SPACE

Towards a lunar economy

The next phase of lunar exploration aims to open up space resource development. *Maria Kielmas* reports.

The year is 2050 and you are out to dinner at a newly fashionable and very upmarket restaurant. The menu has just two items – space risotto and lunar water. The prices are astronomical.

Toronto-based geological and mining consultant Watts, Griffis and McOuat used this scenario in a recent report to illustrate the potential market for space resources. The extraction, processing and commercialisation of water from unconsolidated regolith*, hydrated minerals, or ice on the Moon and asteroids could generate a potential market worth $206bn over the next 30 years. Products like rice or other grains could be exported back to Earth to meet a growing fashionable demand and command larcenous prices, much as the European spice trade developed in ancient and medieval times.

The development of a profitable space economy has become a burgeoning ideas industry worldwide, with participants ranging from student entrepreneurs to billionaires. Most hope to piggy-back their ideas for landers and rovers on future lunar missions such as NASA's Artemis programme that aims for a human landing on the Moon by 2024. Artemis includes a Moon-orbiting module called the Gateway, designed to be a human accommodation section, a hub for lunar landing and a stepping stone to Mars. Others, such as Amazon founder Jeff Bezos' Blue Origin currently suborbital space rocket, hope to take paying passengers to space in reusable spacecraft and, by 2024 land a module, Blue Moon, on the lunar surface. But they are all grappling with the same imponderable – how do you power this enterprise?

Rocket equation tyranny

In space, everything is dominated by the rocket equation – an expression of the momentum balance needed to lift a body into orbit against the force of the Earth's, or other celestial body's, gravity field. One kilogramme of anything – food, water, electronics – needs 200 kg of propellant at the launch pad. According to NASA figures, it costs $13,000–14,000/kg to lift the combination of spacecraft, fuel and payload from Earth to lower Earth orbit (LEO). The greater the payload or the more distant the ultimate destination, the more fuel is needed, which adds extra weight, needing more fuel.

Space scientists call this the 'tyranny of the rocket equation'. Enterprises planned by aspiring space explorers will require megawatts of electrical power. So far, space missions have only managed to generate just over 100 kW of solar power and have designed for 200 kW. In addition, spacecraft hulls suffer fatigue at 10 times the rate of aircraft, as experienced with the now retired Space Shuttle. So, genuinely reusable spacecraft are still awaiting invention.

The Artemis lunar Gateway will follow an 'eccentric' or near rectilinear halo orbit (NHRO) around the Moon, limiting the number of eclipses created by the Earth or Moon's shadow and so preserving access to solar power. But the NHRO orbit is unstable, needs multiple correctional procedures using solar propulsion and so more power than a conventional lunar orbit. The Gateway's power and propulsion element designed by Colorado-based Maxar Technologies has a roll-out solar array whose output can be scaled to 200 kW, twice as high as the International Space Station's current solar power generation capacity and enough for the module, but not for lunar surface operations.

In-situ resource utilisation

As a result, an initial cis-lunar (the space between the Earth and the Moon) economy would require lunar refuelling facilities – namely, propellant manufactured on the Moon from its resources. In-situ resource utilisation (ISRU) – the use of materials on celestial bodies for propellants, power generation and manufacturing – has been studied by NASA since 1965, when the agency conducted experiments on simulated lunar regolith to extract oxygen.

'Currently, the most valuable lunar resources are water and/or oxygen. Both are required as first steps for being able to extract any additional materials that might be useful,' says Carolyn van der Bogert, Planetary Geologist at the University of Münster, Germany.

The idea is to liquefy extracted oxygen to use as fuel, or create liquefied oxygen and hydrogen from sublimated water ice. Traditionally, lunar geologists have considered ilmentite (titanium

The power and propulsion element for the lunar Gateway project was designed by Maxar Technologies and has a roll-out solar array whose output can be scaled to 200 kW, twice as high as the International Space Station's current solar power generation capacity
Photo: Maxar Technologies

oxide) found in lunar basalt (mare) deposits and certain pyroclastics as the best source of oxygen. This can be produced by reacting the mineral with hydrogen or methane. However, this only produces a small amount of oxygen per tonne of mineral and the reactant gases need to be brought from Earth, Van de Bogert adds.

Water ice observed at the lunar poles could solve this dilemma. 'The motivation for the next lunar missions to visit the poles is partly driven by the perception that ISRU of ice deposits would be more straightforward than oxygen extraction from regolith or pyroclastic deposits,' Van de Bogert says. But the spatial extent of ice around the lunar poles is not well known. The 2009 Lunar Observation and Sensing Satellite (LCROSS) infrared spectrometer observed about 5.6± 2.9% of water from debris ejected after crashing an upper spacecraft module into ice in the south pole's Cabeus crater. However, other remote sensing data at different locations all contradict each other.

Overcoming solar obscurity

Space explorers aim to produce liquefied oxygen and hydrogen for fuel. But no one knows how to explore in an environment where solar energy is obscured for between a few hours to 14 days per month and temperatures vary between 127°C in direct sunlight to –173°C in an obscured crater. A wholly robotic enterprise consisting of production facilities, cryogenic tanker transport to storage facilities, plus landers or ascenders, would require 2.8 MW of electrical and 0.8 MW of thermal energy. A human operation would require a 10-fold energy increase. This is too big even for space nuclear batteries (radioisotope generators) that weigh 45 kg each on Earth and generate just 100 W. Transporting 30 of these from Earth would be unfeasible. NASA plans to dispatch its Volatiles Investigating Polar Exploration Rover (VIPER) in 2022 to look for lunar ice. But the agency has not disclosed how this will be powered in lunar crater regions in permanent shadow.

The answer is regolith electrolysis – the co-production of oxygen and metals on the lunar surface to generate electricity, says Elliot Carol, CEO of Houston-based Lunar Resources, a company investigating energy generation and manufacturing on the Moon. 'You don't need to employ additional reagents on the Moon because you have a fantastic vacuum. You use regolith pyrolisis to make feed to power drives and solar cells.' Earth's atmospheric pressure is a standard 760 Torr **. The Moon's scant atmosphere means its surface is an effective ultra-high vacuum of 1 x 10^{-9} Torr. Silicon solar cells can be fabricated from the regolith using this vacuum and a small (200 kg) solar cell powered rover brought from Earth – called a vacuum deposition paver – in a staged molten oxide electrolysis process. The result would be a complete electrical system.

Ross Centers, student entrepreneur and co-founder of Los Angeles-based Radiant Lunar, believes laser transmission can be used in a solar generation and distribution network to direct energy for water exploration and production into obscured crater regions. Wired transmission is too heavy and would have to overcome the Moon's extreme topography. Elevation differences between lunar crater bottom and its unweathered rim can be up to 3 km.

TRL tyranny

The Artemis programme plans 37 NASA and private rocket launches, and a mix of human and robotic landers on the Moon by 2028, culminating in a long-duration crew stay four years after the initial crewed landing. However, manufacture and deployment of ISRU is still 20 to 30 years away, thinks Dan Britt, Pegasus Professor and Director of the Center for Lunar and Asteroid Surface Science at Orlando-based University of Central Florida. This is due to any project's technological readiness level (TRL) – space scientists' second 'tyranny'.

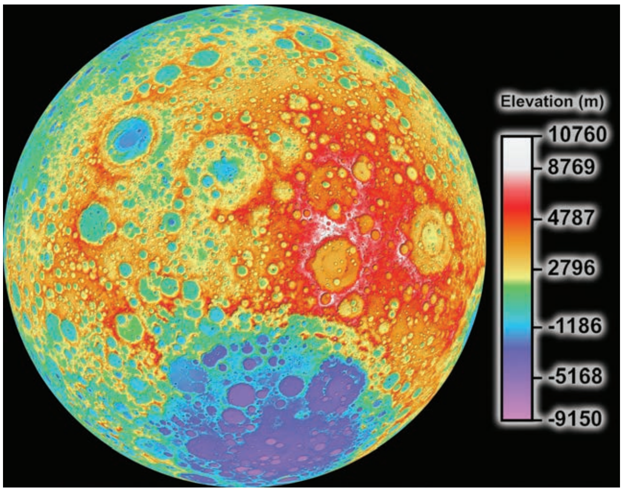
Devised by NASA in the 1970s, TRL values range from TRL-1, an explanation of basic principles, to TRL-9, a flight proven system. TRL-3 is still a vague engineering model. 'TRL-6 is something that's operating at more or less a known size, mass and power consumption. Mission planners can take it, repackage it and fit on their spacecraft,' Britt says. Currently, most ISRU project are at TRL-3 to TRL-4, although a few of the best are at TRL-5. The technology for Lunar Resources' vacuum deposition paver is at TRL-4, while Radiant Energy's wireless transmission system is TRL-2.

To reach a TRL-6 or TRL-7 level, private sector projects need investment of $40–50mn/y over five years to build up a portfolio of technologies that can operate in space, Britt notes. Funding is also a major issue with the Artemis programme. The project has changed design several times over past decade during the Obama and Trump administrations. At the time of the 1969 first Moon landing, NASA received funding equivalent to 5% of the US federal budget revenues. In today's money that programme would cost $130bn. Total Artemis funding has not been disclosed, but is quoted variously as $20–30bn.

But aspiring space explorers dream of mega profits in the future space economy. Pittsburgh-based space robotics company Astrobiotic Technology is developing a lander that will charge research companies, universities and others $1.2mn/kg for payload deliveries to the lunar surface. If the space entrepreneurs manage to grow vines on the Moon by 2050, well-heeled customers in Earth-based fashionable restaurants will be able wash down their space risotto with astronomically priced wine. ●

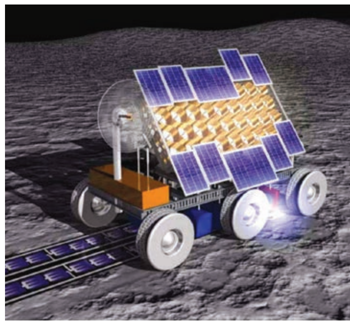
* Regolith is layer of unconsolidated solid material covering the bedrock of a planet

** Torr is a unit of pressure that is roughly equivalent to 133.32 Pa



High resolution topographic map of the Moon

Photo: NASA/Goddard Space Flight Center/DLR/ASU



Artist's impression of a mobile solar cell fabrication facility fabricating solar cells directly on the lunar surface

Photo: Lunar Resources

Apollo 17 landing site

Photo: Lunar and Planetary Institute