The approach to sustainable space mining: issues, challenges, and solutions

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Abstract. Harvesting and using space resources and energy has always been a dream of mankind for centuries as well as a popular topic for science fiction novels. In recent years, technological development makes space mining possible or even a reality in the near future. Accordingly, not only governments but also ambitious private actors are engaged in space mining activities. In addition to increasing investment, the USA and Luxembourg have erected their national space law to answer industrial needs. However, existing international law fails to address these activities in an effective manner, and many issues remain unresolved. Without further regulation, a laissez-faire approach would be detrimental to the growth of this nascent industry. Some challenges are likely to happen, such as conflicts between multiple States, inequalities in benefits sharing, and environment contamination. As a result, for promoting sustainable exploitation and use of space resources and energy, this article suggests some solutions, including: 1) guaranteeing legal certainty; 2) ensuring sufficient investment; 3) strengthening international cooperation; 4) promoting environment preservation and protection.

1. Introduction
As the resource and energy supplies of the Earth continue to dwindle, outer space is the only place we could find fresh supplies of both energy and raw materials. An asteroid belt between Mars and Jupiter, and near-Earth asteroids, with an abundance of resources, are capable of exploitation. For example, the Moon contains vast amounts of natural resources, like uranium, titanium, silicon, etc. And it’s estimated that Helium-3, a light and non-radioactive fusion fuel that is abundant on the lunar surface while rare on Earth, is enough to power human energy needs for up to 10,000 years [1]. At present, the extraction and use of space resources and energy is not technically feasible, but is expected to happen in the near future. Many believe that space mining could support commercial application, stimulate technological innovation, produce economic return and give important contribution to create and redistribute wealth in the world. Consequently, not only governments but also ambitious private actors are engaged in space mining activities. For example, National Aeronautics and Space Administration (NASA) launched OSIRIS-REx spacecraft in 2016 to explore the asteroid Bennu before collecting a sample to return to Earth, which will improve our understanding of the resources in near-Earth space. Similarly, China is devoting more effort to the space-based economic opportunities just on the horizon. On January 3, 2019, China soft-landed the Chang’e-4 robotic lander and rover on the far side of the moon, and released Yutu-2 to explore the lunar landscape. Besides, Planetary Resources embarking on the world’s first commercial deep space exploration program has announced plans to mine asteroids for gold, platinum and rare minerals and transform asteroid water into rocket fuel.
time’ has come, the exploitation and use of space resources and energy require proper governance now.

Space sustainability has become an important concern at modern times, aiming for the balance between economic growth, care for the environment and social well-being. Although a multifaceted approach is being adopted to promote space mining, the current legal framework suffers various inadequacies in addressing this issue effectively. When the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (19 December 1966) (the Outer Space Treaty) and the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (24 October 1970) (the Moon Agreement) were concluded, there was no urgency to regulate it. In particular, there was no sufficient scientific information available regarding space resources and the possibility of their economic use. Consequently, the two treaties do not regulate the exploitation and use of space resources directly. Nevertheless, the Outer Space Treaty, as the cornerstone of international space law, could provide guidance for space mining, but their contents are not at all clear. The Moon Agreement further emphasized and developed the Outer Space Treaty, which were not accepted by the major space-faring countries.

Thus, so far there are no international agreed rules to govern the exploitation and use of space resources and energy. A laissez-faire approach would be detrimental to the growth of this nascent industry. This article focuses on the issue of promoting sustainable exploitation and use of space resources and energy. Part 2 analyses the latest developments in space resources and energy and summarizes deficiencies of the current legal framework in addressing this issue effectively. Part 3 discusses possible challenges due to lack of proper regulation at the dawn of space mining. Part 4 suggests solutions for sustainable space mining.

2. Latest Developments in Space Resources and energy
As shown in Figure 1, many modifying factors need to be considered to convert Mineral Resources to Ore Reserves. There include mining, processing, metallurgical, infrastructure, economic, marketing, legal, environment, social and government factors. Hence, in recent years, a multifaceted approach is being developed to advance the technological, economic, and legal readiness for the harvest and utilization of space resources and energy.

Figure 1. JORC, 2012. Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (The JORC Code).

2.1. Advances in technology and hardware
Many technologies and hardware have been developed to promote space mining, such as Remote Sensing, Visible Imaging, Neutron Spectrometer, Lunar Reconnaissance Orbiter, Cosmic Ray Telescope for the Effects of Radiation (CRaTER). And a substantial breakthrough has been made to
achieve the benefits of In Situ Resource Utilization (ISRU) for a reasonable cost, mass, and risk. As we all know, space resources can be used in situ or transported to Earth. ISRU means any hardware or operation that harnesses and utilizes ‘in-situ’ resources to create products and services for robotic and human exploration [2]. And ISRU will change the way we explore the outer space. For example, Moon Direct would be the most effective transportation system to access to the lunar surface. By making using of LOx/H2 propellant produced at a lunar polar base, it could support the operation of a lightweight Lunar Excursion Vehicle (LEV) flight system. These space-sourced propellants can dramatically reduce the cost of every other activity in cislunar space. Table 1 provides some examples. Besides, ISRU could also support lunar missions in other ways. For example, a repairable lunar power system can be generated founded on the fabrication of silicon solar cells by thin film growth technology in an ultra-high vacuum environment, resulting in an energy-rich environment for the Moon.

| Cislunar Activity                                      | Space-Sourced Propellant Benefit          |
|--------------------------------------------------------|------------------------------------------|
| Transportation from Earth to Geosynchronous orbit      | 10-20% lower cost                        |
| Transportation from Earth to Lunar surface             | 70% lower cost                           |
| Cost of a human mission to Mars                        | 2-3 times reduction                      |
| In-space transportation                                | Essentially the cost of space-sourced propellant |

* The data are collected from the Lunar Polar Prospecting Workshop: Findings and Recommendations.

2.2. Economic support from public and private entities
With a potential customer base, space mining is considered to be promising and interests States as well as private actors recently. In addition to USA and China, Luxembourg is also taking part in the race by setting up a $227 million fund to entice space mining companies to open offices in the country and make it the hub of space mining innovation. Similarly, the United Arab Emirates is making a multipronged effort to establish a space mining industry, such as an investment of more than $5 billion. At the same time, governments are turning to private companies increasingly and providing confidence for investors in order to generate revenues and open new markets. Accordingly, several commercial initiatives have started for asteroids and the moon, by Planetary Resources, Deep Space Industries, Google Lunar X-Prize, Lunar Missions Ltd, Moon Express and so on.

2.3. Inadequacies of the current legal framework
To answer industrial needs, the US has adopted Commercial Space Launch Competitiveness Act (CSLCA) to facilitate the commercial exploration for and commercial recovery of space resources by U.S. citizens. Luxembourg followed suit and erected its national space law. Concerns have been raised about whether the domestic legislation conflicts with international law. Under the Outer Space Treaty, States shall carry on activities in the exploration and use of outer space in accordance with international law. However, the current legal framework suffers various inadequacies in addressing space mining activities effectively.

The Outer Space Treaty provides that outer space shall be free for exploration and use by all States; such freedom shall be non-discriminatory, equal and in conformity with international law; all areas of celestial bodies shall be freely accessible; and scientific investigation in outer space shall be free in Article I. It’s worth noting that the Outer Space Treaty restricts such freedom to science investigation, without referring to commercial exploitation and use of space resources. It is argued that the freedom
to engage in scientific exploration of outer space does not justify large-scale exploitation of extraterrestrial resources for commercial purpose. Meanwhile, Article I of the Outer Space Treaty also provides that exploration and use of outer space shall be carried out for the benefits and in the interests of all countries, regardless of their degree of economic or scientific development, and shall be the province of all mankind. Under this provision, the obligation of countries to share benefits is legally binding. However, States Parties hold opposing positions on what constitutes ‘the interests of all countries’ and how to share benefits might rely largely on their good faith.

Besides, Article II of the Outer Space Treaty embodies the non-appropriation principle, which proscribes the national appropriation of outer space ‘by claim of sovereignty, by means of use or occupation, or by other means’. From article VI of the Outer Space Treaty, it can be inferred that ‘national appropriation’ covers both States appropriation and private entities appropriation. Although this principle precludes the possibility of appropriation of outer space and celestial bodies, whether it extends to natural resources therein is uncertain as the Outer Space Treaty never makes a distinction between them, and the term ‘outer space’ does not suffice to include both outer space broadly considered and its natural resources.

What’s more, Article IX of the Outer Space Treaty has laid the basis for environment protection of the outer space. It requires that States pursue studies and conduct exploration of outer space so as to avoid their harmful contamination and also adverse changes in the environment of the Earth. And States are obliged to consider the environmental aspects for the authorization and supervision of national activities in outer space and adopt appropriate measures when necessary. However, the provisions contained in this principle are rather vague and broad.

3. Possible challenges at the dawn of space mining

3.1. Conflicts between multiple States
Space resources, as res communis [3], can be appropriated to some extent on the basis of freedom of exploration and use of the outer space. However, it is likely to follow a ‘first come, first served’ approach to space resources activities. In fact, the ‘first come, first served’ approach drove early and rapid development of oil industry of the US in the 19th century, although a frenetic race among surface owners followed and led to an extraordinary waste of oil and gas. Given that so far there are no agreement or property rights on space resources, they are essentially in a ‘state of nature’. Allocation by the ‘first come, first served’ approach is simple and requires very little government involvement to deter another one (called a ‘junior’) from displacing the rightful first comer (called a ‘senior’). However, overprotecting the senior by priority rights could run the risk of disorder, waste, inequality, and even monopoly. The Outer Space Treaty, requires State parties to conduct all their activities in outer space ‘with due regard to the corresponding interests of all other States Parties’. Without specific coordinating rules, conflicts between multiple States are likely to happen. Private entities may choose to arm themselves to safeguard their own interests. In extreme cases, States may also protect them by placing weapons of mass destruction in outer space if necessary [4]. As a result, priority rights should not be absolute but subjected to some arrangements.

3.2. Inequalities in benefits sharing
Basically, the exploitation and use of space resources would bring a wide-range of benefit and interests to all countries. Space-faring countries who have invested much on such activities are certainly entitled to profit from the work of their own labor. Developing countries, despite with limited capabilities for space exploration, could also benefit from such activities. Nevertheless, the common benefit and interests of all countries are not equivalent to the common benefit and interests of every country. It’s conceivable that, with different level of economic or scientific development among States, the benefits and interests they gain from space mining vary. However, under current space law, developing countries hardly benefit from space mining. Because of the competing views and interests among different countries, substantial disagreement also exists with regard to benefits sharing. This
issue has become more tangible and pressing especially given that space mining would become a reality soon. Specifically, space-faring countries are reluctant to sacrifice the ‘hard earned’ benefits to those who don’t have the capacity to invest or gain them on their own, while developing countries are pressing for equitable distribution of benefits.

3.3. Environment contamination
Space resources activities are *per se* ultra-hazardous activities, which may be harmful to both the outer space and the Earth environment. Forward contamination arising from Earth affects the environment of outer space. This type of contamination may include: all forms of debris found in outer space of nonhazardous nature; hazardous waste which is chemically or physically dangerous; radioactive waste which is the residue of nuclear powered space objects; biological material from Earth to a planetary body with space probes or human space missions, etc. [5]. While backward contamination arising in space adversely affects the surface or atmosphere of Earth. In particular, returning spacecraft may also spread pollution or bring back waste, such as radioactive debris and extraterrestrial material. For this reason, we should carry out these activities with a high standard of care and due diligence, in spite of uncertainties about specific contamination at present.

4. Solutions for sustainable space mining
The World Commission on Environment and Development (WCED) defines the concept of sustainable development as ‘development that meets the needs of the present without compromising future generations to meet their own needs’ in its report *Our Common Future* in 1987. After continuous development, some principles are incorporated into sustainable development concept, such as sustainable use and integration, intragenerational equity and intergenerational equity, precautionary approach, international cooperation. For sustainable space mining, these principles could provide a useful reference for us.

4.1. Guaranteeing legal certainty
The negotiating history of the Outer Space Treaty demonstrates that the term ‘appropriation’ in Article II is primarily concerned with the expansion of State territory. But the legal status of natural resources is not necessarily the same as the surface of land, drawing from three different types of property over natural resources of the subsoil in Earth: i) the regime of accessio; ii) the national property model; and iii) the model of absolute property of the State. Consequently, the land in outer space not under national or private dominion doesn’t mean that exploitation of natural resources in the subsoil is unlawful under Article II of the Outer Space Treaty. And many examples confirm that the exploitation and use of resources to some extent can occur in areas beyond national jurisdiction or of global interest. For example, the protection of property rights over resources that private actors may recover from the deep seabed, doesn’t necessarily amount to a sovereignty claim over the territorial area. Mineral resources could become the property of miners based on their labor or effort rather than their sovereignty over the deep seabed. Hence, considering the recent resurgence in public and private interest in the mineral exploitation in space, an international regime should be formulated for the purposes of clarity and legal certainty. Otherwise, the investment pool would shrink and the process of the exploration and use of outer space by mankind would be hindered.

4.2. Ensuring sufficient investment
The financial support for the research and application of related technology is essential. In particular, commercial incentives could promote investment in the exploration of space resources and enable the development of the most efficient use of resources. With the prospect of property rights, private sectors would make every effort to invest and develop technology for profits. For instance, Deep Space Industries (DSI) is pioneering a new capability for space exploration with low cost and great performance. However, without government interference, the commercial approach does indeed generate extreme distributions of wealth. Due to huge economic and technological disadvantages,
developing countries may be left far behind by space-faring countries. As a result, the international community needs to carefully balance the interests of developed and developing countries which are reconcilable and not mutually exclusive.

4.3. Strengthening international cooperation
To avoid the risk of conflicts, the international community should not vest an absolute monopoly in the senior and deprive a whole neighborhood or community of his rights. By international cooperation, rights therein can be distributed equitably and waste and abstract claims be avoided. Besides, a dual system may be another good choice to coordinate international competition for space resources. Due to the vastness of outer space and the uncertainty of resources, it’s more advisable to establish reserve zones on the moon and Mars for those countries with limited capabilities for space mining.

Additionally, space mining is beneficial in a general sense, as it is sufficient to achieve ‘the greatest good for the greatest number’. But, to make these benefits truly accrue to all countries and avoid tragedy of anti-commons, international cooperation could provide a feasible way to strike a balance among different players. By international cooperation, States would conduct space resources activities with due regard to the corresponding interests of other States and the international community. Developing countries could be enabled to bridge the still widening gap of technology and knowledge, which is beneficiary for their future development and considerably contributes to worldwide stability and peace. And there are various options we could use to carefully balance the interests of developed and developing countries, such as joint ventures, compensation and other measures of economic assistance for affected developing countries.

4.4. Promoting environment preservation and protection
Recently there is also a growing tendency not only towards tackling the problem of environment preservation and protection in the outer space, but also towards trying to avoid their harmful contamination to the maximum possible extent. Space sustainability has become an important concern at modern times. Regarding forward contamination, the fragility of space environment itself and our general lack of much understanding of that environment are behind the reasoning of the precautionary principle. And it is always easier to avoid contamination than deal with it after it emerges. As for backward contamination, we should also take prudent precautions to protect Earth’s environment. For instance, Committee on Space Research (COSPAR) promulgated Planetary Protection Policy as an international standard on procedures to avoid organic constituent and biological contamination in space exploration. Category V pertains to all Earth-return missions. For the subcategory defined as ‘Restricted Earth Return’, destructive impact upon return is absolutely prohibited and strict containment and timely analyses are needed after the mission. In addition to maintain the Planetary Protection Policy, the proposed international legal regime on space mining could also refer to corresponding measures in the Draft Building Blocks (DBB) for the Development of An International Framework on Space Resource Activities of the Hague Space Resources Governance Working Group (HSRGWG). For example, it could require States to review prior to the authorization of space resources activities, develop technical standards, assess conformity to avoid harmful impacts, and conduct response measures if a harmful impact occurs.

5. Conclusions
As ‘money time’ has come, the exploitation and use of space resources and energy require proper governance now. Although a multifaceted approach is being adopted to promote space mining, the current legal framework suffers various inadequacies in addressing this issue effectively. When the Outer Space Treaty was adopted, the issue of exploitation and use of natural resources and energy did not emerge, thus not be addressed expressis verbis. But no explicit prohibition, does not amount to lawfulness. Without further regulation, a number of issues can be anticipated, such as over-consumption, disorder, intra-generational inequality even monopoly, and environment contamination. Given that space sustainability is becoming more popular at modern times, sustainable
development concept would be very useful for the international community to handle these problems. As a result, four approaches should be highlighted for promoting sustainable space mining, including: 1) guaranteeing legal certainty; 2) ensuring sufficient investment; 3) strengthening international cooperation; 4) promoting environment preservation and protection.

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