Assessing the plausibility of mining lunar titanium

Renaud Merle [1], Mikael Höök [1], Valentin Troll [1] and Alexander Giegling [1]*

https://doi.org/10.5281/zenodo.12205838

Exploring the Solar System requires large amounts of resources. However, many critical resources on Earth cannot be diverted from vital productions required for establishing a sustainable society. Resource extraction from extraterrestrial bodies such as the Moon might be an attractive alternative. Here, we assess the potential of the Moons' Titanium (Ti) resources, which is known to contain significant amounts of this metal. We used mathematical models comparing historical trends of Earth mining operations to build explorative scenarios for future lunar mining operations of Ti resources. The results provide a timeframe for the mining operation and estimates of the quantity of extracted material. We further discuss how lunar resources can be primarily used for in-situ resource utilisation but also as a backup supply source in the worst-case scenario of Earth's resource depletion.

1. Introduction

The pioneering astronautics scientist Tsiolkovsky envisioned venturing into space as a necessary step for ensuring human survival and obtaining resources for continued growth. Before venturing further in the solar system, it is sensible to explore and eventually exploit the Moon first, being the closest celestial object [1]. After the initial race to the Moon, further exploration was overlooked for nearly 50 years, while its exploitation was seen as a futuristic vision. Recently, the Moon has returned on the top-priority list of space agencies with spectacular achievements, like India's Chandrayaan-3 mission successfully landing near the moons' south pole on 23 August 2023. The renewed space race has led nations and commercial companies to aim for long-term exploration and eventual colonisation of the Solar System.

The Moon is seen as a natural stepping stone for missions to Mars and beyond [2], and Space Resource Utilisation (SRU) is considered key to achieving this goal. SRU was originally proposed in the 1960s to reduce launch mass and reduce the dependency on Earth [3]. Space privatisation and investment have resulted in renewed interest in SRU to produce propellant [4] and supply oxygen [5], which is one of the main challenges for future space operations.

Lunar resources exploitation could also benefit society in other ways. For instance, Wingo [6] and Metzger et al. [7] claimed that lunar resources could revolutionise the supply of raw materials. Current global requirements for key raw materials has surged, driven by the growth of renewable and clean energy [8]. Since 2010, the worldwide demand for minerals – like lithium and nickel – has risen by over 50% [9] with leading suppliers including Chile, Indonesia, the Democratic Republic of Congo, Afghanistan, and the Russian Federation [10]. In addition, initiatives for carbon neutrality have turned a blind eye to poor conditions and devastating socio-economic effects in many mines and mineral processing facilities around the world [11; 12]. New policies, like the EU Critical Raw Materials Act, often aim to reduce imports by increasing domestic mining, but this can lead to a mixed bag of social, environmental and justice issues that hinder future energy security [13]. Lunar resource exploitation may circumvent some of these challenges and diversify supply.

Crawford [14] found that the Moon possesses large amounts of chemical ele-

[1] Department of Earth Sciences,
Uppsala University, Villavägen 16,
75236 Uppsala, Sweden.
* renaud.merle@geo.uu.se

ments of potential economic relevance, but it is hard to identify a single one that would be capable of driving an extraction industry of its own. In this manuscript, we explore the potential of lunar deposits as a possible supply for vital resources. To date, few studies investigated the time frame of scale lunar mining activities and what its potential output would imply for our society. This study fills the gaps in existing literature by providing structured and quantitative production scenarios that can be helpful for assessing lunar resources and their viability as significant contributors to future resource supply.

We chose titanium (Ti) as a case study due to the metals' potential significance in future technological developments, particularly in space exploration. First, Ti has excellent properties such as a high strength-to-weight ratio and outstanding resistance to corrosion and temperature, which are crucial for engineering applications [e.g. 15]. It also has useful properties for nanotechnology [16] and biomedicine [17]. As a pigment, TiO_2 is non-toxic, insoluble, has excellent heat stability, weather resistance, and hiding power, is easy to disperse in resin systems, and is resistant to discoloration [18]. Cai et al. [19] found that titanium alloys are gaining significant traction in aviation, aerospace, chemical, shipbuilding, and many other industries. Consequently, future demand for titanium is likely to increase due to its attractive properties.

Lunar rocks tend to have higher TiO_2 contents than any other known extra-terrestrial material, making the Moon, due to its proximity to Earth, more attractive than metal asteroids for titanium mining [15]. Importantly, lunar titanium is a useful illustration of the concept of integrated use of minerals, which involves the comprehensive extraction and processing of valuable chemical elements from multicomponent mineral raw materials [20]. One of the main lunar Ti ores is ilmenite ($FeTiO_3$), which has the significant advantage of yielding titanium as a by-product of oxygen production. Ilmenite is easy to process and offers a high oxygen yield [21]. Based on recent investigations of industrial processes applied to extract Ti from lunar regolith (FFC Cambridge process, [22]), lunar regolith mining scales of 30 – 65 kg/h would be necessary for producing 1 000 kg of O_2 annually, which is the scale required for initial stages of a lunar outpost designed for the NASA architecture [23]. As such, it has been found that SRU oxygen production would likely require a continuous large-scale operation to be viable.

To assess the potential of lunar Ti deposits as a future supply source, we used a comprehensive chemical dataset of lunar rocks to establish exploratory large-scale mining scenarios that includes time-frame of mining operation and estimation of quantity of extracted material. We compare the results with structured analogies based on terrestrial counterparts. We further discuss the use of lunar titanium as a pathway to sustain both future spacefaring endeavours and supply Earth with additional resources for its decarbonisation and transition efforts.

2. Materials and Methods

The purpose of this study is to create exploratory scenarios for future lunar mining activities capable of extracting Ti on societally relevant scales. A secondary aim is to quantify and assess the plausibility of lunar mining and infrastructure needs that would be required to achieve production volumes significant for modern society. This is accomplished by using structured analogies based on quantitative production data and historical experience from Norway, primarily the Tellnes titanium mine, and combining this with available geochemical data on typical concentrations in lunar rocks.

An analogy is a type of scientific model used to analyse and explore the behaviour of other systems with some degree of similarity [24]. Here, historical titanium production in Norway is used to create a structured analogy built around concentrations, production volumes and mining operations that could be used for lunar conditions. This judgemental approach aims to explore and confine future lunar exploitation using known facts and parameters as tentative boundary conditions. While technical details and factors differ, making the analogy imperfect, leveraging available information can reveal the driving forces and key factors, aiding in the exploration of future trajectories.

Scenarios are simplified and plausible descriptions of how future mining operations and technologies may develop, based on a coherent and internally consistent set of assumptions about key driving forces and relationships in economy and society [25; 26]. Scenario analysis balances both quantitative and qualitative approaches to develop projections and gain perspective over a longer time horizon [27; 28].

2.1. Study case locations

Currently, the world produces roughly 12.5 million metric tons (Mt) of titanium compounds, expressed as mineral concentrates, dominated by 11 000 kt from ilmenite and 1 700 kt from titanium slags in 2019 [29]. The titanium industry uses the term ilmenite to refer to both hard-rock ilmenite and ilmenite enriched in TiO_2 through weathering. Titanium slag is an intermediate product usable for Ti pigments, made from ilmenite using high temperature metallurgy processes. Norway currently produces about 5% of the world's ilmenite concentrates and simultaneously holds about 5% of the known reserves [29]. Most importantly, southern Norway contains a world-class deposit in the Rogaland anorthosite province, currently exploited at the Tellnes mine.

2.1.1. Tellnes mine, Norway

The largest titanium deposit in Europe, the Tellnes mine near Sokndal in Norway, is also one of the world's most important operations [30]. The deposit contains significant ilmenite, and the ore body is a massive ilmenite-rich norite (a plagioclase+orthopyroxene-bearing gabbro) averaging 18% TiO_2. It has a sickle-shaped outcrop more than 2 700 m long and over 400 m wide in its central part [e.g. 31]. Estimated ore reserves are 575 million metric tons (Mt), averaging 18 % TiO_2 of which approximately 15% TiO_2 is as ilmenite and 3% of the TiO_2 is within other minerals [32].

2.1.2. Mare Tranquillitatis, Near Side of the Moon

The Mare Tranquillitatis (Sea of Tranquillity) is a very large impact crater with a diameter of 876 km located on the near side of the Moon (Figure 1a). It is filled by basaltic flows that are partly covered by the lunar regolith – the "soil" of the Moon, consisting of unconsolidated and pulverised rock – which is 4.5 meters thick in this location [33]. The regolith contains less than 10% volume of ilmenite [34]. Remote sensing investigation of the lunar surface identified Mare Tranquillitatis as the lunar region with the highest TiO_2 content (~13 wt%; Figure 1b) on the Near Side of the Moon [35]. This high content TiO_2 has to be related to the presence of basaltic rocks such as those collected from the nearby Apollo-

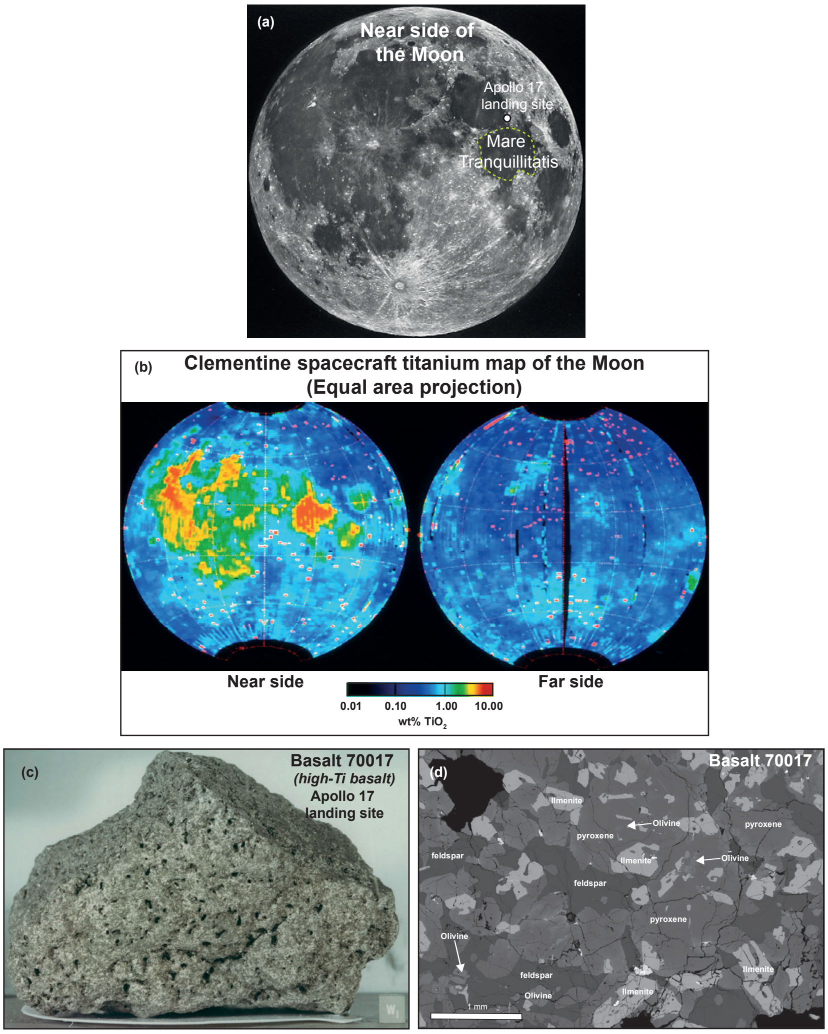

Figure 1: (a) Picture of the near side (Earthside) of the Moon with the location of Mare Tranquillitatis and Apollo 17 landing site (adapted from Lunar and Planetary Institute image database). (b) Remote sensing map of titanium content of the lunar surface. Data acquired by the Clementine spacecraft during the Deep Space Program Science experiment (image modified from Lunar and Planetary Institute image database). (c) Photo of a hand specimen of a high titanium content basalt (high-Ti basalt) collected on the Apollo 17 landing site (image from Lunar and Planetary Institute). (d) Back-scatter electron image of the high-Ti basalt 70017. The main rock-forming minerals are labelled (modified from [38]).

17 landing site (Figure 1c). These basalts, known as "Hi-Ti basalts", display a higher Ti content than those of the other lunar basalts (TiO_2 > 6 wt%, up to 15 wt%); [36]). In these rocks, ilmenite is particularly abundant (Figure 1d) forming up to 20 % of the volume of the rocks [37].

3. Results and discussion

3.1. Titanium production trends in Tellnes mine

The titanium production as mineral concentrate (mostly ilmenite) from the Tellnes mine presents a typical trend of production (Figure 1). The production progressively increased over 20 years (1960-1980), from the start of the mining operation to reach a plateau of approximately 750 kt of ilmenite production, with production peaks just over 900 kt between 1982 and 1984, in 1989 and in 2008. The Ti mineral concentrate has stayed on this production plateau during 34 years (1980-2014) with an equivalent TiO_2 production of approximately 350 kt.

3.2. Explorative scenario for lunar titanium production

Assuming lunar mining production mirrors the production trajectory of the Tellnes mine trend, but with harsher conditions, an annual production plateau of 500 kt of ilmenite (representing 66% of the Tellnes mine production to account for the harsh mining conditions on the Moon) is achieved within 20 years (Figure 3). Considering a mining operation of 4 300 x 3 000 x 4.5 m – which is in line with large open-pit mines on Earth – up to 4 018 kt of pure ilmenite could be extracted from the regolith with a concentration of 3% volume of ilmenite. Considering the prospected cumulative production, the mining operation will exhaust the theoretical ilmenite stock in approximately 20 years.

If Apollo 17-type basalts with 15% volume of ilmenite, are mined in Mare Tranquillitatis, up to 20 088 kt of pure ilmenite could be extracted assuming a mining operation the same size as for the regolith. In this case, the potential ilmenite stock would be exhausted in 50 years. These numbers are consistent with the lifespan of the Tellnes mine.

Earth-based production of ilmenite is approximately 8 000 kt per year. Implementation of twenty mines of such size on the surface of the Moon and extracting ilmenite from the regolith could likely supply enough titanium for ten years of equivalent production on Earth. It should be noted that the 3% volume of ilmenite in the regolith represents the lowest conservative estimate.

3.3. Implementing a mining operation on the Moon

Assuming a compact and integrated layout, on-site processing, and waste handling, a lunar mining operation will reasonably not require more surface area than the Tellnes mine. This allows for using the Tellnes case as an upper bound for production volumes and energy requirements. Presently, the mining operation in Tellnes consists of a large hydraulic mining shovel (model Caterpillar 6040, operating weight: 405 t) with up to 4 000 tons per hour peak productivity and a set of six mining trucks (model Caterpillar 789D, gross operating weight 324 t) with a payload of 194 tons are used for hauling. To transport this machinery to the Moon would represent approximately 250 launches of the Chinese Long March 5 rocket (assuming a payload of 9.4 t for a translunar injection) or 44 launches of a rocket with a payload similar to Saturn V (53 t) that is comparable to the 42 launches required to build the International Space Station. Additional transportation systems and storage silos integrated into the production line should be included into the payload to be transported to the Moon. Nevertheless, the mass of such infrastructure is presently difficult to assess as

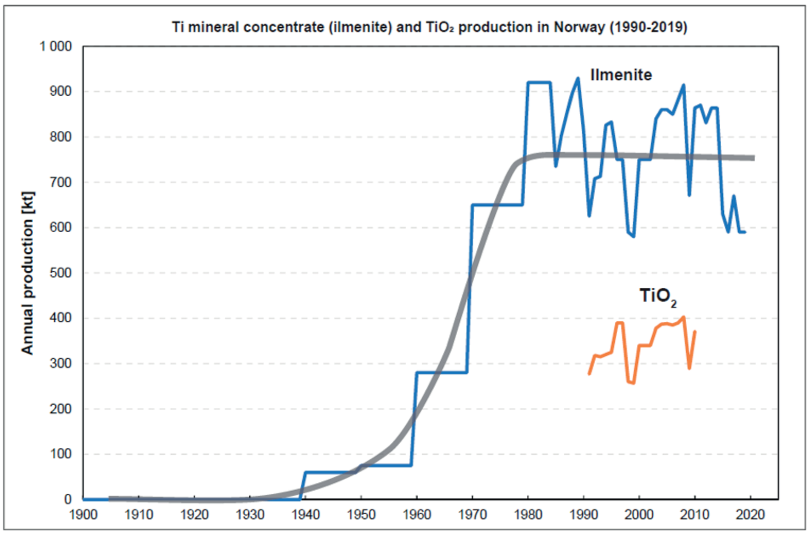

Figure 2: Historical production of Ti mineral concentrates (mostly ilmenite) and titanium oxide (TiO2) in Norway. Production is heavily dominated by the Tellnes mine that opened in 1960, with very minor contributions from other deposits such as Rødsand mine (closed down in 1981). The thick grey line represents the production trend of Ti mineral concentrates.

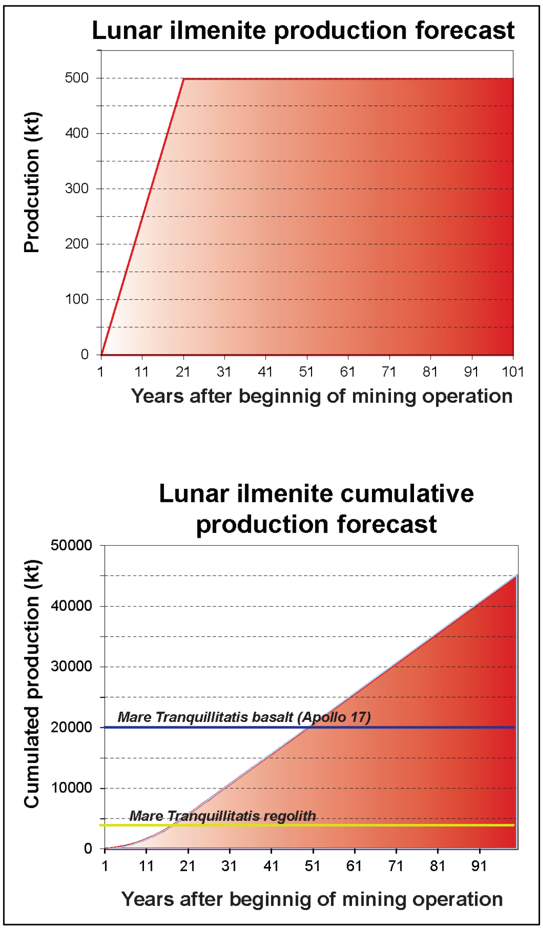

Figure 3: Prospected and cumulated production of lunar ilmenite. Cumulative production is compared to the theoretical mass of ilmenite extracted from the lunar regolith and Apollo 17-type basalts from a 4 300 x 3 000 x 4.5 m mine.

it will be highly dependent on the size of the mining operation.

Gross power demand is 1 550 kW for the excavator and 1 566 kW per truck – in total approximately 11 MW. This amount of energy could be produced by a combination of solar power and lightweight-small size nuclear reactors. For instance, new designs of small modular fission reactors currently under development and able to deliver up to 300 MW could be adapted for the lunar conditions.

Due to the conditions on the lunar surface, dry beneficiation technologies, particularly electrostatic and magnetic separation as the most promising, will have to be used instead of flotation and gravimetric separation [39]. The main challenge remains addressing unknown geotechnical properties of lunar soil. The design of excavation equipment would most likely be different from those used on Earth. Specifically, lunar mining equipment would reasonably be lighter, but still rugged enough to withstand continuous mining operations, excavation and transportation of abrasive dust, cobbles and boulders while withstanding the severe temperate swings of the lunar environment and low gravity. Nonetheless, we assume that no lunar mining equipment will be heavier than its Earth-designed counterparts [40]. Therefore, the mass of the payload would be significantly lower than that estimated above, requiring a smaller number of power production units. Finally, lunar mining will likely be heavily automated, similar to modern mines.

3.4. Oxygen production

The oxygen that can be won from the extraction of titanium from the regolith and soil depends on several factors: first, the initial concentration of ilmenite sets a maximum amount of oxygen that can be stoichiometrically extracted from the rock [22]. This amount is further reduced by the efficiency loss from the hydrogen reduction process. In experimental setups, up to 3.4 wt.% of oxygen can be extracted from a sample with 95% ilmenite content heated up to 1 000 degrees for four hours to induce hydrogen reduction [41].

In terms of oxygen production, using ilmenite from the regolith, up to 137 kt of oxygen can be produced in 20 years from the theoretical amount of ilmenite extracted. If ilmenite for oxygen production is extracted from Apollo 17-type basalts, up to 683 kt of oxygen could be produced over 50 years (Table 1). These amounts could be increased to 178 and 888 kt of oxygen respectively, when heating the material up to 1 100 degrees resulting in an increased extraction rate of 4.42 wt. % Oxygen [41] from the ilmenite. A large scale Ti mining opera-

Table 1: Total amount of oxygen produced by hydrogen reduction of ilmenite.

	Regolith	High Ti- Basalt	Regolith	High Ti- Basalt
Initial ilmenite concentration	0.03	0.15	0.03	0.15
Prospective cumulative Ilmenite production (kt)	4 018	20 088	4 018	20 088
Oxygen extraction Wt. %	3.4 [37]	3.4[37]	4.42 [37]	4.42[37]
Reduction process	4 h @ 1 000°C	4 h @ 1 000°C	4 h @ 1 100°C	4 h @ 1 100°C
Total produced Oxygen (kt)	137	683	178	888

tion would therefore be able to supply substantial volumes of oxygen for various uses.

5. Conclusions

The significant costs of developing and deploying mining equipment, along with technical challenges in extracting and transporting materials, pose major hurdles to commercialising lunar exploitation. However, the successful Indian Chandrayaan-3 mission, landing a rover on the Moon for an estimated $90 million, challenges the notion of prohibitive costs. This success suggests that lunar resource exploitation may be economically viable sooner than previously thought, without significant delays. Therefore, there is no insurmountable gap to fill or a long time to wait until lunar resources could be accessible to humankind. Nevertheless, it seems unrealistic to consider exploitation of lunar resources within the next ten years, while no man has returned to the Moon since 1972.

Significant technical, legal, and ethical challenges remain to be addressed, and further research and evaluation will be needed to fully understand the feasibility and the potential impacts of lunar mining. Speculative scenarios, like those presented here, indicate that lunar resources could provide substantial volumes of resources and are within seemingly plausible reach in terms of infrastructure requirements. The possibility to coproduce oxygen for life support or propulsion could also be a vital part of laying the first stepping stones toward extending human presence within the solar system. However, more detailed studies are encouraged.

There is a need for careful consideration and evaluation of the potential benefits and risks of lunar mining, and for the development of appropriate regulations and standards to ensure that mining activities are conducted in a responsible and sustainable manner. Finally, lunar mining would require significant investment in new technologies and systems, as well as in the development of new supply chains and markets for lunar materials.

Author Contributions: Conceptualisation, R.M., M.H. and V.T.; methodology, M.H.; writing—original draft preparation, R.M. and M.H.; writing—review and editing, R.M., M.H., V.T. and A.G.

Funding: R.M. and V.T. acknowledge the support of Swedish Research Council (Vetenskapsrådet, VR) research grants 2020-03828 and 2020-03789. This study has been supported by the STandUP for Energy research initiative.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Schmitt, H.G. Return to the Moon: Exploration, Enterprise, and Energy in the Human Settlement of Space, Copernicus Books, Springer Science + Business Media, New York, USA, 2005, 352 pp.

[2] Creech, S., Guidi, J., Elburn, D. Artemis: An Overview of NASA's Activities to Return Humans to the Moon, 2022 IEEE Aerospace Conference (AERO), 1–7.

[3] Carr, B. Recovery of water or oxygen by reduction of lunar rock. AIAA Journal 1963, 1, 921–924.

[4] Kornuta, D., Abbud-Madrid, A., Atkinson, J., Barr, J., Barnhard, G., et al. Commercial lunar propellant architecture: a collaborative study of lunar propellant production. REACH, 2019, 13.

[5] Lee, K., Oryshchyn, L., Paz, A., Reddington, M., Simon, T. The ROxygen project: outpost-scale lunar oxygen production system de-velopment at Johnson space center. J. Aero. Eng., 2013, 26, 67–73.

[6] Wingo, D. Moonrush: Improving life on Earth with the Moon's Resources, Burlington: Apogee Books, 2004.

[7] Metzger P.T., Muscatello A., Mueller R.P., et al. Affordable, rapid bootstrapping of space industry and solar system civilisation. J. Aero. Eng., 2013, 26, 18–29.

[8] Islam, M.M., Sohag, K., Alam, M.M. Mineral import demand and clean energy transitions in the top mineral-importing countries. Res. Policy, 2022, 78.

[9] Viebahn, P., Soukup, O., Samadi, S., Teubler, J., Wiesen, K., Ritthoff, M. Assessing the need for critical minerals to shift the German energy system towards a high proportion of renewables. Ren. Sust. Energy Rev. 2015, 49, 655–671.

[10] McCullough, E., Nassar, N.T. Assessment of critical minerals: updated application of an early-warning screening methodology. Miner Econ., 2017, 30, 257–272.

[11] Marin, A., Goya, D. Mining—The dark side of the energy transition. Env. Innov. Soc.Trans., 2021, 41, 86–88.

[12] Troll, V., Arndt, N.T. European Raw Materials Resilience — Turning a Blind Eye. Earth Sci. Syst. Soc., 2022, 2, 10058.

[13] Kamran, M, Raugei, M., Hutchinson, A. Critical elements for a successful energy transition: A systematic review. Ren. Sustain. Energ Transition, 2023, 4:100068.

[14] Crawford, I. A. Lunar resources: A review. Progress Phys. Geograph.: Earth Environ., 2015, 39, 137–167.

[15] Peters, M., Kumpfert, J., Ward, C.H., Leyens, C. Titanium Alloys for Aerospace Applications. Adv. Eng. Mat., 2003, 5, 419–427.

[16] Bai et al. Titanium Dioxide Nanomaterials for Photovoltaic Applications. Chem. Rev., 2014, 114, 10095–10130.

[17] Sarraf et al. A state-of-the-art review of the fabrication and characteristics of titanium and its alloys for biomedical applica-tions. Bio-Design & Manufacturing, 2021, 5, 371–395.

[18] Perks, C., Mudd, G. Titanium, zirconium resources and production: A state of the art literature review. Ore Geol. Rev., 2019, 107, 629–646.

[19] Cai, C., Hu, B., Zhao, L., Liu, S. Titanium alloy production technology, market prospects and industry development. Materials & De-sign, 2011, 32, 1684–1691.

[20] Larichkin, F., Tsukerman, V., Ivanova, L., Comprehensive utilization of multicomponent mineral resources of the Arctic: Chal-lenges and solutions. IOP conf. ser.: Earth Environ. Sci., 2020, 459, 062047.

[21] Chambers et al. Quantitative mineralogical characterization of lunar high-Ti mare basalts and soils for oxygen production. J. Ge-ophys. Res. Planets, 1995, 100, 14391–14401.

[22] Chen, G.Z., Fray, D.J., Farthing, T.W. Direct electrochemical reduction of titanium dioxide to titanium in molten calcium chloride. Nature, 2000, 407, 361–364.

[23] Cilliers, J.J, Rasera, J.N., Hadler, K. Estimating the scale of Space Resource Utilisation (SRU) operations to satisfy lunar oxygen demand. Planet. Space Sci., 2020, 180, 104749.

[24] Green, K.C., Armstrong, J.S. Structured analogies for forecasting. Int. J. Forecast, 2007, 23, 365–376.

[25] Hiltunen, E. Scenarios: Process and outcome. J. F. Studies, 2009, 13.

[26] Amer et al. A review of scenario planning. Futures, 2013, 46, 23-40.

[27] Godet, M. The art of scenarios and strategic planning: tools and pitfalls. Technol. Forecast. Soc. Change, 2000, 65, 3–22.

[28] Durance, P., Godet M. Scenario building: uses and abuses. Technol. Forecast. Soc. Change, 2010, 77, 1488–1492.

[29] USGS, 2023. Minerals yearbook & mineral commodity summaries for titanium. Available online: ***https://www.usgs.gov/centers/national-minerals-information-center/titanium-statistics-and-information***

[30] Korneliussen, A., McEnroe, S.A., Nilsson, L.P., Schiellerup, H., Gautneb, H., Meyer, G.B., Storseth, L.R. An overview of titanium deposits in Norway. Norges Geologiske Undersokelse, 2000, 436, 27–38.

[31] Charlier, B., Duchesne, J.-C., Vander Auwera, J. Magma chamber processes in the Tellnes ilmenite deposit (Rogaland Anorthosite Province, SW Norway) and the formation of Fe–Ti ores in massif-type anorthosites. Chem. Geol., 2006, 2343, 264–290.

[32] NGU report, 2017. Information on Deposit Area 1111 – 019 Tellnes. Available online: ***https://aps.ngu.no/pls/oradb/minres_deposit_fakta.Main?p_objid=4998&p_spraak=E.***

[33] Nickerson, R.D., Bart, G.D., Lawder, M.T., Melosh, H.J., Global lunar regolith depths revealed. 42th Lunar and Planetary Sci-ence Conference, Houston, USA, 2011.

[34] Heiken G.H., Vaniman D.T. Characterisation of lunar ilmenite resources. Proceedings of the 20th lunar and planetary Science Con-ference, 239-247, Houston, USA, 1990.

[35] Sato, H., Robinson, M. S., Lawrence, S.J., Denevi, B. W., Hapke, B., Jolliff, B. L., Hiesinger, H. Lunar mare TiO2 abundances estimat-ed from UV/Vis reflectance. Icarus, 2017, 296, 216–238.

[36] Shearer, C. K., Papike, J. J. Magmatic evolution of the Moon. American Mineralogist, 1999, 84, 1469–1494. Available online: https://doi.org/10.2138/am-1999-1001.

[37] Neal, C.R., Taylor, L.A. Petrogenesis of mare basalts: A record of lunar volcanism. Geochim. Cosmochim. Acta, 1992, 56, 2177–2211.

[38] Snape, J. F., Nemchin, A. A., Whitehouse, M. J., Merle, R. E., Hopkinson, T., Anand, M. The timing of basaltic volcanism at the Apollo landing sites. Geochim. Cosmochim. Acta, 2019, 266, 29–53.

[39] Rasera, J., Cilliers, J. J., Lamamy, J., Hadler, K., The beneficiation of lunar regolith for space resource utilisation: A review. Planet. Space Sci., 2020, 186, 104879.

[40] Just, G., Smith, K., Joy, K., Roy, M., Parametric review of existing regolith excavation techniques for lunar In Situ Resource Uti-lisa-tion (ISRU) and recommendations for future excavation experiments. Planetary and Space Science, 2019, 180, 104746.

[41] Sargeant, H., Abernethy, F., Barber, S.J., Wright, I.P., Anand, M., Sheridan, S., Morse, A. Hydrogen reduction of ilmenite: Towards an in-situ resource utilization demonstration on the surface of the Moon. Planet. Space Sci., 2020, 180, 104751.