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Lunar Cold Microtraps as Future Source of Raw Materials—Business and Technological Perspective

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Abstract: The article uses the Lunar QuickMap tool to analyze and select five highly promising cold microtraps on the Moon in terms of the size of the deposits they contain and their accessibility with the use of rovers and other wheeled vehicles. Since the thickness of the layer containing raw materials is subject to high uncertainty, three arbitrary scenarios for the value of this parameter were assumed: pessimistic (1 cm), nominal (5 cm), and optimistic (1 m). For the analyzed sites, a preliminary market valuation of the raw materials contained therein will be obtained at USD 74 billion; USD 370 billion; USD 7403 billion for the assumed pessimistic, normal, and optimistic scenarios, respectively. The article presents a business and technological perspective on the issue of space mining on the Moon. It is also a selected synthesis of the state of knowledge about space mining on the Moon.

Keywords: moon; moon deposits; moon mining; space mining; space resources; carbon deposits on the moon; carbon

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1. Introduction

There is pressure around the world to urgently find alternative low-emission sources. New technological and business models for extracting mineral resources must also be developed to make mining a more sustainable and green industry. Moreover, there are raw materials (e.g., Rare Earth Elements (REE) and Platinum Group Elements (PGE)) that are critical for the development of modern technologies but are running out or controlled by a group of several countries [1] (China, India, Russia, Malaysia). Space mining offers a chance to solve many of these problems. Given the current state of technological development, not all space resources are equally accessible and promising.

The imagination of scientists and businessmen is fired up by the possibility of obtaining mineral resources from asteroids, which would not require interference in Earth's ecosystems. Some asteroids, at the current level of consumption of mineral resources, could provide a source of some metals (PGE, Fe, Co, and Ni) even for thousands of years [2], and the value of the raw materials they contain may even reach many billions of dollars. The Asterank online database [3] provides a ranking of asteroids in terms of their estimated market value. This is a scientific and economic database of over 600,000 asteroids. Other estimates can be found in paper [4]. Of course, these estimates are based on our current knowledge of the formation and composition of individual types of asteroids, and often on measurements of light reflected from their surfaces, which do not provide information about their internal structure. This results in high uncertainty in the estimates of the content of mineral resources accumulated in asteroids, and therefore also in their market valuation.

The Luxembourg Space Agency in its 2018 report [5] predicts that by 2045 there will be between 845,000 and 1.8 million full-time employees working in the space mining industry. Not all of them will work in space—some of them will work on Earth, e.g., in the design, construction and servicing of mining equipment, remotely control the operation of devices, etc.

However, the exploitation of raw materials from asteroids involves many technical challenges. Microgravity occurring on asteroids eliminates the possibility of using many mining techniques and devices known on Earth, which require gravity to operate. Examples of such devices that require gravity to function properly include wheeled vehicles, excavators, bulldozers, drilling and impact devices, gravity separators, conveyors transporting excavated material, and robot arms. The lack of gravity changes the dynamics of these devices, often making it difficult for them to function correctly or effectively. The devices must also have a high degree of autonomy and reliability, which can be a significant technical challenge. For example, during drilling typical borehole in oil and gas industry on Earth, many potential failures and drilling complications can occur [6,7] and some of them can occur also during drilling in space objects like planets and asteroids. Robotic mining equipment sent to asteroids that would use drilling methods (e.g., to collect samples) would have to be able to detect and respond to many known and unknown failures and technological problems, which would require the development of highly advanced control systems. The time scale of the project is also unacceptable to potential investors. We currently do not have the drives that would enable us to reach distant asteroids in a short time. For example, a trip to Mars takes minimum seven months [8] and requires waiting for the launch window, which appears once every two years. Asteroids rich in raw materials are much further away. What does this mean from an economic point of view? The first mission is unlikely to be successful. Raw materials also need to be brought back to Earth. This extends the time horizon for returns on investments from space mining operations on asteroids to 10 years or longer. Considering the high risk of mission failure, this could be unacceptable to most investors. There are NEOs (Near Earth Objects)—asteroids that are closer to the Earth, but they still suffer from the same technical problems as for more distant asteroids. Until humanity invents faster space drives, the exploitation of asteroids on an industrial scale will not be possible. Work is currently underway on nuclear drives [9,10] and even concepts of thermonuclear drives [11].

In the case of Mars, the economic calculus of exploiting its raw materials may be more favorable and its considerable distance from Earth would not have to be an obstacle if it could be colonized. In such a case, many mining operations would be carried out by people and devices would not have to have such a high degree of autonomy as in the case of asteroids. Mars' gravity would enable the use of mining solutions known from Earth—of course improved and adapted to local environmental conditions. Raw materials could be processed locally into high-margin, high-tech products and shipped to Earth. However, to make this possible, it is first necessary to colonize Mars, which will be a big logistical and technical challenge and will require the involvement of significant financial resources. Elon Musk is conducting R&D work aimed at developing a Starship space vehicle that will enable the colonization of Mars. Starship is still being tested and has not yet reached Low Earth Orbit (LEO) at the time of writing this article. Additionally, the problem that will need to be solved is refueling in orbit so that it can make further interplanetary journeys—it is necessary to develop a logistics system here. It is worth adding that the colonization of Mars could also facilitate the exploitation of raw materials in the asteroid belt, which are closer to Mars than to Earth, and starting from Mars requires less energy than from Earth. However, this is still too distant a perspective to be considered in the next decade. There are also many meteorite craters on Mars, some of which may be a source of raw materials. Over 384,000 craters over 1 km in diameter have been identified on Mars [12]. When a meteorite impacts, some of its material is thrown into space, but some remains at the point of impact. If the meteorite was metallic, there may be metallic deposits where it fell. The famous Sudbury metal deposit in Canada (Sudbury Basin) was formed 1.8 billion years ago as a result of the fall of a meteorite with a diameter of 10–15 km.

The Moon is a much more convenient place to conduct the first mining operations in space than asteroids or Mars. The flight time to the Moon takes about three days [13], which means that you can relatively quickly obtain feedback from failed space missions and send improved versions of the devices. Similarly, raw materials obtained on the Moon can be brought back much faster. The delay time of the Earth–Moon signal (propagation time to the Moon and back) ranges from 2.4 to 2.7 s, with an average of 2.56 s (the average distance from Earth to the Moon is 384,400 km), which allows you to control many devices on the lunar surface from Earth without leaving your home [14,15]. The lunar environment is also well known to us, we have been there, there is a lot of data from past space missions [16], and the future presence of people on the Moon in connection with the Artemis program gives in some locations a chance for astronauts to intervene if any problems with the equipment occur. The gravity on the Moon is 1/6 of the gravity on Earth, but it is sufficient to use many mining solutions known from Earth, which require gravity to operate. All this radically shortens the time horizon for return on investment and radically reduces investment risk, which is why space mining will probably start on the Moon.

2. Moon Raw Material Surveying Strategy

The surface of the Moon is 37 million km^2, which is larger than the surface of Africa. This provides enormous operational depth. It is necessary to significantly narrow down the search area for raw materials and carefully select places for future commercial space missions. Satellite data on the lunar surface can provide a lot of information about mineral resources, but without in situ research it is not possible to accurately estimate their size and whether their exploitation will be economically profitable. Until the deposit is confirmed in situ, e.g., by geological drilling with core collection, only probable deposits can be considered. In the case of satellite imaging of the Moon's surface, a big problem is that the space missions to date have been mainly scientific missions and the resolution of the obtained images (in the order of tens of square kilometers per pixel) does not meet industrial requirements. However, currently available data obtained by remote methods (e.g., spectroscopic measurements, neutron spectroscopy, SAR imaging, gravitometry, magnetometry) (lunar missions, e.g., Chang'e 1, Chandrayaan-2, Grail A, Grail B, Lunar Reconnaissance Orbiter, LCROSS, Korea Pathfinder Lunar Orbiter (Danuri)) can significantly narrow the area of further searches, enabling the selection of the most prospective places for future industrial mining space missions. However, a slightly different strategy for searching for such places should be used for each type of deposit.

2.1. Metal Deposits

The first type of deposits for which strategies for searching for prospective exploitation sites will be discussed are metal deposits on the Moon. According to current knowledge, the vast majority of metals on the Moon are located in Lunar Maria. However, their exploitation will be ineffective if their concentration is low. You should strive to find places with a limited area (operating depth) and a high concentration of metallic raw materials. In 2019, the world media reported sensational news about the detection [17] of a huge gravitational anomaly in the Lunar South Pole–Aitken Basin, with a length along the long axis of about 2000 km, which reaches up to 300 km deep into the Moon. This is an area of material with a density greater than the average density of matter on the Moon. The total mass of the anomaly is estimated at a minimum of 2.18×10^{18} kg. One likely explanation is that it contains the remains of a large metallic asteroid that hit the Moon billions of years ago. This would mean that there could be huge deposits of valuable metals worth tens or even hundreds of billions of dollars. Exploitation of such a deposit would probably require the construction of underground mines on the Moon, which is currently unlikely. It is more likely that space mining on the Moon in its initial phase will resemble surface mining rather than be based on large open-pit/underground mines, which would require gigantic investment outlays and prior precise geological reconnaissance on an industrial scale, including drilling numerous research wells. Hence, selecting the right places on the Moon for industrial metal exploration becomes even more important. Such places may impact craters. Asteroids are sometimes knocked out of their stable orbits into collision trajectories with other space objects, eventually crashing into their surfaces. If a "free" meteorite hits the Moon's surface, on average about 22% of the impactor's mass is located inside the crater created as a result of the impact. The size and shape of an impact crater depend on many factors including the speed of the impactor, the angle of impact, the mass of the impactor, as well as the type of ground on which the impact occurs. However, the most important factor is speed, which is related to the fact that the kinetic energy of the impactor is proportional to the square of its speed. An approximate relationship has been observed that in the case of meteorite falls, the size of the resulting crater is usually about 10 times larger than the diameter of the impactor, and in the case of comets, about 100 times larger, which results from the fact that comets, as a result of the degassing of their matter, obtain higher speed than classic meteorites. This allows us, based on the size of the craters on the Moon, to estimate the size of the meteorite that fell and how much material may be left behind in the crater. Of course, not every falling meteorite will contain valuable metals, especially since the most common asteroids in the Solar System are C-type asteroids (chondrite), which contain a relatively low content of metals compared to M-type asteroids (called "metallic"). However, one of the valuable raw materials that type C chondrites (called "carbonaceous chondrites") may contain carbon. There are plenty of impact craters on the Moon. The database [18] contains over 2 million craters. Of those craters, 1.3 million have diameters $\geq$1 km, approximately 83,000 are $\geq$5 km, and 6972 craters are $\geq$20 km. Two factors are important for the formation of resources in craters resulting from meteorite falls: what percentage of the impactor (whose fall formed the crater) will be thrown irreversibly into space and what concentration of individual raw materials the impactor has. In the report [19] (p. 9), you can find typical concentrations of elements and chemical compounds in various types of asteroids on the example of NEO asteroids, and [19] (p. 7) prices and market size for individual elements that may be present in asteroids. Even if a significant part of the primary impactor material is thrown into space, the exploitation of the remaining part may be economically profitable. Unfortunately, valuable metallic deposits in craters are often covered by a layer of dust and regolith formed in later periods after the fall of a meteorite, which is formed, for example, as a result of the fall of micrometeorites. By analyzing SAR satellite images of lunar craters, it is possible to determine whether they are young impact craters (usually the material contained in them reflects the radar beam more strongly and therefore has a brighter color) or old ones, and this determines whether raw materials will be easily available in subsurface layers or deeper buried. In particular, polymetric SAR radars may be useful in detecting erratic matter resulting from meteorite impacts [20], and therefore it is possible to detect shattered fragments of meteorites, which may contain e.g., metals. It is possible to relatively easily check whether a given crater contains metallic raw materials using gravimetry and magnetometry methods. Metallic raw materials will have a higher density than ordinary rocks, which will be visible in gravimetric images. Metallic raw materials will also be visible in magnetometric images, and a high-strength meteorite impact may strongly magnetize the surrounding rocks. Therefore, the places of occurrence of metallic raw materials are clearly visible in the compilation of gravimetric and magnetometric images. Craters, as places of meteorite falls, have another important feature—being part of the impactor's matter, which was destroyed into smaller fragments and thrown into space, and it falls to the surface over time.

2.2. Helium-3 Inventory

Another very valuable raw material found on the Moon is the helium-3 isotope. It is called the fuel of the future because it will be used in future generations of fusion power plants using aneutronic reactions, i.e., reactions that do not generate neutrons that destroy reactor shields and cause the formation of secondary radioactive elements as would be the case when using tritium. Thermonuclear reactors built to operate on the basis of ^{3}He fuel will be small, compact, ecological, highly effective, and highly competitive with classic nuclear energy. A detailed discussion on the advantages of D + ^{3}He fuel over D + T fuel can be found in the publication [21]. Helium-3 also has other important applications, e.g., cryogenics, quantum computers, and the detection of fissile materials through its use in neutron detectors. Unfortunately, on Earth, the helium-3 isotope is extremely rare and extremely valuable. It occurs in much larger quantities on the Moon. α particles, i.e., the nuclei of the helium atom, are a component of the solar wind with the ^{4}He/^{3}He isotope ratio of 2500:1. The Earth's magnetic field protects it from the influence of the solar wind. In the case of the Moon, for billions of years it has been deprived of a strong magnetic field that would protect it from the effects of the solar wind, and only has residual local magnetic fields. The Moon also has no atmosphere. As a result, solar wind particles reach the lunar ground and can be intercepted by it. For billions of years, the solar wind carried helium atoms, creating a huge inventory of helium (including helium-3) on the Moon. The resources of helium-3 on the Moon [22,23] were estimated at 6.50×10^8 kg. This is a resource that can be classified as renewable because the solar wind constantly deposits nuclei of helium atoms (including the helium-3 isotope). However, the given estimates of the resources of helium-3 on the Moon [22,23], it may be underestimated, because scientists currently believe that the Moon may have lost its magnetic field earlier than expected in previous analyses, and therefore the period of helium accumulation (including helium-3) on the moon could have lasted longer. The average [24] concentration of ^{3}He in the lunar regolith does not exceed 20 ppb. This means that with a ^{3}He concentration of 20 ppb, 150 tons of regolith would have to be processed to obtain 1 g of ^{3}He. Scientists believe that there may be areas of higher concentration of Helium-3 on the Moon. The results [25,26] of the Change-1 probe indicate that there may be regions with ^{3}He concentrations of 80 ppb/m^2 or higher on the Moon most of all in lunar maria. When looking for high concentrations of helium-3, attention should be paid to the presence of titanium and iron, and specifically the mineral ilmenite ($FeTiO_3$). Ilmenite can store up to 10 to 100 times more helium than other minerals in the regolith. Helium atoms are dissolved in the ilmenite crystal lattice, the structure of which allows helium atoms to penetrate and store in it. However, to extract helium (including helium-3) from ilmenite, it is necessary to heat it. In work [22], tests were carried out on the thermal release of helium from ilmenite. The optimal heating temperature for helium-3 was found to be around 1000 K, giving a cumulative release rate of 74% [27]. For an optimal heating temperature of 1000 K, the heat release time of helium-3 is approximately 1 s. At lower temperatures, helium-3 is also released from ilmenite, but the process is less efficient, mainly helium-3 is released from the shallower layers and the amount of helium-3 released is smaller. This means that obtaining helium-3 from ilmenite using thermal methods will be energetically expensive. Therefore, the discovery [28] made by the Chinese Chang E-5 probe that in the glassy surface layer of ilmenite helium is stored in gas bubbles is extremely important. The researchers were intrigued by why higher concentrations of helium were observed in the thin near-surface layer than shown by theoretical diffusion models. The disordered atomic packing structure of glass was found to play a key role in capturing and retaining helium. Compared to helium dissolved in the crystal lattice of the lunar soil material, which requires high temperatures to be released, helium contained in bubbles is much easier to extract through the use of mechanical grinding at ambient temperature (e.g., ball mills). It was determined that the upper surface layer of ilmenite is a glassy layer with dense, disordered atomic packing structures, and is approximately 40–50 nm thick. Beneath the glassy layer is an area of partial glass approximately 30 nm thick, followed by a crystalline phase. The glassy layer is formed as a result of irradiation of the surface with high-energy ions/particles from the solar wind or cosmic radiation. The mentioned bubbles [28] have a spherical shape and a diameter of 5–25 nm, and the pressure inside them is estimated at 1 to 39 GPa (for comparison, the pressure on the Moon is 0.3 nPa). The mass of ^{3}He in the bubbles should be up to 0.26×10^9 kg, which may constitute from 1/10 to 1/4 of the total

^{3}He reserves on the Moon. Fusion energy generated by approximately 100 tons of helium-3 could meet the world's energy needs for a year. Thus, the helium retained in the lunar glass bulbs, at current energy consumption, would be enough for humanity for about 2600 years. When looking for easily accessible helium-3 deposits, one should look for places where ilmenite occurs, most of all lunar maria, and that would be strongly exposed to solar wind and cosmic radiation, so that its surface layer becomes glassy, and helium can be stored there in the form of bubbles.

2.3. Water Ice Deposits

Another resource available on the Moon is water ice. Access to water for astronauts will be an important factor influencing the location of lunar bases. Water can be electrolyzed to give the components hydrogen and oxygen, i.e., components of rocket fuel (LOX, LH2). The oxygen obtained in this way can also be used for breathing by astronauts. However, the production of oxygen from water in the regolith is energetically profitable if the water content is above 2% [29]; otherwise, it may be much more effective to obtain it directly from the regolith, and what is more, the extraction of water from the ground may involve involves additional energy expenditure. Therefore, when looking for water ice deposits for oxygen production, one should look for those whose water content is at least above 2%. It should also be remembered that the reduced gravity on the Moon will affect the efficiency of the electrolysis process [30,31]. Local specific environmental conditions occurring on various space objects will have a strong impact on various chemical and physical processes, which will be slightly different than in Earth's conditions. The temperature of the Moon's surface varies from +110 °C in the middle of the lunar day to −180 °C in the middle of the night. It would seem that water ice cannot exist on the Moon. However, in some craters, there are permanently shaded areas where the temperature is low and water ice may occur in such conditions. This is due to the lack of an atmosphere that would scatter light and equalize the temperature. Shadows on the Moon are very sharp, and you can be in a sunny area where the surface temperature during the day can be as high as +110 °C, only to move just a few meters further into the shadow zone and find yourself in an ultra-cold area. The presence of water ice has been found [32] even in permanently shadowed areas in craters at the north pole of Mercury, which is the planet closest to the Sun and whose surface temperature in sunny places can be as high as 427 °C. Water ice on the Moon has three sources of origin: (1) solar wind—hydrogen atoms are captured by the ground and recombine with oxygen atoms contained in it; (2) comets that hit the lunar surface; (3) volcanic. The origin of water ice affects the substances it contains. If water ice is of volcanic origin, it will also contain compounds released during a volcanic eruption. This is of great importance for the search for possible substances that may accompany water ice, but also for water treatment processes for astronauts and industrial operations. Wilkoski et al. [33] suggest that ~41% of the total mass of H_2O emitted in volcanic eruptions during the period (4–2 Ga) could have condensed in the form of ice in the polar regions, up to several hundred meters thick. Their simulations show that the South Pole has twice as much water ice as the North Pole and the southern sediments are thicker. The simulation also shows that large amounts (8.2×10^{15} kg) of volcanic water ice could have been sequestered at the poles. These are only predicted results based on numerical analysis and require empirical verification. A more conservative approach to estimating water ice deposits on the Moon is presented by NASA [34], which in its report on water resources on the Moon notes that there is great uncertainty in the estimated values and recommends taking certain steps to be able to estimate these deposits with greater accuracy. Research is being conducted around the world on more accurate methods for estimating water ice deposits, including the use of radar technology [35]. Regardless of the source of water ice, appropriate temperature conditions are necessary for it to survive longer. The temperature limit for the occurrence [36] (Figure 3A,B) of stable water ice is 110 K (−163.15 °C) [37]. Such low temperatures occur in permanently shaded regions (PSR—Permanently Shadowed Regions). Areas on the Moon where various substances settle due to the low temperature are called cold traps. The temperature [38] in the permanently shaded regions (PSR) can drop even to −170 °C. However, there are even colder places on the Moon [39] that are ultra-cold traps. These are [38] double-shaded areas where the temperature can drop even to −250 °C. The ordinary permanently shaded regions (PSR) never reaches the light rays directly emitted by the Sun. However, heat rays emitted by sun-heated slopes or radiation reflected from these slopes may reach the area. A double-shaded area is one that does not even receive this secondary radiation, resulting in it being extremely cold and temperatures lower than in regular PSR areas. The importance of cold traps for the formation of some deposits on the Moon can be understood on the example of the mechanism for the formation of gold deposits proposed in [40]. There is no atmosphere or strong magnetic field on the Moon, which allows charged particles of the solar wind and cosmic rays to freely reach the lunar surface, which has its consequences. Charged particles falling on the lunar surface electrify the surface layer of the lunar soil. This means that particles of various minerals, if charged, can levitate in an electrostatic field. Particles [40] of gold can reach a dynamic equilibrium height of about 9 m in a few minutes. The levitating particles are carried away by particles of the solar wind, and their movement is influenced by the lines of the local residual magnetic field. The movement of charged particles is possible until they reach a non-electrified area, which occurs where sunlight does not reach, i.e., in shaded areas, which are therefore cool areas. The described mechanism affects not only the formation of gold deposits on the Moon, but also other minerals, as well as deposits of the so-called volatile substances that accumulate in colder regions. This is the reason why such places are called cold traps, and why looking for them is so important. Even in the case of helium-3 deposits, the described mechanism is important. Incident solar rays heating the regolith cause some of the helium contained in them to be released and carried away by particles of the solar wind, and then deposited in the areas of cold traps. A similar phenomenon also occurs for ilmenite, but to a lesser extent, because ilmenite binds helium more strongly. Therefore, higher concentrations of helium-3 should also be expected in shaded regions in cold traps. The ranking of cold traps in terms of the abundance of volatile substances can be found in the publication [41]. In turn, publication [42] presents the relationship between the crater depth and diameter ratio (d/D). The authors analyzed the d/D ratio for 753 craters ranging from 200 to 1000 miles in diameter and with an inclination of less than 25° located at the Moon's south pole and grouped the craters into two groups: craters containing perennially shadowed regions (PSR) and those without PSR. The d/D ratios of craters containing PSR compared to craters without PSR fall into two distinct groups, which means that these two groups may show some geomorphological differences. According to the authors, the difference in d/D ratios may be caused by the presence of a subsurface ice layer in the PSR. However, the influence of diffusive degradation of craters or various geological units cannot be rejected. Using this relatively simple method, it is possible to automatically pre-select craters containing PSR areas that are suspected of containing subsurface ice. When analyzing water ice deposits, the occurrence of the "Moon gardening" process should be taken into account [43]. This is a process in which the lunar surface material is mixed as a result of the bombardment of the moon by micrometeorites. As a result of these processes, water ice is mixed with regolith, or is located under a layer of regolith up to several meters high. In work [43], simulations of this process were carried out for water ice deposits on the Moon and Mercury. When looking for deposits of water ice and volatile substances on the Moon, you should first look for cold traps. These usually occur in craters in permanently shadowed regions (PSR). However, not every cold trap will contain water ice, or it may occur in deeper layers such that remote surface survey results suggest that the location is dry. In satellite imaging of such places, techniques should be improved to enable the analysis of deeper layers.

2.4. Carbon Deposits

Another important raw material on the Moon is carbon. It will be important for the production of fuel for Starship vehicles [44], which use a mixture of liquid oxygen (LOX) and liquid methane (LCH4), i.e., the so-called metalox. Classic fuel using a mixture of liquid oxygen (LOX) and liquid hydrogen (LH2) has many disadvantages. Hydrogen is highly penetrating and after some time the so-called hydrogen poisoning of engine materials. Based on a fuel mixture containing hydrogen, it is much more difficult to develop a reusable rocket engine, and therefore, a reusable rocket with a cheap operating cost. Matalox has no such disadvantages. It is therefore expected that in the future, there will be more rockets powered by this fuel. After being launched into Earth's orbit, the Starship must first be refueled in orbit to continue its journey to further destinations (such as the Moon or Mars), just like before returning to Earth. Thus, lunar carbon deposits will be important for methane production. While carbon occurs in large quantities on Mars (even in the atmosphere, which contains 95.32% CO_2), the situation is completely different on the Moon. Carbon is [45] present on the Moon in limited amounts, mostly as solar wind im-planted in the bulk regolith, and as carbon-bearing ices in the coldest regions at the poles. Carbon from the solar wind has a low concentration (about 100 ppm) and the resulting carbon deposits may amount to about 7×10^{13} kg in all surface regolith available near the lunar surface. In turn, polar carbon deposits may contain as much as 20% wt. C in the coldest regions, but are more likely to be in the range ~0–3% wt. C. The total abundance of all these deposits may be approximately 1×10^{11} kg. The author presented an analysis [45] (Figure 7, p. 10) of how much material would have to be mined to produce enough carbon to fill the Starship with 1200 tons of methalox fuel for three different cases: bulk regolith, polar ice with the LCROSS composition, and a hypothetical carbon-bearing subsurface ice deposit with 50 wt.% ice and 6.5% CCOI. Currently known sources of carbon on the Moon are unlikely to support long-term human presence on the Moon. However, looking at the chemical composition of asteroids in the solar system, some of them are carbonaceous asteroids. It is therefore highly probable that there will be impact craters on the Moon containing fragments of large carbonaceous asteroids with high carbon content, which may be covered by a layer of regolith. New discoveries are not excluded and it may turn out that the Moon contains more carbon than is currently known.

If we analyze the state of knowledge presented in this point, a certain pattern emerges as to where most of the valuable raw materials should be sought. Particularly interesting places are craters, especially the permanently shadowed regions (PSR) found in some of them, which can create cold traps. Of course, not every crater on the Moon contains permanently shadowed regions (PSR). It is assumed that the minimum latitude for the formation of permanently shadowed areas is 75° latitude, for the south and north poles of the Moon. The shape of the terrain must also enable the creation of permanently shaded regions (PSR) inside the craters. Not every permanently shaded regions (PSR) will be a good cold trap either, not to mention the exploration aspects which will be discussed later in the article. There is an observed relationship [46] between hydration and the content of TiO_2 and other elements. It is probable that the so-called "sweet points" will contain high concentrations of a few raw materials. Such places should be the starting point for a space mining mission on the Moon, as they offer a great chance to recoup the investment.

3. Moon Cold Traps Exploration Challenges

Since a large number of craters occur in the Moon's circumpolar regions and there are Permanently Shadowed Areas (PSR), including water ice deposits, it is not surprising that these areas are currently the subject of the greatest interest when it comes to lunar exploration, especially the southern pole, where the interests of rival global powers such as the USA, China, India, Russia, and the EU intersect. Currently [47], over 250 lunar missions, both commercial and scientific, are planned for the next decade. Given the enormous operational depth of the lunar surface, the bottleneck is the lack of a communication and navigation system for future missions. However, work is underway to solve this problem.

ESA is working on the ESA Moonlight communications and navigation constellation [48], which, according to ESA, can activate the development of a space economy worth EUR 100 billion and invites companies to create this system and services based on it. Lockheed Martin, and more specifically Crescent, a company belonging to this concern, is also working on a communication and navigation system called Parsec [49]. Lockheed Martin, together with General Motors [50], is also working on the next generation of lunar rovers.

However, commercial exploration of the Moon's south pole will be a great technological challenge. In the Apollo program, humans landed on the Moon in carefully selected locations that were flat, sunny, and close to the equator. Near the equator, the Δv needed [51] to reach these places is the lowest (~850 m/s), while in the case of the poles, Δv is ~1200 m/s. Since the amount of energy consumed by a rocket is proportional to the square of the change in its speed Δv, this means that landing in the polar regions will require almost twice as much energy, and therefore more fuel. Another challenge will be large differences in height, which in some lunar craters are greater than even the highest peaks of the Himalayas, as shown in [52] on the example of the Haworth crater (Malapert Massif—height difference from the crater floor of over 8 km) and the Shoemaker crater (Leibnitz Beta—height difference from the crater floor of over 10 km). Moreover, the slopes of craters on the Moon can be steep. All this may prevent the safe entry/exit of an exploration rover to/from the crater, not to mention large mining trucks. There may also be stones and other natural obstacles on the road, making it impassable. The rover will consume more energy when climbing steep slopes, which may lead to premature discharge of its battery. Therefore, you should try to choose a route to and from the crater that would allow the rover to use as little energy as possible, i.e., as short a route as possible, with the lowest possible slope and free from terrain obstacles. Most rovers used for space exploration are powered by photovoltaic cells that charge the batteries on board. There are examples of rovers powered by an RTG (Radioisotope Thermoelectric Generator), but these are exceptions rather than the general rule. Moreover, the RTG generates little electricity (about 100 W), although, including the heat generated, its power is significant (about 1 kW).

Many problems would be solved by using nuclear reactors. Unfortunately, the EU is very hostile to the use of nuclear energy in space for fear of possible environmental contamination if a rocket carrying radioactive material explodes while flying in the Earth's atmosphere. The USA and the UK have a much more liberal approach to these issues. Already in 2019, former US President Donald Trump [53] signed a memorandum on the use of nuclear energy in space to power devices and rockets. Work on the development of nuclear reactors for space exploration is already underway [54–57]. However, the use of nuclear reactors on the Moon is limited by their significant size and weight. Moreover, the lack of an atmosphere on the Moon makes it difficult to cool such devices, as they can only transfer heat by radiating it. It is expected that nuclear reactors will be mainly used in human bases and large industrial installations, and not to directly power rovers. The need to use photovoltaic cells to charge rover batteries introduces many limitations. They can only be charged during the day in sunny areas. If the rover performs any operations in shaded areas, it must move from these areas to sunny areas to recharge the batteries before the battery discharges.

A separate issue is the survival of the device at extremely low temperatures that occur in shaded areas and during the long lunar night. One day on the Moon lasts 27 (exactly 27.3) Earth days, including day and night lasting 14 Earth days each. Protecting the batteries of rovers and mining trucks against complete discharge, especially during the lunar night, will be a great challenge. The Moon is seismically active [58], which may also affect the stability of crater slopes. Due to the complex terrain and the rotation of the Moon, the movement of shadows [59] at the South Pole is very complex in time. The problem of selecting the optimal route for rovers and mining dump trucks should be viewed as a time optimization problem. Given routes may be impassable during certain time periods due to the fact that they are in a shaded area, and moving along them during this time may involve an increased drain on the battery charge. The time of the simulation of the movement of shadows at the South Pole [59], which was performed for the years 2025–2028, is not accidental, as this is the period of the NASA Artemis program.

Another problem will be the safety of places where rockets will land and take off. The test launch of the SpaceX Starship rocket in April 2023 showed how big a problem of rock fragments generated during rocket takeoff and landing can be. On the Moon, due to lower gravity, the problem will be even more serious. Therefore, it will be necessary to choose appropriate landing places where there will be no large rock fragments and the surfaces can be easily hardened to create launch pads.

To paraphrase the saying "measure your strength according to your intentions", in the case of the Moon you can say "choose cold traps and their resources according to the technical capabilities of the equipment you have". Therefore, analyzing craters and the cold traps located in them in terms of their easy accessibility is crucial. It is not enough that they contain valuable deposits—they must be deposits that can be easily accessed. The authors of publication [60] made an extensive analysis of cold traps for both poles of the Moon in terms of their availability.

4. Materials and Methods

The state of knowledge on the effective search for space resources presented in the work is the result of several years of literature studies conducted by the Polish space mining startup Solar System Resources Corporation Sp. z o. o. in cooperation with scientists from Polish and foreign research units. It is also part of the extensive know-how acquired by this company. The information bottleneck of all space mining projects to date is the lack of accurate industrial data, but also the lack of ordering and synthesizing the already available scientific data. Another is the lack of cheap transportation in Cis-Lunar space, but that could change the SpaceX Starship and other future competing solutions. The business world makes rational decisions based on accurate data and information about the current or future market. Unfortunately, the data collected so far about the Moon and other objects in the solar system has served scientific rather than industrial purposes. Only now are we observing plans for the first missions more focused on obtaining industrial data—an example here is the Polish Moon Mission [61], which is planned by the Polish Space Agency (POLSA), which will use the MIRORES instrument, the aim of which is to select areas on the Moon with the highest resources potential, especially in terms of metals, sulfur, and helium-3 [62]. The first results from the Korean Pathfinder Lunar Orbiter (KPLO) mission should be published soon [63]. The analysis conducted leads to the conclusion that the most promising areas on the Moon in terms of raw materials are craters and some of the cold traps located inside them. Are there places on the Moon with a higher concentration of raw materials that could be more profitable to exploit? The answer to this question is positive. For example, the Cabeus crater has a diameter of 100 km, an area of 7815 km^2, and a depth of 4 km. It will not be an area easily accessible on the Moon, and its operational depth is large: over 6 times greater than New York City (USA) and 24 times greater than Krakow (Poland). The permanently shaded areas in this crater cover an area of 315 km^2 or approximately 40% of the land area of New York City (USA). Given the limitations of rovers in terms of power and mobility, this is a huge area to explore, which creates a high risk of mission failure. It would therefore be worth finding smaller cold traps that would be rich in resources. The answer may be the so-called cold microtraps. Cold micro traps are basically the same as regular cold traps, but their sizes are much smaller, ranging from a few centimeters (even such small craters may have permanently shaded areas) to several kilometers. They are also much shallower, which means that a rover or mining dump truck will be able to easily enter/exit such an area, and therefore it will be easier to manage the limited reserves of electricity in these devices. Cold microtraps may also contain significant resources of valuable raw materials. On the Moon, a bigger crater does not always mean better. If the deposits are formed as a result of the mechanism described in the publication [39], the high edges of large craters may impede the movement of charged particles so that they can reach the cold trap and be deposited there, which should not be the case in the case of cold microtraps and theoretically should be easier deposits form in them. At Solar System Resources Corporation Sp. z o. o., at the end of the second quarter of 2022, a project was launched to develop a commercial interactive map of the Moon, which would be a repository of data on deposits and contain information useful for teams designing commercial and scientific lunar missions. The reports contained in this repository are intended to respond to the problems described in point 3 and other potential problems, so as to increase the success of missions—especially commercial missions. The product development strategy assumes the gradual creation of increasingly complex information layers for which potential customers would pay. The first information layers were to be based on simple and less computationally expensive algorithms (e.g., analyzing the slope of the terrain) to increasingly more complex and computationally expensive algorithms. This strategy also takes into account the fact that the first industrial high-resolution data on lunar resources will be obtained only in the coming years. Interestingly, some of the algorithms may also have potential terrestrial applications. It is increasingly common that new resources (e.g., metals) are found in hard-to-reach, forested areas far from civilization. Implementation of the developed algorithms for the Moon to Earth's conditions could help mining companies in a more rational development of such newly discovered deposits, limiting losses to the natural environment and carbon footprint, and at the same time reducing costs. Mining companies have been using satellite data and increasingly sophisticated remote sensing methods for decades and could be interested in such a solution. The first stage of the described project was to perform a trial, simplified analysis for several selected places on the Moon using available satellite data using generally available IT tools. It was supposed to be a simple and unsophisticated form of MVP (Minimal Valuable Product) and PoC (Proof of Concept) to be shown to the first potential investors. To create such an MVP and PoC, the Lunar QuickMap tool [64], which was developed by Applied Coherent Technology (ACT) Corporation [65], was used. The tool runs in a web browser. Lunar QuickMap integrates data from multiple lunar missions and is shown in Figure 1. This is a great convenience for researchers and people planning space missions because previously they had to combine data from many space missions scattered across different bases and plot them on one coordinate grid, which was not always an easy process. Lunar QuickMap allows you to create terrain cross-section profiles along a line selected by the user. The disadvantage of this solution is that if you have a weaker computer and Internet connection, the applications do not always run smoothly. ACT is also working on similar tools for Mercury and Mars.

Figure 1. Lunar QuickMap [64] by Applied Coherent Technology (ACT) Corporation.

Unfortunately, the analysis of microtraps with a diameter of less than 1 km using the Lunar QuickMap tool did not make sense due to the low resolution of data from previous space missions. It was therefore necessary to select larger craters with a larger diameter. Also, the crater and the permanently shadowed area (PSR) within it cannot be too small, as the exploitation of the small deposits contained therein may be economically unprofitable. QuickMap contains data from Sony's NASA Lunar Reconnaissance Orbiter (LRO). The QuickMap tool gives you the ability to select the data layers displayed. The "Polar Water Equivalent Hydrogen" layer was used to search for water deposits on the Moon. A search was carried out for places that could be promising for industrial exploration. Assumptions were made that the crater depth should not be greater than 1000 m, the slope should not exceed 25°, and the crater diameter should be in the range of 5–10 km. One of the goals of the analysis was to propose an entry and exit route to the crater for an exploration rover (e.g., containing a drilling device). Solar exposure on the crater wall was taken into account here to provide an energy source for the rover, and places with large amounts of erratic boulders were eliminated to minimize the possibility of damage to the rover. Of course, the resolution of the photos in Lunar QuickMap only allows you to see large erratic boulders, but such an analysis is valuable in terms of increasing the safety of operations of rovers and mining dump trucks. When selecting prospective sites, the following geological parameters of lunar resources were analyzed:

- Crater diameter;
- Size of the permanently shaded area;
- Crater depth;
- Maximum crater slope;
- Maximum crater slope along the rover's route;
- Length of the descent route to the crater floor;
- Length of the exit route from the crater floor;
- Crater latitude (LAT);
- Longitude of the crater (LON);
- Amount of water;
- Amount of CO_2 (carbon source);
- Crater distance (total route length to travel);
- Crater surface;
- Minimum temperature;
- Maximum temperature;
- Number of other deposits, if they occur in the analyzed cold microtrap

The analyzed cold microtraps were also checked for the presence of titanium compounds, which could suggest the presence of ilmenite, which has the ability to store helium. The groundbreaking work of Chinese researchers [28] on helium in bubbles was published in June 2022 and reached us when the work was already being carried out, hence the analyses did not take into account the possibility of the occurrence of this type of deposits.

5. Results

The process of manual analysis of cold microtraps using Lunar QuickMap was very long and tedious. Several dozen places were analyzed, of which only a few were selected for further detailed analysis. Places were marked with a combination of the letter B and subsequent numbers. The following sections present the results for each of them. Table 1 summarizes the results for all five cold microtraps analyzed.

Table 1 summarizes the results for five selected cold microtraps for which a detailed analysis was performed using Lunar QuickMap. The location marked B-1 is a crater with coordinates (−88.20990; 305.92639). You can choose an access road to a permanently shaded area with a slope angle of no more than 23°. It contains deposits of water, CO_2, iron, and thorium. Does not contain titanium deposits. The presence of iron is important because metallic raw materials will be needed to build bases. The location marked B-5 is a crater with coordinates (−89.12808; 273.21226). You can choose an access road to a permanently shaded area for which the slope angle will not exceed 25°, which is a slightly worse result than for site B-1. However, it contains more water deposits than site B-5, as well as deposits of CO_2, iron, and thorium. Like site B-1, site B-5 does not contain titanium deposits.

Table 1. Cold microtrap parameters.

Parameter	B-1	B-2	B-3	B-4	B-5
Pole	South	South	South	South	South
Crater approximated diameter [km]	7.777	8.413	5.393	7.898	5.211
Size of the permanently shaded area [km^2]	8.135	23.659	7.888	8.090	6.959
Crater depth [m]	1100	1400	1000	800	1000
Maximum crater slope [°]	25	26	33	28	30
Maximum crater slope along the selected rover's route [°]	22	13	25	20	24
Length of the descent route to the micro trap [km]	1.615	4.030	1.852 *	2.690	2.373
Length of the exit route to the micro trap [km]	2.221	4.030	3.126 *	2.690	5.717
Crater latitude (LAT)	−88.20990	−79.29052	−78.26205	−80.31803	−89.12808
Crater longitude (LON)	305.92639	69.71826	272.85840	290.27836	273.21226
Amount of water [wt%]	0.2	0.1	0.2–0.3	0–0.1	0.3
CO_2 amount [log10 kg/m^2/Gyr]	14–21	-	-	14–21	10–20
Crater distance [km]	24.455	26.859	16.802	17.353	16.380
Crater area [km^2]	47.073	57.017	22.266	23.609	21.227
Global minimum temperature [K]	-	50–60	55–60	55–65	-
Global maximum temperature [K]	-	230–245	230–240	240–250	-
Average summer temperature [K]	70–170	-	-	-	-
Average winter temperature [K]	60–150	-	-	-	-
Minimum summer temperature [K]	-	-	-	-	40–70
Maximum summer temperature [K]	-	-	-	-	100–300
Minimum temperature in winter [K]	-	-	-	-	30–60
Maximum temperature in winter [K]	-	-	-	-	50–270
Surface temperature at night	-	-	-	-	-
Iron deposits [wt%]	6	6	6	6	5–7
Thorium deposits [ppm]	2	1	1	1	0–2
Titanium deposits [wt%]	none	0.5	<1	0–1.5	none

* To/From crater floor in the area of PSR.

With the data from Table 1, it is possible to estimate the value of the deposits contained therein. These estimates will be subject to a large error, because, as mentioned earlier, data obtained remotely from satellites provide information about probable deposits and should be confirmed by in situ research (e.g., drilling). Moreover, the information obtained concerns only the surface layer and larger amounts of deposits of a given raw material may lie deeper (this may be especially the case for water ice deposits), just as the deposits may turn out to be smaller than estimated. Therefore, assessing the thickness of the deposit-rich layer is a key issue when estimating deposits. Bearing in mind that this parameter will be subject to a large error, the thickness of this layer was conservatively assumed to be:

- 1 cm—pessimistic scenario;
- 5 cm—nominal scenario;
- 1 m—optimistic scenario.

The analysis was limited only to permanently shaded areas (PSR), where the probability of deposits is highest. The average regolith density value was assumed to be 1 g/cm^3, which is a great simplification. Having information about the area of the permanently shaded area, the thickness of the layer rich in deposits, and the density of the regolith, the mass of the material contained in this layer was determined. Taking into account the coefficients (wt%) of the content of individual raw materials given in Table 1, their estimated mass in the mentioned 1 cm thick layer was determined. A similar procedure was carried out for CO_2 deposits, assuming a conservative concentration value of 1000 ppm for places where the presence of CO_2 was detected and 0 ppm for places where no CO_2 was detected. When adopting these values, it was taken into account that the CO_2 concentration [45] in the lunar water ice detected by the LCROSS probe was 5000 ppm. The CO_2 concentration values given in Table 1 expressed in units [log10 kg/m^2/Gyr] are highly imprecise and lead, for cold microtraps B-1 and B-5, to calculations giving astronomical CO_2 contents, which are unlikely in the light of the current state knowledge. The conversion factor used in the calculations was 1 ppm = 0.0001%. If a range of concentration values was given for a deposit in Table 1, the lowest non-zero value was taken into account in the calculations. The concentration values of individual raw materials finally adopted for the calculations are presented in Table 2. Tables 3–5 present the estimated deposit sizes in metric tons for the pessimistic, normal, and optimistic scenarios, respectively.

Table 2. Raw deposit concentrations used for calculations.

Parameter	B-1	B-2	B-3	B-4	B-5
Size of the permanently shaded area [km^2]	8.135	23.659	7.888	8.090	6.959
Amount of water [wt%]	0.2	0.1	0.2	0.1	0.3
CO_2 amount ppm	1000	0	0	1000	1000
Iron deposits [wt%]	6	6	6	6	5
Thorium deposits [ppm]	2	1	1	1	2
Titanium deposits [wt%]	0	0.5	1	1.5	0

Table 3. Estimated deposit size in tons—pessimistic scenario.

Parameter	B-1	B-2	B-3	B-4	B-5
Water	24,405	35,488.5	23,664	12,135	31,315.5
CO_2	12,202.5	0	0	12,135	10,438.5
Iron	732,150	2,129,310	709,920	728,100	521,925
Thorium	24.40	35.48	11.83	12.13	20.87
Titanium	0	177,442.5	118,320	182,025	0

Table 4. Estimated deposit size in tons—normal scenario.

Parameter	B-1	B-2	B-3	B-4	B-5
Water	122,025	177,442.5	118,320	60,675	156,577.5
CO_2	61,012.5	0	0	60,675	52,192.5
Iron	3,660,750	10,646,550	3,549,600	3,640,500	2,609,625
Thorium	122.02	177.44	59.16	60.67	104.38
Titanium	0	887,212.5	591,600	910,125	0

Table 5. Estimated deposit size in kg—optimistic scenario.

Parameter	B-1	B-2	B-3	B-4	B-5
Water	2,440,500	3,548,850	2,366,400	1,213,500	3,131,550
CO_2	1,220,250	0	0	1,213,500	1,043,850
Iron	73,215,000	212,931,000	70,992,000	72,810,000	52,192,500
Thorium	2440.5	3548.85	1183.2	1213.5	2087.7
Titanium	0	17,744,250	11,832,000	18,202,500	0

With the data from Tables 3–5, it is possible to estimate the value of deposits for the three presented variants. For this purpose, information on the price of individual raw materials is needed. The price of iron was assumed to be the iron ore price from September 2023, which is 0.1218 $/kg. The price of contaminated titanium from September 2023 was assumed to be 6.25 $/kg as the titanium price. In turn, the track price was assumed to be 30 $/kg. In all three cases, this is the price of low-quality raw material that is not processed. If a metallurgical process were carried out on the Moon and pure iron and titanium were obtained, as well as pure, highly enriched thorium, the price of raw materials obtained from the deposits would be much higher. However, the value of the unprocessed deposit is estimated, and it was decided to use conservative assumptions for the calculations.

However, it is difficult to determine the price for water and CO_2 extracted on the Moon, because markets for these raw materials do not yet exist. In the case of lunar water, the predictions presented in the report [66] can be used. The authors of this report estimated that the price of water for fuel production in space if it were imported from Earth would be 10 M$/ton, and if water were extracted from ice on the Moon and brought to low Earth orbit (LEO) it would be 0.5 M$/ton. We can, therefore, make a reasonable assumption that the price of water from lunar water ice will be $500/kg.

It is much more difficult to estimate the price of CO_2. This raw material will be used to produce methane for the fuel of the SpaceX Starship vehicle. SpaceX's contract with NASA to deliver astronauts to the lunar surface and take them back to a lunar orbital base under the Artemis program is USD 2.8 billion. The fuel mass of fully filled Starship tanks is 1200 tons, part of which is liquid methane and part is liquid oxygen. Starship takes off from Earth with only partially filled tanks to reduce launch mass—it is carried to low Earth orbit (LEO) mainly by the Super Heavy first stage, which returns to Earth. In order for the Starship vehicle to continue its flight to the Moon or Mars, it will need to be refueled in orbit. The payload capacity of a Starship launched from Earth is 100 tons, which means that it would take 12 Starship vehicles acting as tankers to refuel one Starship vehicle in orbit as it travels to the Moon or Mars. Elon Musk announced that the cost of the Starship operation into Low Earth Orbit (LEO) will be no higher than USD 10 million, which means that refueling Starship in LEO will cost 120 M$, which gives a theoretical fuel cost of 100 $/kg without distinction, whether it is liquid methane or liquid oxygen. Refueling in orbit will not be without fuel losses, as liquid methane and liquid oxygen will evaporate, hence it can be assumed that the fuel cost may be as high as 200 $/kg, which allows for taking into account fuel losses and the costs associated with the production and storage of fuel in space. Of course, the price of refueling on the Moon should be lower than on LEO, but 200 $/kg can be considered the upper limit of the price for fuel, including CO_2 raw material, acceptable to SpaceX. However, this is a highly speculative price, as SpaceX's plans for obtaining methane for Earth-Moon travel are not known yet, and it is possible that SpaceX has already solved this problem in a different way. With this fuel price, SpaceX will not be able to offer a ticket to Mars for PLN 250–500k as announced by Elon Musk. Tables 6–8 present market values of deposits for the three scenarios considered (pessimistic, normal, and optimistic).

Table 6. Estimated deposit market value in USD million—pessimistic scenario.

Parameter	B-1	B-2	B-3	B-4	B-5
Water	12,202	17,744	11,832	6067	15,657
CO_2	2440	0	0	2427	2087
Iron	89	259	86	88	63
Thorium	0.7	1	0.3	0.3	0.6
Titanium	0	1109	739	1137	0
TOTAL	**14,732**	**19,113**	**12,658**	**9721**	**17,809**

Table 7. Estimated deposit market value in USD million—normal scenario.

Parameter	B-1	B-2	B-3	B-4	B-5
Water	61,012	88,721	59,160	30,337	78,288
CO_2	12,202	0	0	12,135	10,438
Iron	445	1296	432	443	317
Thorium	3.6	5.3	1.7	1.8	3.1
Titanium	0	5545	3697	5688	0
TOTAL	**73,664**	**95,568**	**63,291**	**48,606**	**89,048**

Table 8. Estimated deposit market value in USD million—optimistic scenario.

Parameter	B-1	B-2	B-3	B-4	B-5
Water	1,220,250	1,774,425	1,183,200	606,750	1,565,775
CO_2	244,050	0	0	242,700	208,770
Iron	8917	25,935	8646	8868	6357
Thorium	73	106	35	36	62
Titanium	0	110,901	73,950	113,765	0
TOTAL	**1,473,290**	**1,911,368**	**1,265,832**	**972,120**	**1,780,964**

6. Discussion

The economic analyses presented in Section 5 are highly speculative and may be subject to large errors. On the other hand, the analysis and exploration of space deposits should be carried out in a strict economic context. The high uncertainty of the estimated values of the deposit size results from the fact that we only have surface information. Satellite imaging technologies, apart from a few techniques, are unable to show what is beneath the surface layers. Moreover, existing data on the Moon is mainly low-resolution scientific data—one pixel often corresponds to tens of square kilometers. In order for the industry to invest in the exploration of deposits on the Moon, it must have precise information to select the most promising areas that guarantee a high return on investment with the lowest possible technological and business risk. Without in situ research, it will not be possible to accurately estimate the size of the deposits and whether there are any technological problems that prevent their exploration. The parameter that causes the estimates to be subject to a large error is the thickness of the layer containing the deposits. We are unable to precisely estimate whether the thickness of this layer is several meters, centimeters, or even micrometers, as is the case with helium bubbles in the vitrified regolith. This uncertainty strongly affects the estimates. Valuation of deposits is also difficult because it is impossible to predict exactly what the price dynamics of individual raw materials will be over many years. For example, the exploitation of many of the Earth's shale gas deposits was profitable while global gas prices were high, and when the price dropped, many projects were closed because they became unprofitable. The valuation of deposits presented in Section 5 is static and based on current prices. The most profitable deposits for exploitation turned out to be water ice and CO_2 deposits. However, the valuation of these deposits is highly speculative, as mentioned earlier, unlike iron, titanium, and thorium deposits for which we have a reference in their contemporary prices. However, if mass exploitation of lunar deposits begins and there is an oversupply on the market, this will result in a drastic drop in the prices of individual raw materials, and the presented analyses will differ significantly from reality. Based on the analyses were performed, it can be concluded that the deposit in the B-2 cold micro-trap is the most valuable, although in terms of percentages of individual raw materials, it seemed that the B-5 deposit should be the most promising. The adopted CO_2 concentration values were highly speculative. For cold microtraps B-1, B-4, and B-5, the values read from Lunar QuickMap gave astronomical values of CO_2 content, which were unlikely. Hence, a more probable CO_2 concentration value of 1000 ppm was adopted, based on the currently known state of knowledge [45] about the occurrence of carbon on the Moon. However, it is worth verifying the data for places B-1, B-4, and B-5. The least profitable deposits to exploit were thorium deposits and then iron deposits. However, there is a mistake in reasoning here. Prices for iron, titanium, and thorium were assumed on the earth's market, and even for low-processed raw materials. If highly profitable industrial installations are built on the Moon, the price of raw materials for their construction, such as iron and titanium, may be higher. Similarly, thorium may find use in future nuclear power on the Moon, and a market for lunar thorium may emerge. It cannot be assumed that the terrestrial price of individual raw materials will certainly translate into their prices in space, the best example of which is water. The analysis showed that there are easily accessible deposits on the Moon that can be worth billions, the technological complexity of the mission does not have to be too high, and the technological risk is significantly reduced.

7. Conclusions

The information presented in the article is the result of several years of work by Solar System Resources Corporation Sp. z o. o. related to organizing information about space resources available in world literature and our own R&D works on the creation of tools enabling the search for prospective space resources for commercial and industrial exploration. This work was carried out in cooperation with specialists from Polish and global scientific institutions. In the first chapter, we explained why the most promising place for the exploitation of space resources in the next decade will be the Moon. It is located close, many devices can be controlled remotely from Earth, its environment has already been known to some extent, and gravity allows the use of mining devices known from Earth—of course, after adapting them to the environmental conditions prevailing on the Moon. The Moon provides the fastest return on investment compared to other locations in the Solar System and lower technological and business risk. Fascinating business prospects related to space mining in general can be found in the City bank report [67]. In point 2, we presented strategies for searching for specific types of raw materials on the Moon. The general conclusion from this chapter is that an effective search for raw materials requires knowledge and the combination of many facts that are described in various scientific publications scattered in various databases. Scientists often focus on a selected fragment of knowledge about the space environment and space resources, but only the selection and combination of fragmented information gives powerful know-how that is not obvious, even though much of this information is publicly available. The analyses conducted show that the most promising places on the Moon will be craters and the permanently shadowed areas (PSR) located within them, creating cold traps. In point 3, we presented the technological challenges that future teams will face when conducting industrial exploration of the Moon. We have shown that, due to the presented technological problems, it would be most reasonable to exploit raw materials not in large craters and large area cold traps, but in much smaller cold micro traps. We also demonstrated that there is a strong need for a commercial repository that would contain information useful for planning scientific and industrial space missions. Solar System Resources Corporation Sp. z o. o. is trying to develop such a tool. Section 5 presents the results of the analysis of five cold microtraps using the publicly available Lunar QuickMap tool. The analysis shows that using such a simple tool as Lunar QuickMap, you can initially estimate deposits, select optimal places for future space missions, and plan their course. The total market value of the estimated deposits is USD 74 billion; USD 370 billion; USD 7403 billion for the assumed pessimistic, normal, and optimistic scenarios, respectively. The basic mistake that discourages VC funds and is made by some of the startups involved in space mining is the assumption that the first return on capital investment must occur only when the exploitation of space deposits begins. It is worth taking advantage of the experience of the local oil and gas industry. In this industry, one person is often responsible for geological exploration, another is the owner of the deposit, another is the operator, and another is the investor. The oil and gas industry (similarly mining) usually pays up to 1 to 3% of its value for detailed exploration of a deposit. Therefore, if prospective deposits of space raw materials are detected, it is possible to make money by selling information about them to larger entities that are able to make the necessary capital investments to start exploitation. Of course, taking into account the high risk of the investment and the fact that the deposit may not be exploited in the near future, information about a well-documented space deposit could probably be sold for 0.1 to 0.3%, assuming a 10% chance of success of the project. Such an estimate applies only to confirmed deposits, i.e., those that would be additionally explored and confirmed by in situ tests. Deposits that have been identified only using remote satellite techniques are probable deposits and a 1% chance of success for the project should be assumed, which gives a valuation of 0.01% to 0.03% of the estimated value of the deposit. It can therefore be concluded that the market value of the presented article (due to the results presented in Section 5) is, assuming a conservative valuation of 0.01%, USD 7.4 million; USD 37 million; USD 740 million for the pessimistic, normal, and optimistic scenarios, respectively. Of course, the presented valuations are in fact much lower due to the high uncertainty of estimating the size of deposits and the highly speculative (despite reasonable and actual assumptions) assumed price of some raw materials, which was discussed in point 6. However, such a theoretical valuation of this article shows how useful and confirmed information about space deposits and the conditions of their exploitation will be valuable. This has been noticed by the well-known global consulting company PwC, which in its report [68] on the lunar economy predicts that [68] (p. 22) the cumulative value of the lunar environmental data market in 2021–2040 will be in the scenario nominal value in total worth USD 8.3 billion. As a summary of this article, it is stated that another additional derivative resource of the Moon for the 21st century is the information itself about it and the old saying that "knowledge is the key to power" takes on a new meaning. Future scientific and industrial space missions, such as the Polish Lunar Mission [69] or future in situ exploring (e.g., drilling) devices [62], may provide the necessary more precise data that the industry is waiting for.

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