demonstrate these systems. By using vibration-based dust removal, ultrasonic suitports minimise the amount of dust that enters habitats while providing spacesuit entry and exit points. Charged dust particles are repelled by electrostatic screens in airlocks. Solar panels and equipment are mechanically cleaned as part of routine maintenance procedures. Dust exposure is decreased by strategically placing structures behind topographic features or in lowland basins. Before entering the primary habitat areas, airlocks use a series of steps to allow dust to settle.

Factor	Earth-Based Construction Costs	Mars-Based Construction Costs
Labour	$5M	$15M
Energy	$10M	$20M
Assembly	$20M	$30M
Transport	$80M	$15M
Total	$115M	$80M

Cost Reduction: 30.4% through Mars-based approach

Key Finding: A moderate cost factor with a moderate potential for reduction is dust mitigation. Dust accumulation reduces solar panel efficiency, wears down mechanical systems, and poses health risks if it enters habitats, making dust management essential for long-term operations even though it is not the biggest cost driver. Although the technology is more developed than some other systems, it still requires maintenance over the course of the mission.

Scaling Considerations: The mitigation of dust scales fairly well. Although per-watt costs drop with scale, larger solar arrays require proportionately more EDS capacity. Airlocks and suitports scale approximately linearly with the number of habitats. However, reliance on dust-sensitive solar panels is lessened with the development of alternative power sources (nuclear reactors). In order to reduce exposure, established colonies may create covered facilities or equipment designs that are resistant to dust.

4.2.7 Energy Generation and Storage

Cost Reduction: 50% through Mars-based approach

Key Finding: Due to the high mass of power systems and the possibility of producing support infrastructure locally, energy generation exhibits the largest cost reduction percentage when built on Mars. Because it makes everything else possible—life support, food production, ISRU, communications, and mobility all depend on sufficient power—energy is also the most fundamental component of habitability. All other systems benefit from investments in energy infrastructure.

Scaling Considerations: Due to economies of scale in power generation and storage, energy scales favourably with colony size. Although an average colony of 100 people may need 500 kW to 1 MW of power, larger, more effective systems result in lower per-capita costs. Because a single, larger reactor is more affordable than several smaller ones, nuclear reactors exhibit particularly strong scaling benefits. With ISRU, energy also generates a positive feedback loop: sufficient power permits resource extraction and manufacturing, which can generate more energy infrastructure components.

4.3 Comparative Cost

Cost comparison between Earth and Mars

Figure 1

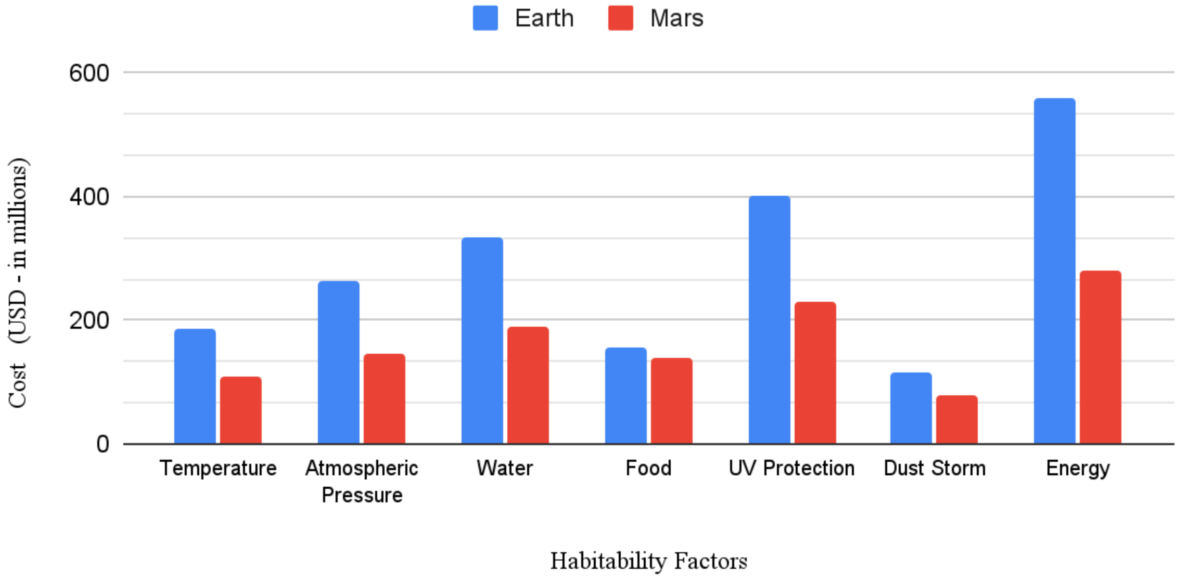

Figure 1 displays the total estimated cost comparison between building infrastructure for each factor on Earth and then transporting it to Mars versus transporting materials to Mars and then constructing the base. As shown in Figure 1 and Table 2, these numbers indicate a starting base that can sustain roughly 10 people. The significant economic benefit of ISRU and Mars-based construction is shown by the overall cost reduction of 41.7%. These estimates do not, however, account for the billions to tens of billions of dollars that would be required for program management and testing, surface mobility systems, communications infrastructure, medical facilities, or transportation infrastructure (launch systems, transfer vehicles, and landers).

4.4 Scaling and Additional costs

Factor	**Implementation examples (from your methods)**	**Estimated cost impact — Starter base (≈10 people)**	**Estimated cost impact — Expansion (≈100 people)**	**Key assumption / reason**
Temperature control	Underground habitats; domes with ETFE; multi-layer insulation; HVAC, heat recovery, fluid thermal control	\$5M – \$200M	\$50M – \$1B+	Cost dominated by habitat fabrication & mass to launch (or heavy excavation robots if buried).
Atmospheric pressure (pressurised cabins)	Pressure hulls, monitoring & backup systems, structural reinforcements	\$10M – \$300M	\$100M – \$2B	Pressure systems cost scales with habitable volume and safety redundancy requirements.
Water (ECLSS, UPA, filtration)	ECLSS modules, urine processors, dehumidifiers, trace-gas scrubbers	\$10M – \$200M	\$100M – \$1B+	NASA life-support studies show development + reliability drive cost; ECLSS lifecycle ≈ billions at program scale.
Food (hydroponics/aeroponics/vertical farms)	Vertical farms / hydroponic racks, LED lighting, nutrient systems, water recycling	\$1M – \$10M	\$10M – \$200M	Terrestrial vertical-farm CAPEX ≈ \$500–\$1,500 / m²; on Mars energy & ruggedisation raise OPEX and capex.

UV protection / radiation shielding	Regolith shielding (buried), dosage monitors, possible superconducting active shielding (concept)	$1M – $50M	$50M – $1.5B+	Regolith shielding reduces launch mass (use local material) but requires excavation equipment & structural reinforcement — costs move from launch to robots/energy.
Wind / dust storm mitigation	Electrodynamic dust shields (EDS), airlock/suitport design, terrain siting, maintenance regimes	$0.5M – $30M	$5M – $200M	Technology maturity matters — EDS demonstrated in labs; deployment & scale drive cost.
Energy generation & storage (HyPS)	Solar arrays, batteries, regenerative fuel cells, small fission (Kilopower / Fission Surface Power), CAES concepts	$20M – $800M	$200M – $3B+	Small kilowatt reactors and early FSP ROM estimates run from a few $10s–$700M for first systems; larger capacity drives substantial cost.
ISRU (oxygen/fuel/water)	MOXIE-scale oxygen production, scaled plants to make propellant, water extraction rigs	$50M – $1B	$500M – $10B+	R&D + flight-qualification of ISRU repeatedly shows high up-front cost but large long-term savings on transport.
Surface infrastructure & construction (pads, factories)	Landing pads, roads, 3D printing	$10M – $500M	$500M – $20B+	Large uncertainty — if you can

	(Marscrete), local manufacturing & spare parts			manufacture locally you save launch mass but pay for heavy equipment & power on Mars.
Human factors & medical systems	Medical bay, telemedicine infrastructure, behavioural health, training programs	\$1M – \$50M	\$10M – \$300M	Not the largest hardware cost, but life-saving redundancy and recurrent staffing are essential and add operating cost.
Communications & navigation	Mars relay satellites, surface relays, Earth-Mars ground ops	\$5M – \$200M	\$50M – \$500M	Comms is moderate capex but important for safety & science return.
Testing, R&D & program management	Hardware testing, flight demos, human factors studies, contingency reserves	\$500M – \$5B	\$5B – \$100B+	Historical programs (Apollo, ISS) show program overheads are large — often a very large fraction of total.

5. Discussion and Conclusion

5.1 Interpretation of Cost Reductions

The analysis reveals that Mars-based construction reduces habitability infrastructure costs by about 42% compared to Earth-based approaches for a starter base. The main reason for this significant decrease is the avoidance of launch expenses for low-value, high-mass materials such as thermal insulation, structural elements, and radiation shielding. The trend across factors is instructive: systems that rely on complex manufactured components that cannot be produced on Mars initially (such as food production electronics and life support sensors) reduce the least amount of money, while systems that can replace massive imported components (such as radiation shielding, pressure structures, and thermal mass) with local materials reduce the most.

Energy generation stands out as the area with the greatest potential for cost reduction at 50%. This is due to the fact that power systems are inherently large. Solar panels, batteries, and mounting structures together weigh tons. Some parts, like support structures and possibly even photovoltaic cells, could eventually be made from Martian materials. Energy plays a crucial role in supporting all other systems, making its importance extend beyond just direct cost savings. Having enough power allows for in-situ resource utilisation (ISRU), which then supports local manufacturing. This creates a positive cycle of increasing self-sufficiency.

Food production's minimal 9.6% cost reduction deserves close examination. This does not mean food is unimportant; in fact, it is essential. Food production is vital for sustainability because ongoing resupply costs are very high. Instead, the small savings in construction show that food systems need to rely on imports no matter the building method. The real economic advantage lies in achieving high agricultural productivity and closure ratios, not in producing infrastructure locally. This indicates that technology development should focus on improving crop yields, resource efficiency, and closure instead of infrastructure manufacturing.

5.2 Economic Viability

colonising Mars requires a significant investment and comes with many risks and chances of failure. However, it is necessary and can be accomplished through a series of phases over several years.

Near-term viability (10-20 years): A small outpost with 10-50 people focused on scientific research and technology demonstration seems economically possible for government programs or well-funded private projects. Costs could reach $50-200 billion over 10-15 years, which is similar to the International Space Station program when adjusted for inflation. These missions could justify their costs through scientific discoveries, technology developments, and strategic value, although not through direct economic returns from Mars itself.

Medium-term viability (20-50 years): A settlement of 100-1000 people achieving partial self-sufficiency becomes possible if launch costs drop significantly due to fully reusable vehicles and if ISRU technologies improve. Costs could reach $200 billion to $1 trillion over several decades. Making a strong economic case is harder without major technological breakthroughs that cut costs or finding export goods from Mars. Returns from the knowledge economy, such as patents, innovations, and intellectual property, could offer some economic justification, as Zubrin suggested.

The economic viability threshold is likely when Mars achieves over 90% closure in essential consumables like water, air, food, and energy, and has the ability to produce most infrastructure components locally. At this stage, the costs of the colony would shift from relying heavily on outside resources to mainly focusing on internal operations and maintenance. Our analysis indicates that this shift could happen with 100-500 people if ISRU technologies develop as expected, though there is still significant uncertainty.

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