The Impact of Reuse and Recycling in Orbit on Lowering the Cost of LEO Missions

CosmoDust

Mert Yıldırım
Barış Akkan
Ahmet Buğra Binpınar
Mehmet Mert Topçu
Atlas Rüzgar Şahin
Doğukan Kıvanç

Introduction

On July 20, 1965, five years later, while 650 million people watched from around the world, the Apollo 11 mission successfully landed, taking man to the moon for the first time. then the space shuttle on 12 April 1981, each becoming a defining success in human spaceflight history. These historic moments sparked a renewed surge of public interest in space travel. In recent years, the efforts of private companies like SpaceX and Blue Origin have driven down the cost per kilogram for delivery to orbit, bringing space within the reach of smaller players. Currently, more government and commercial satellite reliant on space infrastructure are for various applications such as global navigation and positioning systems, weather monitoring, satellite images and intelligence gathering.

Objectives

The near future is expected to see LEO filled with multiple government and commercial space stations as well as a variety of space missions. The goal of this work is to reduce the cost of space operations enough to open up such activities to non-traditional actors, such as academic research groups. This study considers the cost per kilogram for shipping different types of cargo to orbit and assesses the potential for multiple reuse and recycling of these materials.

Methodology

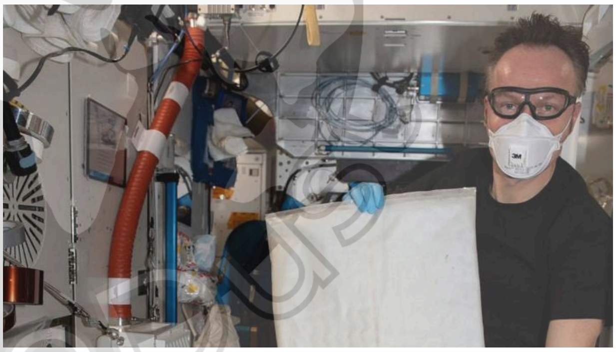
The authors performed an extensive review of the literature from several space agency repositories. Based on this knowledge, the research assessed what materials could be recycled in space and to what degree they could be reused. A comparative cost analysis was made comparing costs of shipping supplies from Earth to orbit with those of recycling and remanufacturing them on site. The results were made accessible through the establishment of a website that establishes the value of in-orbit recycling and features an interactive educational package targeting young viewers.

Results

Historical Background and Economic Development

Space shuttle launches in the late 20th century cost around 1.5 billion USD (44,800 USD per kg). Much too much. The shuttle program never came close to meeting the latter goal of "low cost" operations using the shuttle's reusability, which was critical to making the shuttle cheaper after the costly Saturn V program was complete. The United States had only very limited access to space following the shuttle's retirement, now dependent exclusively on Soyuz craft. To support the International Space Station, the Commercial Resupply Program was established in 2008. Announced in 2011, the Commercial Crew Program has revolutionized human spaceflight, with the first commercial mission to the ISS in 2019. Currently a Falcon 9 Dragon launch to the ISS costs around $140 million to carry 6,000 kilograms, or about $23,300 per kilogram. This massive increase in cost efficiency has encouraged greater involvement in space activities by both government and commercial players. As a result, multiple commercial space station companies have sprung up with the goal to take over for the ISS when it is deorbited. Reuse and recycling are very cost-effective for crew forgoing orbital operations. This study recognized five major areas for recycling application: water, biowaste, used hardware, polymers and logistics.

Water and Oxygen



Water and oxygen recycling are important aspects of life support systems. The ISS now recovers 98% of the water onboard, along with moisture from sweat, condensed breath, and urine, using extraction and filtration methods. The procedure entails vacuum distillation of the urine, then processing the brine residue through the Brine Processor Assembly (BPA) to extract additional water. Although the development of the system was both technically challenging and financially costly, the investment was recovered after 402 days of orbital operation. While full closure in the water loop cannot be achieved, this example of subsystem will be used as a model for future SS architectures.

In-space oxygen production in spacecraft and space station environments is typically achieved via the Oxygen Generation Assembly (OGA), part of the Environmental Control and Life Support System (ECLSS) developed by NASA. Through electrolysis of clean water (H2O), the OGA generates oxygen (O2) and hydrogen (H2). The oxygen produced is added to the cabin air, while the hydrogen is vented into space or recycled in secondary processes.

NASA also uses the Sabatier process to increase the efficiency of resource use. This process reacts the crew exhaled carbon dioxide (CO2) with hydrogen to generate water (H2O) and methane (CH4). The water then is recycled through the electrolysis system, thus completing the carbon-oxygen cycle. Methane, however, is vented to space with small losses of hydrogen that prevent to close the loop perfectly. Operation expenses on the ISS are reduced by product approximately from 240 million USD to 10 million USD per annum by these coupled systems.

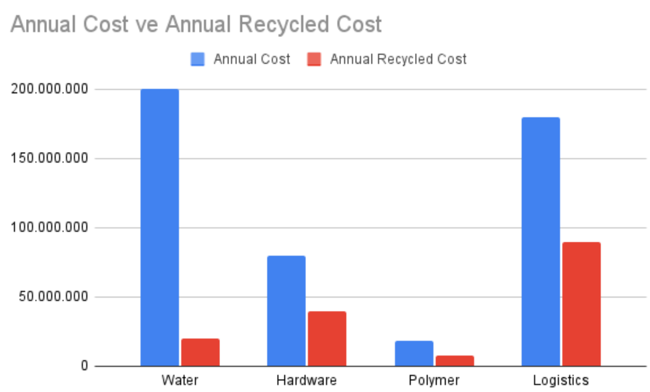
Biowaste

Organic waste materials, such as urine, feces and organic refuse (including food waste), pose hygiene and resource management issues in closed living situations. The ISS processes urine for water reclamation with a recovery efficiency >90%; solid wastes are stored and incinerated during atmospheric reentry. A crew of seven produces about 700-900 pounds of solid waste per year, a large portion of that is water (Fecal matter consists of 75% water), representing lost resources worth millions of dollars, in terms of launch mass.

Novel technologies being developed in 2025 are filling this gap. The Heat Melt Compactor (HMC) prototype developed by NASA processes waste at 150°C, sterilizing it, recovering water vapor and compacting the residual material into dense tiles that can be used for radiation shielding or storage. Studies indicate fecal water recovery potential in excess of 80%, with the ability to recover more than 400 kg per year for larger crews. In addition to water recovery, bioregenerative systems, such as the European Space Agency's MELiSSA program, utilize microbial processes and plants to turn waste into nutrients, oxygen, and, in some cases, food.

The LunaRecycle Challenge, launched in 2024 with further development expected in 2025, incentivizes pioneers to come up with viable solutions to the problem of lunar waste recycling; this time there is more focus on sustainability in deep space. Phase 2 focuses on scalable tech for moon missions where a crew of four could create 2,100 kilograms of trash a year. Proposed ideas include thermochemical reactors that convert waste to methane fuel, reducing propellant needs. Issues such as pathogen control and odor management are handled through sterilization methods and filtration systems. Although the efficiency of recycling the current solid waste is none, the two new technologies could generate savings of eight to ten million US$ per year by reducing resupply infrastructure and allowing for closed loop ecosystems, which are critical for Mars transit missions since earth based resupply and support are not feasible.

Used Hardware

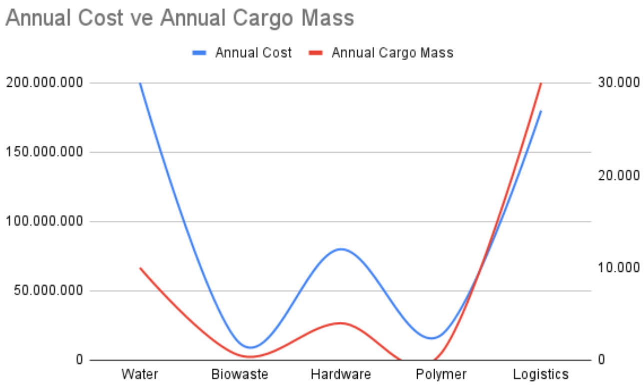


Space stations are not just living units but high-level laboratories that must be maintained. Defunct hardware components, such as an exhausted pump or an outdated C&DH board, contribute to 3,000-4,000 kg of annual resupply needs associated with launch costs of USD 60-80M. Normally, nonworking parts are shelved or trashed, but as of 2025 there are indications that this is about to change, with ISM becoming the dominant mode of production in space. The portfolio of NASA In-Space Manufacturing (ISM) that highlights recycling of metals and electronics components. The Micro Space Foundry transforms space debris into a metal feedstock, which could then be turned into additive manufacturing of propellant tanks or other structural elements. While modular concepts, like Orbital Replacement Units (ORUs), make the replacement of components easier, full materials recycling — wherein the cases are melted down and reprocessed into new ones via electron beam fabrication techniques — is on the horizon. Some challenges: microgravity safety risks, mining requirements for power. Despite the challenges, the benefits could be enormous: The spare-parts inventory could be slashed by 50%, which would mean annual savings ranging 30 to 40 million dollars. Redwire's microgravity manufacturing focus continues to drive formulation capabilities in LEO. Proposed solutions, like turning dead satellites into orbital foundries, show promise. As the ISS is moving more and more toward commercial station operation, these technologies provide an operational resilience in turning orbital debris into usable assets.

Polymers

ISS waste is mostly polymeric and includes food packaging (0.26 kilograms per crew-day, or 570 kilograms per year for a crew of six), tools and containers for storage. In the absence of recycling, this waste occupies scarce storage space and the replacement shipments are expensive. The 2019 Refabricator was a dramatic step forward as a combined additive manufacturing and recycling system for turning plastic waste into filament that could be used to manufacture new parts. Though we are through with operations, the system met closed-loop potential by turning wrenches into other tools, like uses," said Heiken. In 2025, the company will focus on developments to improve filament quality and add support for more types of composite materials. Strategic collaborations, such as with Made In Space and Braskem, now make possible zero-gravity polymer processing capabilities. At a launch price of 20,000 USD per kilogram, reusing 50% of the polymer yields an annual savings of about 10 million USD. Future ISM concepts include processing lasers for making robust parts to decrease reliance on Earth and support on-demand manufacture for long-duration missions.

Logistics



Food and clothing are the major logistical burden, with annual replenishment needs of 6,000 kg of food and 1,700 kg of clothing, at a cost of $150-180 million. These materials are now classified as throwaway, and generate a significant waste; but circular resource systems are coming online in 2025. The Veggie plant growth system is used to grow fresh vegetables, such as lettuce, on the ISS, partially meeting crew dietary

needs and converting carbon dioxide back into oxygen. Studies produced that may be 10-50% food self sufficiency, to a potential cost savings of 50-100M USD.
Though there are no laundry facilities in space yet, some of the possible solutions for clothing are antimicrobial fabric technologies and small washing machines. Packaging waste is being taken care of through programs, including LunaRecycle, that are turning these materials into resources. As the commercial LEO stations come online, integrated systems that allow for resupply-minimization will increasingly be needed to enable sustainable orbital habitats.

Conclusion

This study establishes the technical feasibility and economic viability of a closed loop recycling and reuse system in orbital environments for sustainable space operations. The analysis suggests that life-cycle cost of currently installed recycling technology on ISS especially water and oxygen recovery system is greatly improved with astonishing efficiency of 98% water recovery, demonstrating the economic feasibility of such systems by short payback period (402 days for water recovery systems). The total annual cost savings from the current recycling infrastructure, cutting operating expenses from $240 million to $10 million for water and oxygen alone, makes a strong case for further expansion of recycling.

Analysis of the five key recycling areas (water, biowaste, used hardware, polymers, and logistics) reveals additional cost-saving and operational autonomy opportunities. New technologies such as the Heat Melt Compactor processing biowaste, in-space manufacturing schemes for hardware recycling, and polymer processing capabilities that could add additional annual savings of between $8-10Mil saved annually from biowaste systems to $30-40 million in savings through hardware recycling. The total potential savings in all categories could be greater than $100 million annually and concurrently lessen dependence on Earth resupply.

The steep drop in the cost of launches—from $54,500 per kilogram during the shuttle era to $23,300 per kilogram with the current commercial systems—has allowed for more access to space but also highlights the ever-present economic importance of recycling in orbit. As human space exploration moves beyond LEO to lunar bases and ultimately Mars missions, where resupply from Earth becomes more and more impractical, if not impossible, the switch from today's linear consumption model to a closed loop system becomes enable the appropriate rhetoric and thought provoker rather than being truly required from an economic standpoint.

New space station development, especially commercial LEO venues and deep-space habitats, must be designed from the ground up to include full recycling capabilities and can not treat the issue as an afterthought. Demonstrated technological maturation through ISS systems, and continued evolving bilos, in-space manufacturing, waste-to-resource conversion, and the like, provide a solid euphrate for sustaining such a high level of self-sufficiency. Investment in these technologies, well aligned with initiatives such as the LunaRecycle Challenge, will ultimately be instrumental in ensuring a commercially and operationally sustainable expansion of the human presence beyond Earth orbit.

Sources

ABC News. (2023, June 27). *NASA astronaut demonstrates water recovery bladder on the ISS* [Photograph]. ABC News.

Ames Research Center. (2023). *Heat Melt Compactor (HMC) program summary.* NASA.

European Space Agency (ESA). (2022). *MELiSSA (Micro-Ecological Life Support System Alternative) project overview.* European Space Agency.

Frontiers in Space Technologies. (2024). *ISS life support system performance and mass breakdown. Frontiers in Space Technologies, 3*(2).

NASA. (2023, March). *Astronaut installing the Refabricator aboard the International Space Station* [Photograph]. NASA.

NASA. (2023). *Environmental Control and Life Support System (ECLSS) overview.* NASA Facts.

NASA. (2023). *Take or Make: ASCEND study on in-space manufacturing and recycling.* In-Space Manufacturing Office.

NASA. (2024). *ISS life support system performance report 2017–2023.* NASA Technical Reports Server.

NASA. (n.d.). *CRISSP – Customizable Recyclable International Space Station Packaging.* NASA TechPort Project 102610. https://techport.nasa.gov/projects/102610

NASA. (n.d.). *Enabling Sustained Presence Using Recyclables (ESPUR).* NASA TechPort Project 146342. https://techport.nasa.gov/projects/146342

NASA. (n.d.). *In-Space Manufacturing – Recycling & Reuse (ISM-RnR).* NASA TechPort Project 116350. https://techport.nasa.gov/projects/116350

NASA. (n.d.). *Logistics Materials for Reuse.* NASA TechPort Project 182972. https://techport.nasa.gov/projects/182972

NASA. (n.d.). *Positrusion Filament Recycling System.* NASA TechPort Project 18199. https://techport.nasa.gov/projects/18199

NASA Ames Research Center. (2023). *Integrated waste management concepts for long-duration missions.* NASA.

NASA Tethers Unlimited. (2019). *Refabricator demonstration and in-space recycling results.* NASA Marshall Space Flight Center.

Space Foundation. (2024). *The Space Report 2024: Q1 data.* Space Foundation.

Tethers Unlimited, Inc. (2020). *Integrated Refabricator technical brief (SBIR final report).* NASA Small Business Innovation Research Program.