Powering the Final Frontier: The future of sustainable Space Energy

by

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Abstract

Space exploration stands as a universal endeavor designed to unlock the doors to crucial knowledge hidden in the cosmos, and as humanity continues to explore the secrets of the universe for its benefit, the establishment of sustainable energy systems is a prerequisite for maintaining the regular operation of a space base. After Apollo 11's successful landing on the moon in 1969, mankind experienced significant advancement in technology, from computers transformed into microchips to communication networks and satellite systems that support global broadcasting and real-time connectivity. Research and innovation continue in photovoltaic energy, nuclear energy, and fuel cells, each advancing toward space applications that can supply sufficient energy security for long-term missions.

This article examines solar power, nuclear power, and fuel cells as the primary components of a comprehensive space energy system, analyzes their advantages and limitations, and demonstrates how their integration into the Trinary Energy Model can establish a solid and sustainable framework for future space infrastructures. The article also discusses how these systems interact and how their combined operation supports extended human presence and continuous activity in remote and extraterrestrial environments.

Introduction: The Energy Question Beyond Earth.

Humans on the moon is a dream that seemed far-fetched a hundred years ago. Who would have imagined that man would break out of his comfort zone and reach for the very distant stars that lingered in the vast depths of space? As humanity continues to explore the secrets of the universe for its benefit, space exploration stands as a universal endeavor designed to unlock the doors to crucial knowledge hidden in the cosmos. After Apollo 11's successful landing on the moon in 1969, mankind experienced a significant advancement in technology on Earth. Space exploration accelerated innovation across every field of technology through the transformation of computers into microchips, developing materials that could withstand extreme conditions, and streamlining systems engineering to synchronize complex machines with human precision. It advanced communication networks and satellite systems, forming the foundation for GPS, global broadcasting, and real-time connectivity. In reaching beyond Earth, humanity learned to think bigger, build smarter, and live more interconnected than ever before. The establishment of space bases to support human labor and long-term survival is a critical component of space resource exploitation, which is currently the primary focus of space exploration (Dallas *et al*, 2020). However, the establishment of a sustainable energy system is a crucial stage in the construction of a space base. For any activity in space, it is necessary to provide sufficient energy security, and the establishment of a comprehensive space energy system is a prerequisite for maintaining the regular operation of the lunar base (Pu *et al*, 2021).

Research and innovation continue in photovoltaic energy, nuclear energy, and fuel cells. Each is advancing toward space applications. Together, these sources could create a sustainable energy system in space. Sunlight would provide abundant power. Nuclear energy would ensure a continuous output. Fuel cells would enable efficient storage and conversion.

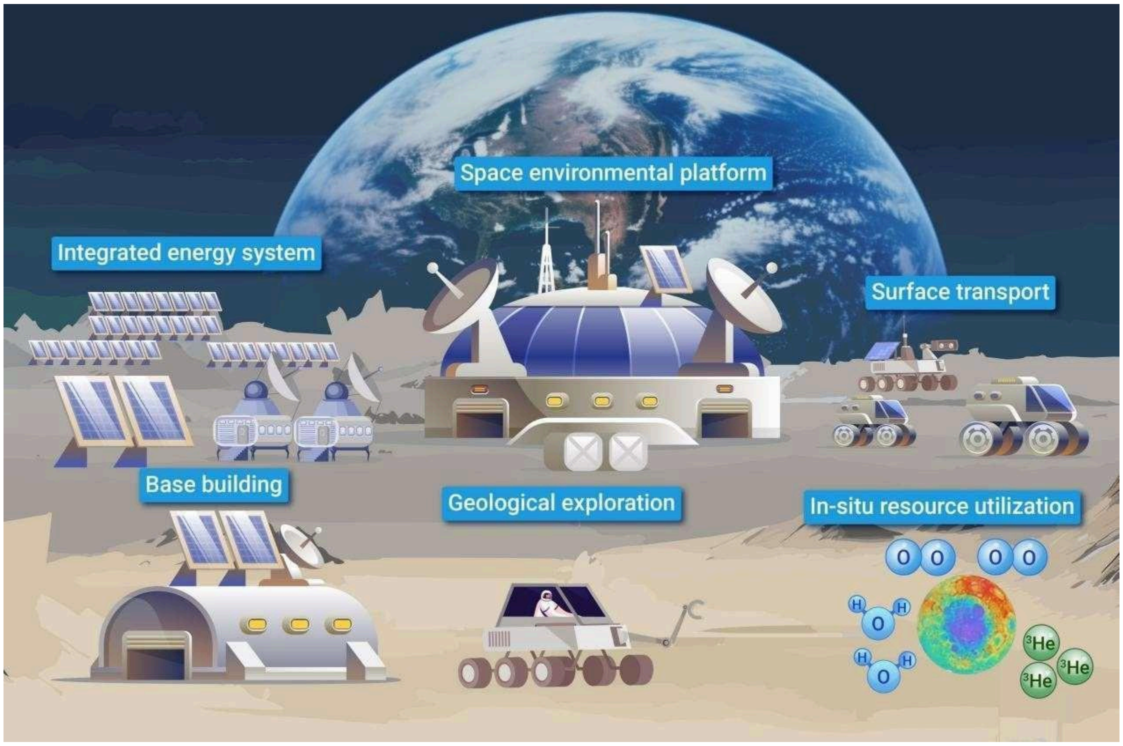

Figure 1.0: Energy system and resource utilization in space (Wu *et al*, 2024)

Solar Power: The Lifeblood of Space Civilization

According to IEA (2024), Solar energy remains one of the largest sources of renewable energy and is predicted by 2030 to become the foremost renewable electricity source, followed by wind, both surpassing hydropower. As the name implies, solar energy is the form of energy harnessed from the sun through the use of photovoltaic and solar thermal systems. Due to its reliability, solar energy has been a primary focus for space exploration. Energy from the sun is not just abundant; it is also a reliable source of energy that, when properly harnessed, can power numerous space exploration activities. Some of these activities include:

powering manned missions to the moon and other planetary bodies, satellites, space probes, space stations, etc. The potential of solar energy in space exploration is immense. Unlike other power sources, it needs no fuel supply or frequent upkeep, making it both practical and cost-efficient for long-duration missions. Its clean, renewable nature also positions it as a sustainable and appealing replacement for conventional fossil fuels in powering future space endeavors. On October 4, 1957, the Soviet Union launched Sputnik, which started the space race. On January 31, 1958, the United States launched Explorer 1, which came in second. However, both satellites died within a few weeks because they were only powered by batteries. Vanguard 1 (shown below), the first solar-powered spacecraft launched by the United States in March 1958, sent data for the following six years (NASA, 2024).

Figure 2: Vanguard 1, the world's first solar-powered satellite (NASA, 2024)

Nuclear Power: The Steady Backbone

In addition to the initial launch of the spacecraft, power is needed for a number of house loads during space exploration, including instrumentation and controls, communication systems, maintaining the operational environment for the space mission's critical gear, etc. Long-term electrical power in space can be supplied by nuclear power. There are various approaches to set up nuclear systems for use in space exploration, and they include: Nuclear power systems, nuclear propulsion systems, and surface power systems (*Atoms for Space: Nuclear Systems for Space Exploration*, 2022). Nuclear power systems are systems that function through the conversion of heat generated by the decay of radioactive elements into electricity, either by fission or fusion. Like nuclear power systems, nuclear propulsion systems utilize the energy generated from fission or fusion to provide thrust to a spacecraft. Surface energy systems. In order to support prolonged exploratory expeditions and the potential for a long- term human presence on other planetary bodies, surface power systems are designed to supply extraterrestrial surface electricity. For one to a few decades, fission surface power reactor designs are microreactors that can produce small amounts of electricity, often in the tens of kilowatts (kW) range (*Atoms for Space: Nuclear Systems for Space Exploration*, 2022). Since 1961, the primary power source for US space operations has been Radioisotope Thermoelectric Generators (RTGs). Plutonium-238's high decay heat (0.56 W/g) makes it suitable for use as a power source in spacecraft, satellites, and navigation beacons' RTGs (World nuclear association, 2021).

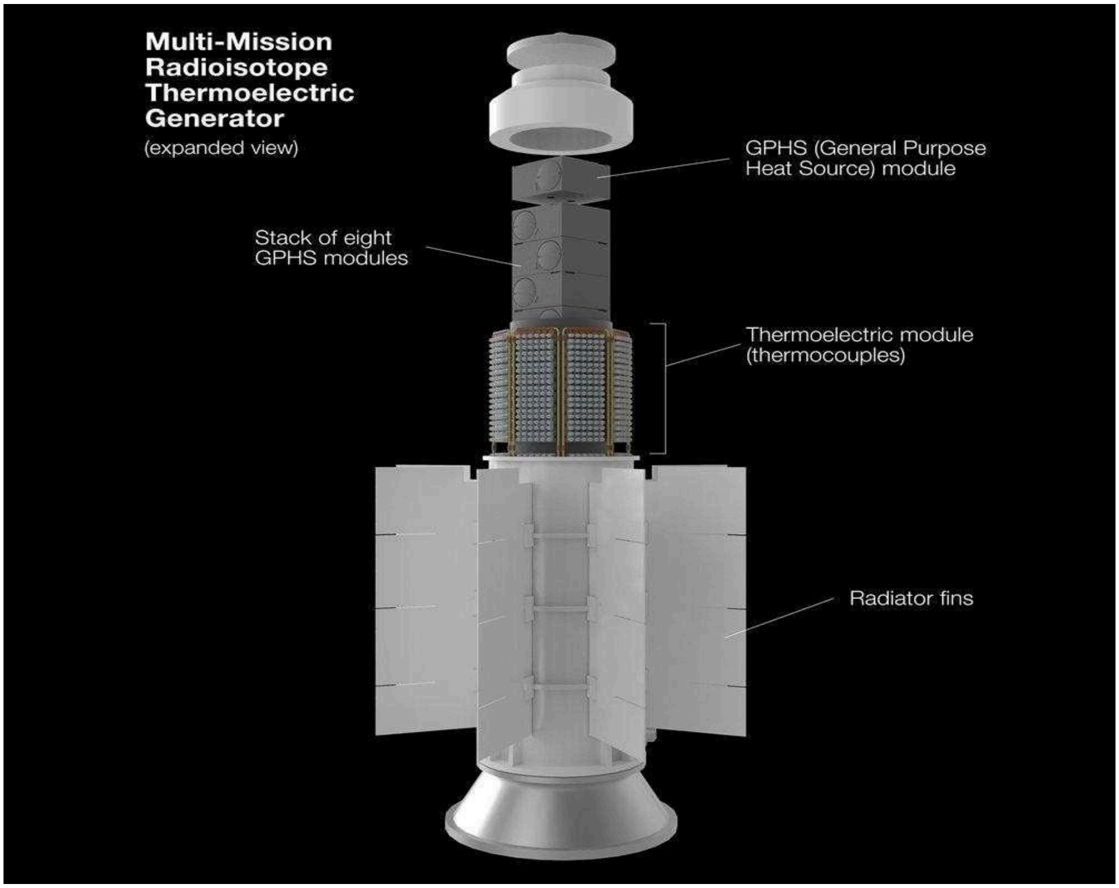

Figure 3: Multi-Mission Radioisotope Thermoelectric Generator (MMRT) (World nuclear association, 2021).

Fuel Cells: The Balancing System

A fuel cell incorporates an electrochemical cell as its main component, enabling the direct conversion of chemical energy from the reaction between a fuel and an oxidizing agent into electrical energy. These cells are often used in stacks. According to Burke (2003), Fuel cells can be categorized as primary (not rechargeable) or secondary (rechargeable). Space-based primary fuel cells use oxidant and fuel tanks that are progressively released without being refilled. Secondary fuel cells, also known as regenerative fuel cells, generate electricity and water from hydrogen and oxygen. To restore the hydrogen and oxygen, the water is electrolyzed using an external power source. Fuel cells are often compared to batteries because both convert chemical energy directly into electrical energy through electrochemical reactions; however, a clear distinction lies between them. Fuel cells can generate electricity, while batteries can only store it. Compared to the energy stored in a normal battery, the fuel and oxidant have a significant quantity of energy stored per unit mass. In contrast to batteries, fuel cells typically store their oxidizer and fuel outside the cell stack rather than inside, like batteries do (Burke, 2003). Fuel cells, particularly hydrogen-powered ones, have proven to function better than batteries in outer space (Ali *et al*, 2024). While a battery could generate up to 250 watts continuously for a maximum of two months, a fuel cell stack of the same size could generate the same amount of electricity for a longer period of time (a year or two) (Fuel Cells Works, 2022). These properties qualify fuel cells for long-term space applications when the cost of launching each kilogram of cargo is high. The Gemini V spacecraft, launched in 1965, was the first to use fuel cells. Beginning in 1962, General Electric created these PEM fuel cells especially for the Gemini spacecraft. In Gemini 7, 8, 9, 10, 11, and 12, these fuel cells were also utilized. Silver-zinc batteries were utilized for peak loads, while fuel cells served as the primary power source (Burke, 2003).

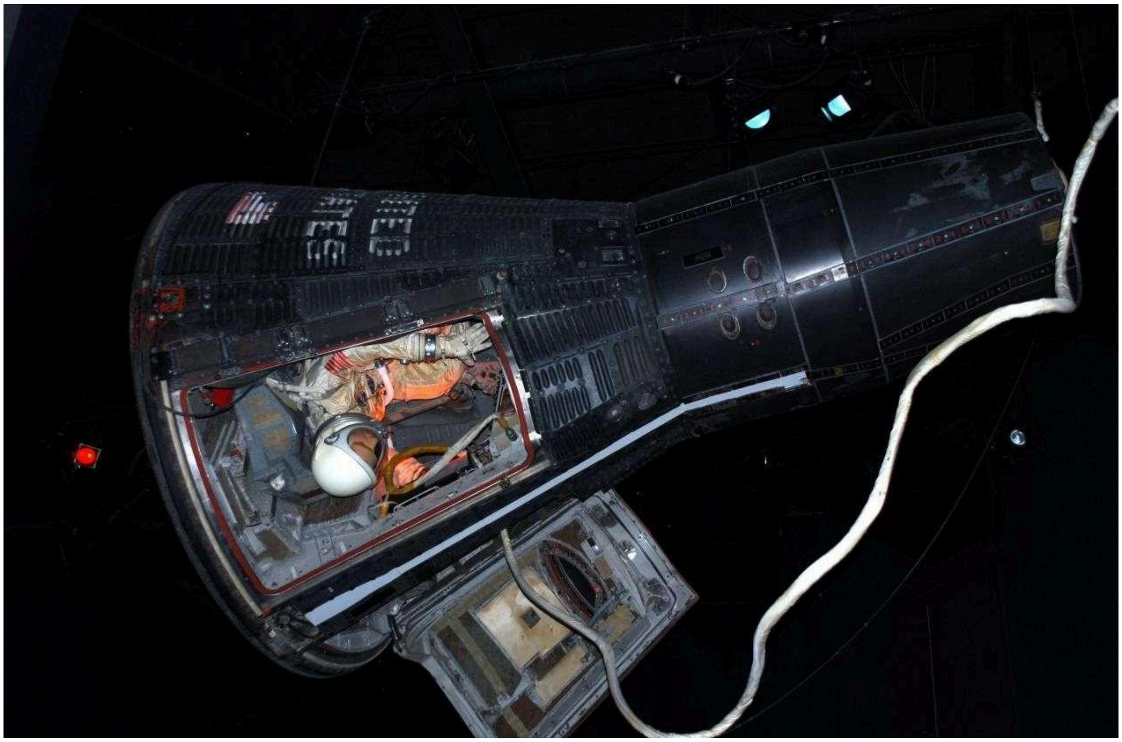

Figure 4: Capsule, Gemini v (Capsule, Gemini v | National Air and Space Museum, n.d.)

The Trinary Model — Sustainability Through Synergy

Criteria	Fuel Cells	Nuclear Energy	Solar Energy
Power Output	Moderate, depends on available fuel (hydrogen)	High, long-lasting power output (RTGs and fission)	Moderate, dependent on sunlight intensity
Operational Lifespan	Long, but dependent on fuel availability	Very long, up to decades without refueling	Long, but dependent on sunlight exposure
Efficiency	High, direct conversion of chemical energy to electricity	High, especially for fission reactors	Moderate to high, varies with solar panel technology
Environmental Impact	Clean, water is the main byproduct	Risk of radioactive contamination, requires secure handling	Clean, no harmful emissions
Suitability for Missions	Ideal for near-Earth missions, lunar/planetary rovers	Ideal for deep-space missions, high-power applications	Ideal for missions near the Sun (Earth orbit, inner planets)
Weight and Complexity	Relatively lightweight and simple	Heavier and more complex, especially fission reactors	Lightweight, but large surface area needed for solar panels

Table 4.1: The comparison of Fuel Cells, Nuclear Energy, and Solar Energy for space applications (Dasuni Hewawasam et al., 2024)

As shown in Table 4.1, each of the three energy systems (nuclear, solar, and fuel cells) demonstrates unique advantages as well as limitations. Although clean and renewable, solar energy is inconsistent and highly dependent on the amount of sunlight. While nuclear energy offers a steady and uninterrupted power source, safety, waste management, and radiation are concerns. Whereas fuel cells are highly dependable and efficient, their operation relies on a consistent fuel supply alongside suitable storage mechanisms. These systems can successfully compensate for the shortcomings of one another when combined into a single framework, as the Trinary Energy Model. Nuclear energy can guarantee continuous operation during times of low solar input; fuel cells can balance fluctuations by offering dynamic energy conversion and storage; and solar power can lower fuel consumption and improve sustainability. When combined, they provide a robust, self-sufficient energy ecosystem that can sustain extended operations in remote locations like space. These developments suggest that a self-sufficient, spacefaring human society may soon emerge.

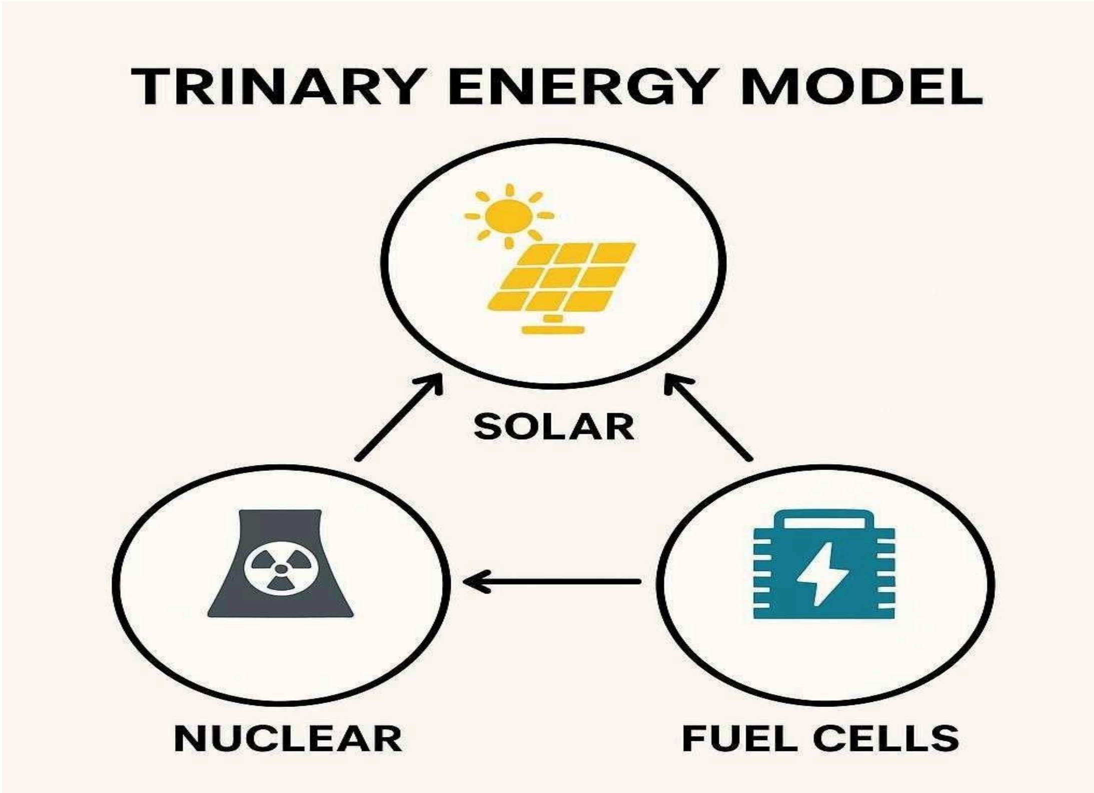

Figure 5: Trinary energy model

Conclusion

In conclusion, given that each system (fuel cells, nuclear, and solar power) possesses distinct operating advantages and disadvantages, their combination in the Trinary Energy Model establishes a solid and sustainable framework for emerging energy infrastructures. In addition to minimizing the shortcomings of individual systems, this synergy increases the overall performance, reliability, and sustainability of the systems. This model envisions beyond self-sustaining settlements; it outlines a course for sophisticated, energy-independent cities in space by combining the renewable potential of solar, the stability of nuclear, and the adaptive energy storage of fuel cells. These hybrid-powered communities would be the first real step toward an independent interplanetary civilization as they would be operating continually without being hindered by Earth's supplies.

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