

Solar-powered in-orbit propulsion: toward autonomous and sustainable space systems

When considering resources in space, one stands out immediately: **the Sun**. It is constant, abundant, and freely available, delivering a level of energy density far beyond what is accessible on Earth. In orbit, there are no atmospheric losses, no cloud cover or weather-related obstructions, and no day–night cycles in the conventional sense. The strategic question is therefore not whether solar energy should be used, but **how it can be effectively harvested and converted into operational capability**.

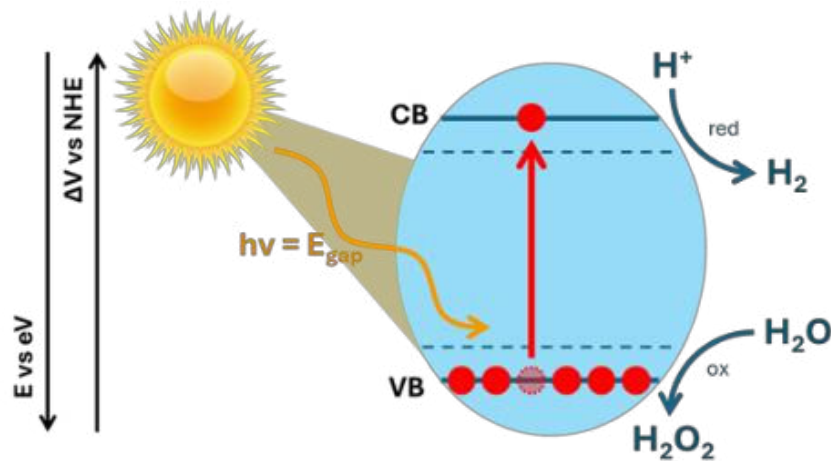
On Earth, solar technologies have already matured into a wide range of applications, from small-scale consumer devices to large infrastructures powering entire cities. In space, however, operating conditions and mission constraints redefine how this energy is used. Solar energy becomes a driver of propulsion, autonomy, and long-term mission sustainability.

As humanity transitions from accessing space to operating within it permanently, this distinction becomes decisive.

The growing limitations of current propulsion technologies are driving **the need for more efficient and sustainable alternatives**. Chemical propulsion, which remains the backbone of space access and manoeuvring, is inherently constrained. It relies on finite propellant reserves, often requiring cryogenic storage and complex handling systems. This imposes strict limits on mission duration, flexibility, and payload capacity. Every manoeuvre consumes mass that must be launched from Earth, creating a structural dependency that is both costly and operationally restrictive. As orbital environments become more congested and missions more ambitious, ranging from large satellite constellations to deep-space exploration, the need for more efficient, sustainable propulsion systems becomes increasingly urgent. Spacecraft must be capable of operating longer missions, manoeuvring more frequently, and adapting dynamically without constant resupply. In this context, the integration of in-situ resources and renewable energy sources is essential, pointing toward a new generation of propulsion systems designed for endurance, flexibility, and autonomy.

Part of the conceptual shift underlying these developments can be understood through an analogy with **photosynthesis**. In nature, plants continuously convert sunlight into usable energy through decentralised and efficient processes, without relying on stored reserves in the conventional sense. This principle of continuous energy harvesting and conversion resonates strongly with emerging space technologies. Rather than carrying all necessary energy onboard, spacecraft can be designed to interact with their environment, capturing and transforming solar energy in real time. **This bio-inspired approach** is increasingly influencing propulsion research across Europe.

Figure 1 : GreenSWaP conversion principle



Within this landscape, the European Commission, through Horizon Europe and the European Innovation Council, is supporting disruptive innovations aimed at **redefining propulsion systems**. Among these, **the GreenSWaP project represents a particularly ambitious attempt to bridge the gap between energy generation and propulsion**. GreenSWaP addresses a fundamental limitation of current systems: the separation between power generation and propulsion. Instead of treating them as distinct subsystems, it proposes the in-situ production of propellants from water using solar energy. This choice is not incidental but linked to the availability and storability of water, which can be converted into hydrogen and hydrogen peroxide, enabling a flexible, sustainable, and multifunctional propulsion architecture.

The core idea of Green SWaP is to use solar energy to produce propellants directly in space from water. These propellants: hydrogen and hydrogen peroxide, can feed both chemical propulsion systems and solar thermal propulsion, enabling thrust generation through complementary mechanisms. At the same time, the system leverages solar energy as its primary input, effectively linking energy harvesting and propulsion within a unified architecture.

To achieve this, the project focuses on the development of innovative systems capable of efficiently converting water into usable propellants using solar energy. These systems must operate under extreme conditions, ensuring stability, efficiency, and safety while maximizing propulsion performance. The challenge is not only technical but systemic: optimizing the interaction between fuel, energy conversion, and thrust generation within a constrained spacecraft environment.

This approach directly addresses several critical limitations of current propulsion technologies. By relying on water as a storable and potentially in-situ resource, it reduces dependency on complex cryogenic systems. By enabling in-space propellant production, it extends mission duration and reduces the need for large onboard reserves. And by linking energy harvesting with propulsion, it enhances overall system coherence and performance.

More broadly, GreenSWaP fits within the evolving landscape of solar-powered and resource-efficient propulsion. While solar electric propulsion and solar sails already demonstrate the potential of harnessing sunlight, they still face limitations in thrust, scalability, and system integration.

Solar electric propulsion offers high efficiency but low thrust, making it suitable for long-duration missions but less effective for rapid manoeuvres. Solar sails eliminate the need for propellant entirely but require large, delicate structures and precise control. Emerging hybrid systems, such as those explored in GreenSWaP, aim to overcome these limitations by combining energy harvesting, convert propulsion into more versatile configurations.

The current state of the art therefore represents a transitional phase. The technologies exist, but they remain compartmentalized and constrained by trade-offs between efficiency, thrust, and operational complexity. Bridging these gaps requires advances in materials, energy conversion, and system integration, precisely the areas targeted by next-generation research initiatives.

The potential impact of GreenSWaP extends beyond space exploration itself. By advancing solar-driven fuel production from water, the project contributes to broader efforts in sustainable energy systems and resource utilization. This dual relevance reinforces the strategic importance of such innovations, linking space technology with terrestrial energy challenges. Ultimately, solar-powered and resource-integrated propulsion systems mark a fundamental shift in how spacecraft are conceived. No longer entirely dependent on Earth-supplied resources, they begin to operate as semi-autonomous systems, capable of harvesting, converting, and utilizing energy within their environment. In this evolving paradigm, **the Sun becomes a central enabler of mobility and endurance.** GreenSWaP illustrates how this transition can be operationalized, combining renewable energy with innovative propulsion architectures to redefine what is possible in space.

The challenge ahead is not conceptual but technological: transforming these promising approaches into reliable, scalable systems. Success in this endeavour will not only extend the reach of human activity in space but also shape the sustainability of that presence for decades to come.