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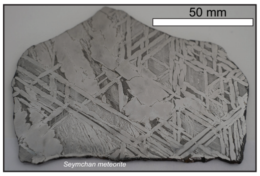

Extra-terrestrial resources: A potential solution for securing the supply of rare metals for the coming decades?

The forthcoming energy transition driven by the need to reduce CO_2 emissions requires large amounts of critical elements to construct renewable energy devices such as car batteries, wind turbines and solar panels. For many elements such as Li, Co, REEs and Ti, the production sources are located in countries with poor social and environmental standards, prone to political destabilization such as military conflicts, or vulnerable to strained relationships with consumer countries. Lately, the volatile geopolitical context has further demonstrated the high dependency of Europe and other developed countries in terms of raw material supply. In addition, there is a debate about the Earth's potential to sustain the transition toward a green society by using conventional resources from mining of terrestrial rocks. As nature conservation and climate mitigation are now priorities for the majority of governments, and since conventional mining on Earth suffers from a growing social resistance, humankind may need to look toward new frontier resources for supplying the mineral needs of the coming decades. Here, we explore the use of extra-terrestrial resources as a potential source to feed the future supply of critical metals. Extra-terrestrial mining may be an opportunity for wealth creation and an option for critical metal resource supply when mining on Earth becomes increasingly untenable. We conclude that the potential impacts of extraction and exploitation of space resources, both good and bad, could be societally profound.

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In the next 30–50 years, humans will face tremendous challenges. Some are linked to the forthcoming decarbonisation of our energy systems and the transition to a more sustainable society to attenuate the risks of human-induced catastrophic climate change. The large-scale deployment of green technologies (solar panels, wind turbines, energy storage, etc.), massive electrification of transportation and other infrastructures/services (e.g., electric cars, trucks and ultimately even aeroplanes) and regained interest for nuclear fission-based electricity production are anticipated to require vast amounts of metals such as nickel (Ni), titanium (Ti), lithium (Li), cobalt (Co), uranium (U) and other critical elements as has recently been discussed, for instance, by R. Herrington from the Natural History Museum in London. Other immediate challenges are connected to the geopolitical context increasingly strained by the supply-chain situation with import-dependent countries, and problematic or unreliable exporters. Furthermore, the current need for high-tech weaponry created by the changing geopolitical situation will have a progressively more profound impact on the supply of elements such as antimony (Sb) and tungsten (W), which are used for a very large range of defence equipment such as optical defence systems, armour-piercing bullets, flares and explosive formulations.

This need would increase strain on the planet's resource base and might lead to a significant depletion of natural resources on Earth. In 2014, in a comprehensive work, H. Sverdrup and K. Ragnarsdóttir suggested that Earth does not provide the necessary amounts of valuable elements. More striking estimates from the Global Footprint Network evaluated the present demand of humanity as the equivalent of the capacity of 1.75 Earths, with the point at which we pass 1.0 Earth capacity in the year now referred as the 'Earth's Overshoot day'. Meanwhile, the world is still struggling to close the gap for ~800 million people in the Global South who still lack basic access to electricity and billions more who lack access to modern energy services.

Critical questions as to what and how much is needed for the global society and economy are still being discussed. It is already clear that vast amounts of Li, Co and Ni, amongst other critical metals, will be required for the energy system transition in the not so distant future. For instance, the shift from internal combustion-based engines to electro-mobility will require tremendous amounts of Co and Ni, which will necessitate an increase of ~500% of the current global cobalt production, according to the latest data by the World Bank. Furthermore, in the present agenda of major geopolitical players (USA, China and EU) and big international organizations (UN), considerable changes are expected by 2050. By that time, it is not certain that the energy transition will be completed, and, if the predictions about the needed amounts of critical elements are correct, the global economy might face a real threat to its critical elements supply.

The need for alternative resource supplies

These realisations call for a re-evaluation of current resource supply chains and availability around the world, and what and how much global society can reasonably extract to feed the energy transition. Many argue that establishing a more sustainable society relying heavily on recycling, reuse, or alternative raw materials can do the trick, as outlined by, for example, Vidal and colleagues in 2013. However, the recycling of critical elements might not be able to supply the needs of the global economy in the coming decades. Considering the current slow rates of development, the deployment of effective recycling technology might be delayed and thus create severe supply shortages in the next 30–50 years. The present recycling rates are low, limitations severe and several decades of intense mining will be required to establish and satisfy the basic needs of a new economic model for these metals. In addition, recycling of many metals would require complex chemical processes that could produce more environmental pollution than mining.

On the other side, a potential depletion in critical resource supply would exacerbate the already strained geopolitical relationships between states and as a result, suppliers would be tempted to use the dependence of some other states as leverage to achieve their specific goals. As a consequence, there is an urgent need for securing possible alternative critical metal supply sources. Since many if not most onshore major ore deposits are now known and are being exploited, the only option left is to look at unconventional resources or 'frontier resources' for the future. Among the potential unconventional metal sources is deep mining into the continental crust, which presents serious technical challenges and might not help solve geopolitical problems related to the geographical location of the supply source. A tentative solution to all these issues would thus be a large supply not owned by any particular actor and accessible to all. Submarine resources are thus one possible option that may satisfy accessibility concerns. However, this avenue comes with major environmental risks of disturbing sensitive ocean floor ecosystems and with a severe impact on biodiversity, and hence faces strong societal opposition. So what options remain? Having in mind that the majority of Earth's reserves would be largely depleted in the next 50 years and that exploiting submarine resources comes with significant environmental and ecosystem deteriorations, it may be sensible to look elsewhere, beyond Earth—and that means *in space*.

We know from both meteorite finds and space exploration that the Solar System contains vast and abundant untapped mineral resources. Our first-hand mineralogical and chemical knowledge of the composition of many solid objects in the Solar System comes from meteorites we recovered on Earth. They can be broadly divided into three main categories: (1) stony meteorites formed mostly by silicates and include rocks from the Moon and Mars; (2) stony-iron meteorites (or pallasite) formed by a matrix of Ni–Fe alloy embedding silicate crystals (e.g., olivine); and, (3) Iron meteorites (or siderites) formed by Ni–Fe alloys (Fig. 1).

From the composition of the meteorites originating from our closest neighbours, the Moon, Mars and near-Earth asteroids, we know that these celestial objects might contain non-negligible resources in terms of valuable metals. For instance, the so-called KREEP-type basalts known to be the most trace element-enriched rocks on the Moon, particularly in potassium (K), Rare Earth Elements (REEs) and phosphorus (P), have higher contents in heavy REEs (Dy to Lu) than some carbonatite-nepheline syenite magmatic complexes that are often mined for REEs (Fig. 2). Nevertheless, for other metals, the Moon might not be as attractive as the Stony-iron and Iron meteorites originating from the main asteroid belt, the region between Mars and Jupiter.

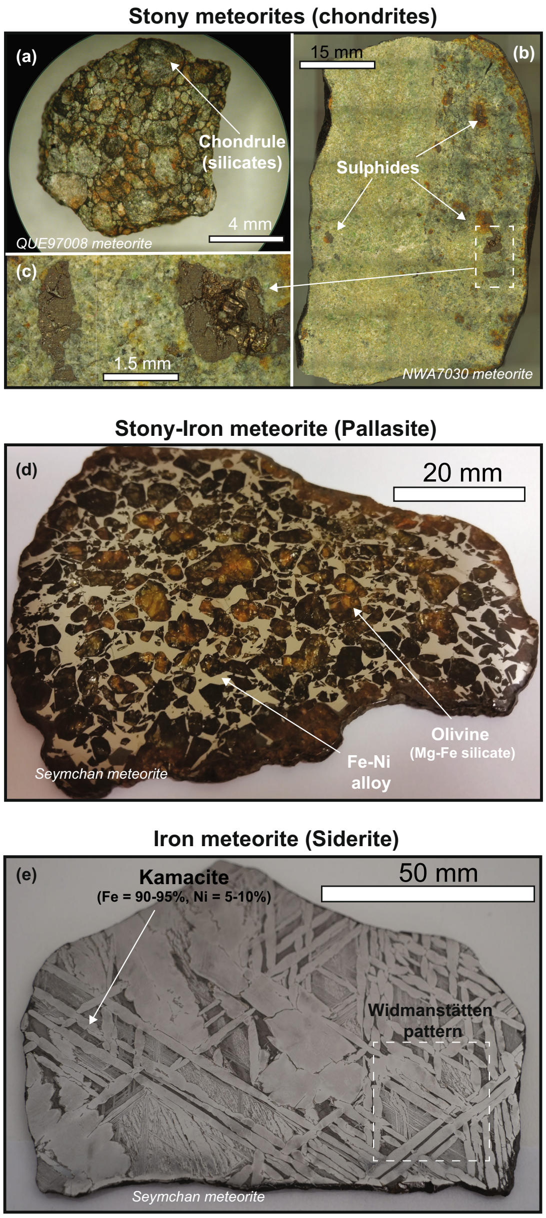


Fig. 1. Photographs of the three main types of meteorites usually found on Earth with their typical identification features. Panels (**a**–**c**) Stony meteorites (chondrites). **a**. Meteorite Queen Alexandra Range (QUE) 97008 collected in Antarctica in 1997 showing mm-size chondrules (small balls of silicates formed during the first 10 Myr of the solar system's life). **b**. Northwest Africa (NWA) 7030 meteorite collected in Morocco in 2011 and showing mm-size sulphides. **c**. Close-up of sulphides in NWA7030. **d**. Pallasite facies of the Seymchan meteorite found in Magadan district in Russia in 2004, showing large olivine crystals up to 1 cm across in a Fe–Ni rich metal matrix. **e**. Siderite facies of the Seymchan meteorite facies with Widmanstätten pattern (interleaving of Fe–Ni alloys kamacite and taenite lamellaes between which gaps are filled with fine grained mixture of kamacite and taenite. This facies of the Seymchan meteorite was initially discovered in 1967 and until the recovery of the pallasite facies in 2004, the Seymchan meteorite was classified as an iron meteorite.

Both pallasites and siderites are particularly interesting as they contain large amounts of metals such as the previously discussed REEs, but also Ni, Co and platinum-group elements (PGEs) such as Pt, Ir, Re, Os that are all critically needed for a fossil-fuel-free future society. Moreover, all these metals are rare in Earth's crust or poorly accessible as they are dominantly stored in the planet's core, but they are present in many asteroids in concentrations exceeding the contents of ore deposits on Earth by orders of magnitude (Fig. 3). Assuming sufficient technological capabilities will become available with time, these elements could be retrieved from asteroids, especially from those orbiting relatively close to Earth. In addition to the high concentration of many critical metals in asteroids, there is no life on those minor bodies, at least to the best of our knowledge, so ecosystems and biodiversity are not at risk if asteroid mining should materialise. As such, the volume of valuable mineral resources available on a given asteroid represents a credible alternative to intensive mining of those same materials on Earth. Furthermore, extracting space resources would safeguard stock on Earth to ensure that future generations will not face dramatic resource shortages. It has therefore been argued by some that exploitation of space resources is in fact, a moral obligation. For instance, a large amount of resources from the solar system would be pivotal to ensure that the global South is given the opportunity to technologically advance to a level presently seen in the Western World, especially if Earth's resources are insufficient to achieve this goal.

Pros and cons of exploiting extra-terrestrial resources

The extraction of extra-terrestrial resources (often incorrectly dubbed as 'space mining') encompasses relatively straightforward activities such as metal recovery from asteroids as well as other more hypothetical operations like gas extraction from atmospheres and ice caps of rocky planets and moons. The idea of 'asteroid mining' has been explored in science fiction literature for many decades, but it is now being considered more seriously. The potentially high concentrations of valuable critical metals are the main reason for the strong interest in asteroid mining shown by companies such as SpaceX, Planetary Resources, or Deep Space Industries. However, there are still huge technical and financial obstacles to 'space mining' as illustrated by these the fact that the last two companies were unable to raise the capital required to continue. Furthermore, using resources from our solar system cannot be seen as the 'miracle solution' for the current issues faced by our society. Indeed, there are obvious major drawbacks to using extra-terrestrial resources. For instance, exploiting extra-terrestrial resources might be perceived negatively by the general public as an extreme expression of greed from different economic actors, and would probably promote hyper-capitalism as only some companies and countries might be able to take advantage of the opportunities offered by space resources. Instead of rethinking the economic model of never-ending economic growth and human exploitation of the geo- and the biosphere, space resources could be seen as a measure to keep this model alive despite the growing concerns about long-term sustainability in a finite-resource world.

Indeed, space could even become the new El Dorado, exemplified by a 2020 executive order issued by the previous US presidential administration, which established US policies regarding the exploitation of extra-terrestrial resources, including on the Moon. Executive Order 13914 allows any American individ-

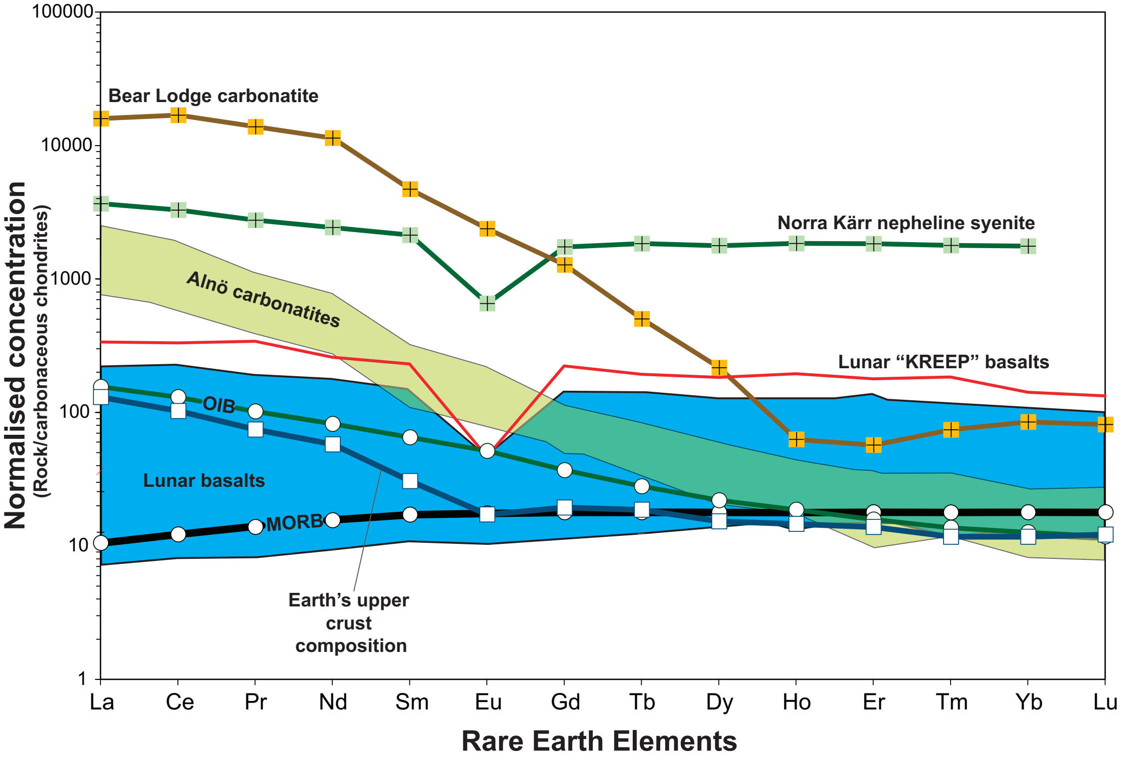


Fig. 2. Chondrite-normalized Rare Earth Elements patterns of lunar basalts including KREEP basalt (data from C. Neal compilation, unpublished). For comparison, are shown the field of the carbonatites from the Alnö alkaline complex in Sweden (unpublished data); Bear Lodge carbonatite (REE deposit actively mined in Wyoming; data from Moore et al., 2015) and Norra Kärr alkaline complex (cancelled mine prospect in Sweden; data from Sjöqvist et al., 2013). Reference patterns of terrestrial rocks are also shown: average composition of the Oceanic Island Basalts (OIB), Mid Ocean Ridge Basalts (MORB) and Upper continental crust (data from Sun and McDonough (1989) for OIB and MORB and from Taylor and McLennan (1985) for upper continental crust). Normalization values from Sun and McDonough (1989).

ual to pursue commercial activity on the Moon and on asteroids. Other states, including Luxemburg, Japan and the UAE have also recently adopted similar regulations, signalling a growing trend for nations to put their own commercial interests first and abandoning the idea of treating space as a 'global commons' before that idea can even be widely shared with humanity at large. Such national viewpoints and legislation or policies do not guarantee an equitable distribution of space resources, but rather promote (whether on purpose or not) another 19th-century-style 'Gold Rush' with potentially similar severe geopolitical and economic consequences. In particular, space resources might become concentrated in the hands of early-moving companies and states with efficient space programs and vast financial resources, eventually leading to quasi-monopoly situations.

On the other hand, it is naive to think that such opportunities for wealth gain will be spurned by corporations or states. The prospective value of off-world resources could potentially transform space into a locus of further tensions between states while 'Earth-based' strained relationships are already spreading into Space as illustrated by the recent military activity in the near-Earth orbit or the withdrawal of Russia from any international collaborations regarding space exploration. With its recent moon landing, China has pushed hard to be a leader in space exploration, especially at this point in time when regulations on using extra-terrestrial resources are not (yet) clearly defined.

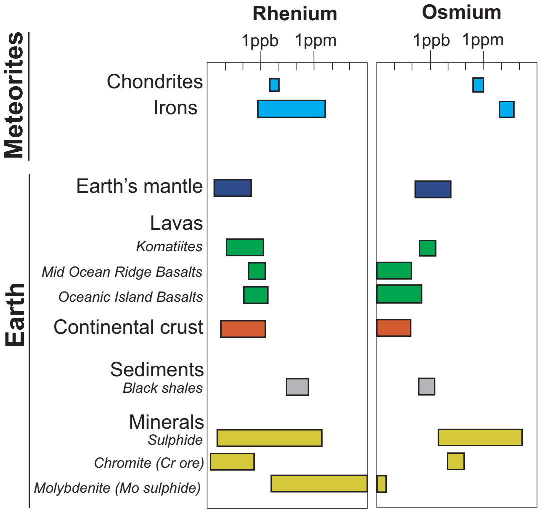
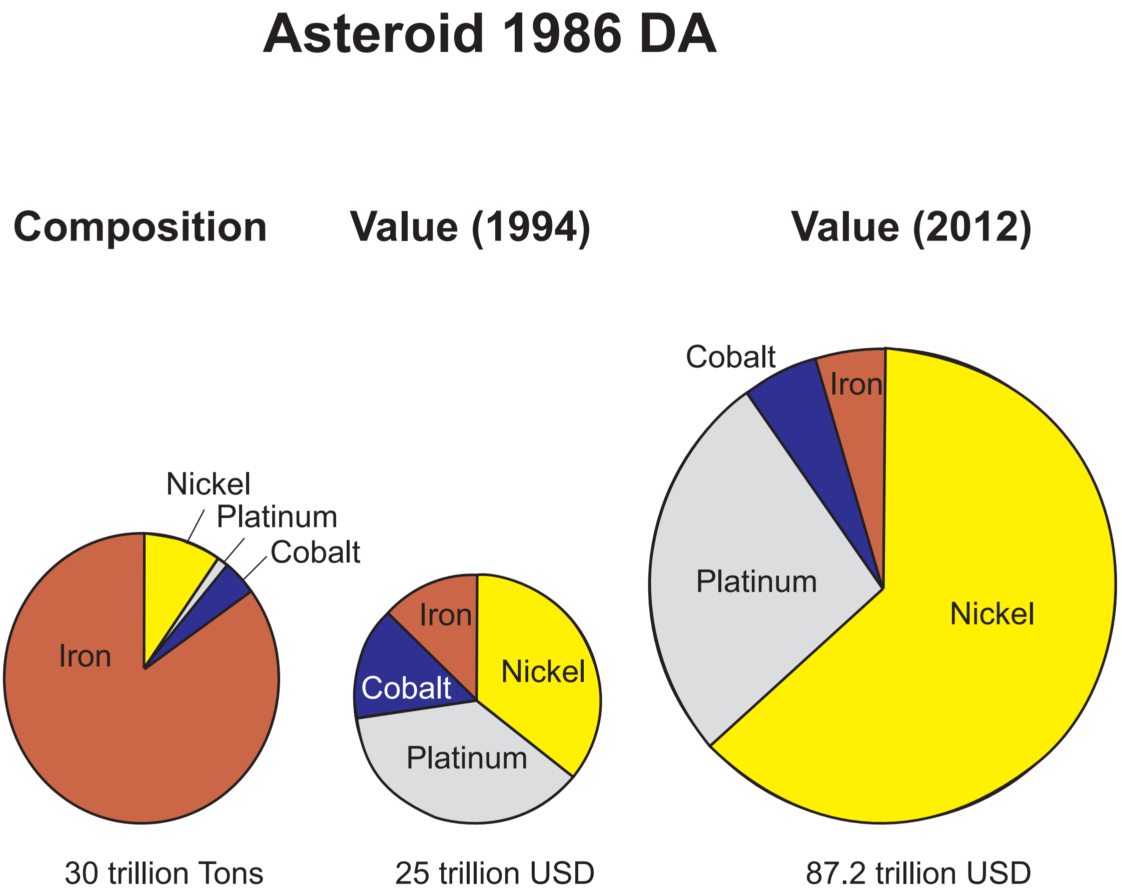


Fig. 3. Rhenium (Re) and Osmium (Os) contents (in part per billion or ppb and part per million or ppm) in different terrestrial rocks and minerals as well as in meteorites. The content range of Re and Os in iron meteorites is up to 1000 times higher than those in the rocks commonly found on Earth. Only terrestrial sulphide ore deposits show rather similar contents but they are much more focussed geographically and restricted in size. Modified from Carlson (2005).

All the states with even an embryonic space program might enter the fray to secure access to unclaimed resources. Even at Sweden's Esrange space complex near Kiruna, work is beginning to take shape to provide satellite launch capabilities. It is an interesting 'coincidence' that this old mining region is now under the management of the Swedish Space Corporation, realising the coexistence of a 'spaceport' and a mining infrastructure in the same locality—as would be required for an operation exploiting space resources.

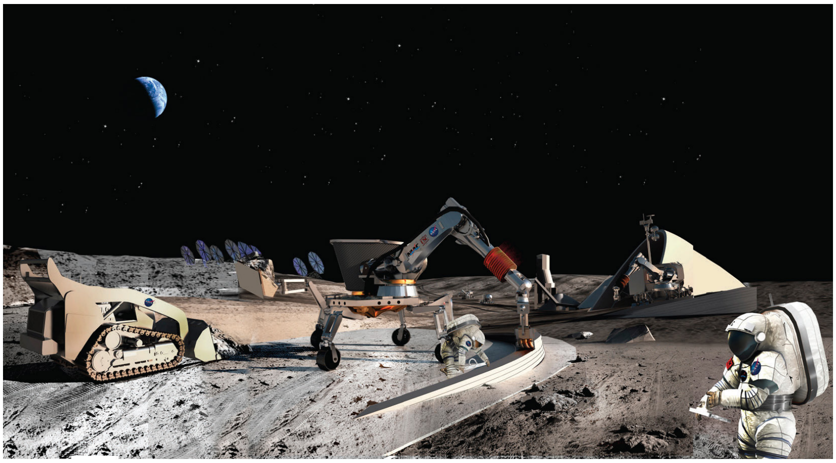
Despite the possible inequalities that may arise from a space exploration 'race' and space resource utilisa-

Fig. 4. Metal contents and estimated value of Near-Earth asteroid 1986DA. This asteroid is classified as near-Earth object and has a diameter of ~3 km that makes it one of the most suitable targets for asteroid mining. The chemical composition of this asteroid has been estimated by remote sensing and as such, the metal contents remain associated with some uncertainties at present. Modified from Shevchenko (2020).



tion generally, the very high value of space-derived commodities in today's market that would be gained could make asteroid mining a highly profitable operation irrespective of the currently high cost of space flight. This potential gain is illustrated by the very first value estimates suggesting that some asteroids could be worth up to 100 billion USD (i.e., close to the nominal GDP of Slovakia in 2020 estimated by the World Bank) depending on size (Fig. 4). However, extra-terrestrial resources will be only valuable at least in part if they are marshalled carefully. Indeed, if we were to mine an entire asteroid and return its valuable materials in one go, that material would entirely devalue its market and possibly the global economy in general.

Fig. 5. Artist's impression of ISRU-based construction technologies for lunar infrastructures. (Image courtesy of NASA)



Because of the at least in part beneficial economical aspects, there is now a strong interest for space exploration with many countries (USA, China, Russia, Iran, India, Japan, EU) and private companies involved. Furthermore, the recent success of Japanese and Chinese sample return missions like Hayabusa (to asteroid Ryugu), Chang'e 5 (to the Moon) or navigation to an asteroid like the recent DART mission, suggests that the technological challenges involved in mining, drilling or scooping material on asteroids are surmountable despite being still formidable. Supported by the appropriate technology, the foreseen rarity of critical commodities on Earth will certainly create at least a temporary value increase for many elements that could make 'space mining' ultimately highly profitable. Under such a scenario, the underlying question will necessarily be: are the raw materials to be brought back to Earth or are they to be processed in space? Bringing large amounts of resources to Earth seems to be the fulfilment of Isaac Asimov's vision of a world, Trantor, that is completely transformed by humans, producing nothing but being fed by 40 other worlds. As such, the utilization of extra-terrestrial resources could herald an entirely new economic and technological era in human history where a traditional market economy as we know it may no longer apply. Yet entering material into the atmosphere for return to Earth's surface is hazardous, and poses critical risks both to any payload being returned and to people and infrastructure on the ground. This trade-off is another of the many that must be considered when deciding whether, and how, to seriously pursue opportunities in space mining, but is unlikely to stop operations that are keen to exploit the vast resources available in space.

These prospective profound economic and societal changes will take time and may only happen at perhaps the end of this century, but there is another potential use of extra-terrestrial resources that could happen earlier, that is, as soon as in the next few decades. Indeed, the recent interest in extra-terrestrial resources has a rather immediate consequence in the framework of the ongoing commercial and national interest in space. To sustain space exploration, the use of extra-terrestrial resources and necessary construction material sourced 'locally' (often referred to as 'In Situ Resources Utilization' or ISRU) will become a likely reality. This might become a necessity as long as the transfer to space from Earth of materials and equipment needed for space exploration remains expensive, and will so prevent further resource depletion on Earth. In other words, the transfer of production and manufacturing operations to space would thus help to preserve Earth's fragile ecosystem. This paradigm is illustrated by the new NASA Artemis program, in which ISRU technologies are being developed to one day produce water, rocket propellant, solar cells, construction materials, etc. on the lunar surface. Ultimately, ISRU would also create stepping-stones for further solar System exploration to Mars and, perhaps one distant day, beyond Mars, which could ultimately lead to the establishment of permanent human settlements off-world.

Outlook

The forthcoming energy system transition will be a game changer that could bring our society to the brink of planetary resource depletion. This scenario could be at least somewhat mitigated if alternative sustainable resource supplies are used and extra-terrestrial resources are one crucial option in this respect. Large-scale exploitation of extra-terrestrial resources might not happen in the next few decades. However, as illustrated in the 1960s, development of space technology is a fantastic driving force for technical and technological innovations with wide applications. For instance, the effects of global warming could not be accurately monitored as they are nowadays without the help of satellites. In the long term, the use of extra-terrestrial resources has the potential to provide an unparalleled source of wealth for humankind in the next 30–50 years. On even longer timescales, using extra-terrestrial resources could enable our species to establish research stations, move to other worlds and ultimately even permanent settlements in the solar system (Fig. 5).

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