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The out-of-this-world hype cycle: Progression towards sustainable terrestrial resource production

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ABSTRACT

The out-of-this-world hype cycle describes expectations and realities for extra-terrestrial resource production. Triggered by a technological innovation cluster in communication/automation/transport for the space industries, it inspires visions of prospecting and inter-planetary travel for economic gains. Visionary narratives are founded on (1) techno-futurism, a linear process of capital accumulation based on innovation; (2) techno-optimism, the belief that innovation will solve modern-day challenges without impacting consumption-based lifestyles; and (3) expansion of the resource base for economic development. We use a constructivist approach to scrutinise the opportunities for, and impediments to, off-Earth extraction through economic, political, sociological, legal, humanities, geological and engineering philosophies. Visionaries elevate the terrestrial activity of mining to the extra-terrestrial environment in a fantastical Martianist narrative while a counter-Martianist narrative simplifies extra-terrestrial prospecting and extractive challenges. The infancy of prospecting and limited engagement with the realities of terrestrial mining practice suggest that off-Earth extraction is a distant prospect. We conclude that expanding industrial activity by outsourcing of raw materials production is inhibited by the Terrestrial actor. Debates about out-of-this-world hype, the limiting factors to access raw materials beyond the Earth, and an immature (high-risk) safety culture for off-Earth extraction, reveal the imperative for multi-actor transformative behavioural change.

1. Introduction

Latour (2018) describes the propensity of modern society to act in a politically binary context: globalization versus localization, progression versus regression, left versus right. Where the global and the local are political attractors, a third attractor also demands attention. It is the Terrestrial, a new political actor that dissolves the modernisation paradigm (Whyte, 2018) with its emphasis on economic progress. Humans are no longer the only actors and the other-than-human Terrestrial attractor has emerged with political potency because the Terrestrial is bound to the earth and to land, and is a way of worlding in that it aligns with no borders, and transcends all identities. For Latour, the Terrestrial thus overcomes the problems with the local/global, human/nature and, now in his framework, Modern/Terrestrial categorisations. The Modern paradigm describes that linear progress, advance and continued growth place economy at the heart of decision-making. In Latour's (2018) conceptualisation, the Terrestrial calls for an anti-colonial agenda to Modern ideas of freedom unencumbered by responsibility, whether extraction is material or societal. Modern ideas of growth are inconvenienced by access to raw materials: Latour (2018) describes globalization as a development *impossibly reliant on the equivalent of several planets*. Advocates of the progressive address planetary limitations by seeking to expand the resource base by space mining. This is an emerging field of science and technology in that research and innovation is not technologically mature, and resources are not currently used in space other than those sourced from Earth.

The attractor that works in opposition to the Terrestrial is the *out-of-this-world* attractor (Latour, 2018): the horizon of people who no longer belong to the realities of an Earth that would react to their actions. Thus, the Terrestrial and the *out-of-this-world* are not synonymous with planet

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Earth and other planetary bodies but are ways in which to consider resource production on- and off-Earth. The binary positions, placed in the context of resource production, allow us to question whether terrestrial attitudes and human actions to produce raw materials adequately appreciate the associated risks. We can specifically question whether proposed and new approaches to off-Earth raw materials production arise from an *out-of-this-world* refusal to address environmental challenges and global inequalities on Earth. We use the term off-Earth extraction, in preference to the term 'space mining' to avoid any confusion. Although connected in the life cycle of mining, we differentiate between prospecting (and proof of viability of ore deposits) and extraction (followed by processing for commodities). We will use the term *off-Earth extraction* to mean mining and processing of commodities on asteroids, the Moon and Mars.

We consider that the terrestrial and out-of-this-world attractors (Latour, 2018) provide an interesting framework in which to consider the subject of resource utilisation and the often-discussed tension between the extractive industries and environmental conservation, whether located on terrestrial land or in extreme environments such as the deep sea or space. Through such a discourse, we can perhaps begin to understand whether *out-of-this-world* actions throw societal negotiations with the Terrestrial into sharp relief or serve as a distraction, impeding reorientation of the modernization front. We investigate underlying subtle colonial behaviours by leaders, combined with philosophies that the sky is not the limit, to indefinitely continue a linear path of economic development and consumption.

Since research into appropriate component technologies is mostly conceptual or tested in a laboratory, and not connected as components in a mining value chain, off-Earth (i.e. space) mining can be considered within the concept of *techno-futurism*. This concept describes linear progress and capital accumulation based on technology and commodities (Stephenson, 2003). Innovation is not a straight-forwardly linear process however, since knowledge and technology transfer encompass prior understanding, re-examination of past experience, ongoing experience, and rejection of inappropriate development, leading to iterative development. A constructivist approach, as described by Simakova and Coenen (2013), therefore underpins this multidisciplinary science and technology study of the potential for mining off-Earth, whereby the prospecting and mining sectors are scrutinised through the plurality of political, sociological, literary and engineering philosophies. In the tradition of Haraway (2016), MacFarlane (2019) and Strathern (1992): it matters what ideas we think other ideas with; words are myth-making; words are world-making. We investigate who has access to the worlds that are created by dominant and competing narratives about Extra-terrestrial resource production. We aim to reduce inertia towards the behavioural changes required for greater sustainability by articulating the challenges with techno-optimistic solutions and responsibility in research and innovation.

2. The prospect of off-earth extraction

To examine the ways in which the *out-of-this-world* attractor (Latour, 2018) is manifest in off-Earth extraction, we will start by examining the techno-futuristic (Stephenson, 2003) perspective, whereby the pseudo-linear process of technology transfer is justified by focusing on the limitations of terrestrial mining and processing. The Earth-based extractive industries produce commodities at the upstream end of the supply chain, at comparatively low cost to the rest of the supply chain where they incrementally accrue value during manufacturing and global trading (Moore et al., 2020). The extent to which commodities are traded, and the distances over which they are transported, depends upon their commercial value relative to the cost of production and transportation (i.e. raw materials have place value). Innovation and optimization maintain low unit costs of production by enabling mining operators to manage large throughputs of rock with consistent properties at low-grade using the efficiencies of scale and remote automation (Rogers et al., 2019).

A technological forecast (Devezas et al., 2012), dated to the start of investment in companies exploring the potential for off-Earth extraction, concluded that space industries would feature largely in the next long-term (Kondratiev wave, or K-wave, of 50 year duration) economic cycle of growth and decline. This is subject to critical question, since (Morone, 2016) predicts the next K-wave involves reshaping of production and consumption behaviour for sustainable growth and Rogers et al. (2019) highlight that mining technology does not provide an industrial step change unless applied with correct logistics and strategy. Nevertheless, off-Earth extraction is debated as a technological possibility following innovations in Information and Communications Technology (ICT), satellite technology for space exploration and the transportation of bulk materials to space (Metzger, 2016).

NASA (2020a) describes extra-terrestrial raw materials in terms of their intended consumer: commodities for *In-situ Resource Utilization* (ISRU) are consumed by space industries; commodities for *Non In-situ Resource Utilization* (non-ISRU) are for consumption by Earth-bound populations. ISRU does not require that commodities are used at the point of production, but remain in space with applications for life-support, propellant, and construction materials at/in multiple off-Earth destinations (Naser, 2019). Table 1 lists the main ISRU and non-ISRU target commodities, suggested mechanisms for mining and processing, and associated challenges. There is a focus on bulk movement of surface material, heating and electrical ($\pm$ magnetic) processes of separation. Gravity-based processing is avoided in low-gravity, off-Earth environments. Despite the challenges of maintaining supply chains, the use of chemicals is nevertheless required in some of the proposed operations.

Andrews et al. (2015) focussed on workable space industrialization architecture (and included a cost where technology readiness level is low) in positive economic feasibility calculations for non-ISRU. The high costs of transporting raw materials to Earth mean that only very high value commodities are promising, so the authors show what is possible using the Platinum Group Elements (PGE) as an example. They concluded that it is '*probably possible to make outstanding profits*' by mining asteroids using a well thought-out, well-financed approach. Dahl et al. (2020) do not propagate this view in their economic analysis using 10 different commodities, perhaps demonstrating what is more likely. They highlight that metals will continue to be available on Earth; that a mining operation in space may not have market power in Earth's markets; and that iron, nickel and cobalt by-products of PGE mining could be abandoned in space or used for ISRU. Dahl et al. (2020) suggested that off-Earth extraction is hype reminiscent of that surrounding proposed deep sea mining, a 'sustainability conundrum' with huge knowledge gaps regarding potential impacts on ecosystems (Hyman et al., 2022; Levin et al., 2020).

Since economic growth and decline cycles are precipitated by industrial innovations that consume the raw materials that are produced by mining, and since the indefinite continuation of economic cycles is '*impossibly reliant on the equivalent of several planets*' (Latour, 2018), then it is logical to couple the growth of space industries with debates about off-Earth extraction. In this case, techno-optimism is fuelled by successes in space research and innovation, projections of extreme profit, and the notion that economic growth can be sustained by escaping mining of the Earth's surface/subsurface.

3. A question of scale

The potential market for resource consumption (i.e. non-ISRU) on Earth is very large. In contrast, the ISRU market is small: the satellite industry is the main potential user of resources at the present time; the space tourism industry is imminent (Amos, 2021a; Rincoin, 2021a, 2021b) but unlikely to require resources in space; the space colonisation industry is emerging and life would depend on ISRU. A small ISRU market would be highly vulnerable to any technical extractive and

Table 1
A brief review of representative research into resources of potential interest for off-Earth mining operations, their source (ore/mineral deposits) and technological feasibility or challenges related to hypothesised extraction methods. The multiple simultaneous challenges arising for resource production in off-Earth environments are not insurmountable, but require solutions that are costly to develop as an innovation cluster. (M-type NEAs are rich in metal phases and are thought to be the source of iron meteorites.).

Potentially exploitable resource (& source)	Techno-optimistic application	Mining and processing operations	Challenge to techno-optimism	References
The Moon				
Regolith (Lunar Surface)	Radiation shielding (human habitats) & construction by additive manufacturing; waterless concrete & aggregate; production of oxygen (life-support, rocket oxidiser), Fe/Al (infrastructure), Ti (aerospace), Si (photovoltaic cells, silane as a possible rocket fuel), Mg (external structures, replacement parts)	Bulk surface excavation; material handling; dry beneficiation (magnetic, electrostatic or size separation); extraction; ilmenite reduction; molten salt electrolysis; fluorination; acid digestion; reduction of Al_2O_3; magma electrolysis; carbothermal reduction; reduction of magnesium oxide with ferrosilicon; vapour pyrolysis; vacuum distillation) product storage; waste management	Visible damage to lunar surface impacts international stakeholders; heterogeneity of feedstock; stability of products under extreme lunar conditions; energy-intensive processes; high purity of products is demanded for some applications (e.g. Si for PV cells); safety risks (e.g. ignition of Mg in the presence of oxygen); legalities of access and ownership	Anand, 2010; Anand et al., 2012; Barker, 2020; Benaroya et al., 2012; Cannon and Britt, 2020; Crawford, 2015; Duke et al., 2006; Fa and Jin, 2007; Hadler et al., 2020; Hertzfeld and Pace, 2013; Just et al., 2020; Lewis, 1991; Lin et al., 1992; Meurisse et al., 2018; Milligan, 2013; Pabari et al., 2020; Pilehvar et al., 2021, 2020; Rasera et al., 2020; Schlüter and Cowley, 2020; Schwandt et al., 2012; Simko and Gray, 2014; Sviatoslavsky, 1993; Taylor and Carrier, 1993; Taylor et al., 1993; UN, 1967; Wingo, 2004; Wittenberg et al., 1986 UN, 1967, 2004; Wittenberg et al., 1986
Water (Polar ice; implanted by solar wind in lunar regolith; hydrated minerals)	Life (drinking, personal hygiene, agriculture); processing; propellant; production of H_2 and O_2	Diverse methods include strip mining; in-situ sublimation; regolith devolatization; ilmenite reduction; condensation; electrolysis	Overly optimistic estimates of extractable abundance & access; extremely high energy requirements; distance between sources, landing sites & sites of consumption; formation of toxic, corrosive & flammable H_2S; low technology maturity of off-Earth cryogenic propellant production, storage & use	
Hydrogen and Helium ^3He, ^4He (Lunar surface; implanted by solar wind in regolith)	Propellant (H); reactant (H); fuel for future nuclear fusion reactors (^3He)	Bulk surface mining operation; material handling; beneficiation; regolith degassing by heating (> 700 °C); product storage; waste management	Heterogeneity of feedstock; low abundance requires processing of high volumes of material; unknown distribution at high lunar latitudes; energy-intensive extraction; significant processing infrastructure disrupting a large surface area; nuclear fusion (^3He) is yet unproven as safe and viable; fair distribution of 'clean' energy	
Urea (Lunar human population)	Additive manufacturing using regolith	Collection from waste management systems	Environmental suitability & scalability unknown; increased initial & final setting times; reduced strength after freeze-thaw cycles; pre-existing human settlement for collection	
Platinum group elements (Meteoritic debris in regolith)	Catalysts; electronics	Excavation; material handling; beneficiation; extraction; product storage; waste management	Uncertainty about viable ore deposits & long-term economic value (highly dependant on local infrastructure development)	
Near-Earth Asteroids (NEAs)				
Platinum-group elements (M-type NEAs, dominantly Nickel-Iron alloys)	Sale in Earth-based market	Bulk surface mining operation; underground and/or *in-situ* extraction; fragmented pieces collected in a bag surrounding the asteroid	Remote sensing limitations for resource definition; initial investment hesitation; price reaction to possible flooding of the Earth-based market; unproven mining & processing technologies; method specific challenges, e.g. ergonomics of asteroid capture	Andrews et al., 2015; Dahl et al., 2020; Elvis, 2014; Gertsch et al., 1997; Hasnain et al., 2012; Hein et al., 2020; Kargel, 1994; Lietaert et al., 2018; McInnes, 2016; Naser, 2019; Ross, 2001; Sanchez and McInnes, 2012
Base metals e.g., iron and nickel (M-type NEAs)	Construction for satellite industry; off-Earth habitation	Bulk surface mining operation; underground and/or *in-situ* extraction	As above	
Water and other volatiles (C-type asteroids; near-Earth comets)	Life processing, propellant etc.	Multiple proposed methods (e.g., heating by solar thermal processes)	As above; energy requirements for breakdown of hydrated minerals in asteroids.	
Mars				
Regolith (Martian Surface)	Construction by 3D printing; production of waterless concrete	Bulk surface mining operation	Heterogeneity of feedstock; stability of products under Martian conditions; challenges of Martian topography	Abbud-Madrid et al., 2016; Arvidson et al., 2010; Feldman et al., 2004; Fischer et al., 2016; Gayen et al., 2020; Hecht et al., 2021; Kading and Straub, 2015; Kleinhenz and Paz, 2017; Reches, 2019; Yashar et al., 2019
Water (Water ice at poles; hydrated minerals; liquid brines)	Life processing, propellant etc.	Diverse methods include ice mining; drilling-based water extraction; regolith devolatization; electrolysis of brine	Accessibility to water-ice sheets unknown; heterogeneity of feedstock; potentially low-grade hydrated mineral deposits; water phase changes; stability of brine not fully understood	
Oxygen and other atmospheric gases (Martian atmosphere)	Life processing, propellant etc.	Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE)	Scalability and comparable efficiency to other methods unknown	

transport challenge when satisfied by a single mining operation, requiring considerable redundancy for failed components and stockpiling.

The viability of a non-ISRU market is inherently tied to terrestrial resource production by commodity price. On Earth, the scale of mining is tied to throughput (of rock) and energy provision, which influences the unit cost of production and whether mining attracts significant capital investment (Moore et al., 2021; 2020; Paneri et al., 2021). Throughput and power are also tied to the economies of scale in the space industries, by fuel consumption and payload size (Fig. 1). Payload size would strongly influence whether robust technologies can be cold-commissioned prior to transportation, or must be constructed in situ, and whether a new mining value chain is needed for maintenance.

Andrews et al. (2015) described a workable space industrialization architecture that includes a nuclear-powered first generation automated miner that will '*simply land and drill. If the ore is not satisfactory, or if they run into a large boulder, they simply pick up and move to the next selected spot.*' The actions of relocating a small-scale mining operation have been tested on Earth: decommissioning was three times faster when an inexperienced workforce had on-the-ground supervision (prior to the Covid pandemic) than for an experienced ground crew with remote communication (during the pandemic) (Moore et al., 2021). The process in either case was less simple than those imagined and described for off-Earth extraction by Andrews et al. (2015).

Robotic mining concepts proposed for off-Earth extraction have a universal wheeled basal platform and do not require a human presence (Kornuta et al., 2019; Mueller and Van Susante, 2012). Whether the proposed solutions are sufficiently robust to withstand the significant physical stress of throughput high enough to recover commodities at low concentration (Table 1) is unknown. The capital cost of development of bespoke automated solutions is generally too high to provide a return on investment for small terrestrial mining operations (Moore et al., 2021; 2020) unless the commodity price is consistently high and not subject to price volatility (e.g. terrestrial production of gold). The proof of commercial viability of extractive mining operations requires extensive geological, geophysical, mineralogical and metallurgical investigations.

Decision-makers in the mining and minerals processing industry face complex problems and risks associated with limited or inaccurate data, resource and reserve estimation that is too local or site specific, poor mining site selection, overly optimistic mine design and scheduling, mining and processing technology selection, inadequate metallurgical test work and sampling that result in scale-up problems and operating parameters (McCarthy, 2003; Sitorus et al., 2019). The proposition that off-Earth mining operations move around boulders and to better prospects (Andrews et al., 2015) shows that visions of off-Earth extraction are similarly guided by geological information. Geological knowledge of other planetary bodies (e.g. Lunar map; Fortezzo et al., 2020) arises dominantly from remote sensing and modelling, with limited analysis of samples with a perfectly known provenance. New remotely-automated methods of sampling can be significantly impacted by simple mechanical problems, causing sample to leak into space (NASA, 2020b).

The Mineral System Concept enables screening of ore deposits for prospectivity, based on variations in the atmosphere-hydrosphere-biosphere-lithosphere through geologic history, lithospheric enrichment and geodynamic context (Banks et al., 2020; McCuaig and Hronsky, 2017). A prospecting geomodel is variably defined somewhere between: (1) a detailed numerical and visual description or a three-dimensional map of the physical quantities in a domain of interest, often deposit-scale; and (2) a model that encompasses multiple ore bodies to find unifying characteristics for a class of mineral deposits. Geometallurgy approaches combine geological understanding with extractive metallurgy tests using bulk samples (hundreds of kg or tonnes of rock) that are difficult to source from off-Earth environments, to predict risks during and beyond mineral processing plant design. Geological certainty is currently inadequate to construct off-Earth Mineral Systems, geomodels and geometallurgy, at either lithospheric or site-specific scales, to support extraction activities.

iSpace (2021a) is a prospecting company established with the very specific remit of robotic prospecting for water, in readiness for establishment of a human base on the Moon (Gibney, 2018). The company is using a Joint Ore Reserves Committee (JORC)-style approach, i.e. a professional code of practice in the mining industry to ensure best reporting standards of resource estimation, to prove viability to investors who will require sustainability-driven approaches. It has raised nearly \$130 million in seed funding and has \$20 million in debt financing (iSpace, 2021b), which demonstrates the initial financial commitment required for innovation to search for off-Earth resources.

The potential for finding viable ore deposits of Platinum Group Elements (PGEs) and water on asteroids was modelled by Elvis (2014) using probabilities and a considerable number of assumptions. Near-Earth Asteroids (NEAs) are attractive propositions for asteroid capture at the L1 and L2 Lagrange points of precarious gravitational equilibrium for economical reasons, with adjustments to maintain position. Importantly, only 10 (a highly uncertain number) Ni-Fe asteroids

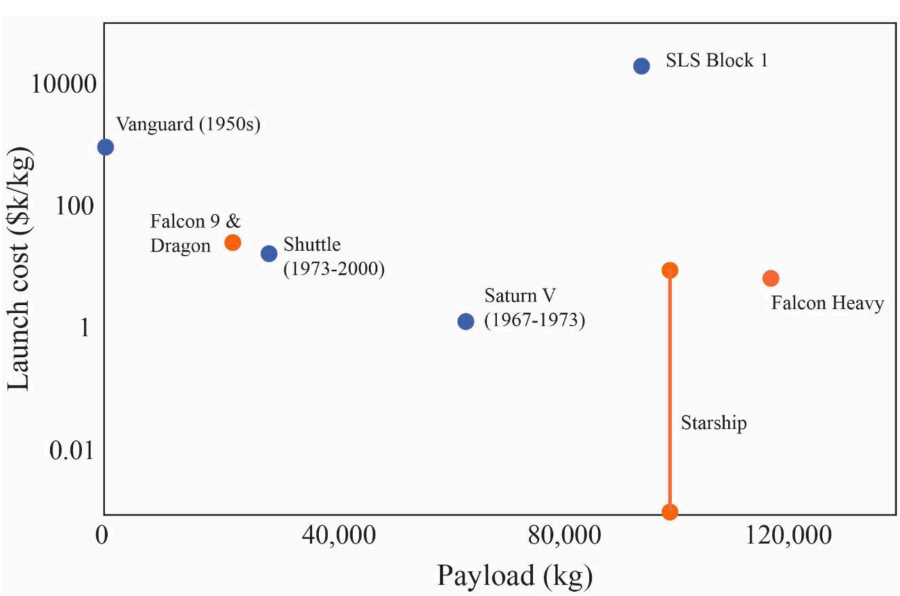

Fig. 1. The economies of scale applied to space transportation in both the 20th and 21st centuries. There is an inverse relationship between payload size and launch costs. Space vehicles are those by NASA (blue symbols) and SpaceX (orange symbols). Space X has a goal for the launch cost of the Starship to drop to \$10/kg (Zafar, 2020) and the >\$2 billion single launch of NASA SLS Block 1 cannot compete with the commercial vehicle (Berger, 2019). Data from Berger (2019); Jones (2018); SpaceX (K.R. 2020); Zafar (2020).

with diameter greater than 100 km would have a value ≥US$1B (Elvis, 2014). Water could be theoretically sourced from smaller-sized asteroids of carbonaceous chondrite composition, which are hard to find. The modelling predicted that approximately 18 NEAs of > 100 km in diameter might be prospective for water (Elvis, 2014). The difference in the levels of certainty around terrestrial and extra-terrestrial ore deposits highlights that investment in off-Earth extraction is highly speculative.

The Asteroid Mining Corporation (AMC, 2021) has a business model based on robotic prospecting, commercialisation of geological data and subsequent development into a mining company, though the eight-strong(in 2021) company management team includes few years mining expertise. The business model requires that geological information will be the preserve of private enterprises, despite operating in competition with the public-private partnerships that underpin space exploration. The company solicits investment on the basis that '*any company that mines an asteroid is going to become immensely rich as asteroids are simply staggeringly valuable resources, with asteroids over a kilometre in diameter being valued in the trillions of pounds due to their relative abundance of Platinum group metals*'.

The Prospectors and Developers Association of Canada (PDAC, 2021) state that, for Earth-based prospecting, '*out of every 10,000 identified mineral prospects, only about 10% will lead to a drilling program and just 0.01% will lead to a new mine*'. Abrahamian (2019) and Wortman (2020) described investment in off-Earth extraction as a 21st century gold rush but there is a significant difference between the historic terrestrial gold rush and the modern off-Earth multi-commodity speculation. A wide participant group engaged in early terrestrial prospecting and indeed continues to engage in modern artisanal mining. Off-Earth speculation is the preserve of an exclusive group of nations and of wealthy individuals, driven as much by international power brokering as by commerce. Kornuta et al. (2019) suggest that it heralds '*a new age of economic expansion, sustained space exploration, settlement, and American leadership in spa*ce'. The techno-optimistic identity of the next economic growth cycle is thereby linked with national and individual identity.

4. The out-of-this-world hype cycle

Devezas et al. (2012) suggest that development of ICT following the 20th century space exploration is the driver for the current resurgence in space activities but that there may be over-optimism regarding the technologies that might become available. They further state that the accuracy of longer-term economic forecasts is inversely proportional to the intensity of capital investment necessary to facilitate expensive and '*not priority entangled*' projects. Gartner's Hype Cycle (Blosch and Fenn, 2018) describes patterns of hype and disillusionment that arise with specific technologies or innovations, higher-level concepts, strategies and disciplines and it can operate over multiple timescales (Fig. 2). It has been used in the mining industry to describe perceived opportunities for profit that drive price spikes and subsequent investment in research and prospecting, particularly where mining of commodities coupled to new technologies is likely to be subject to an over-optimistic forecast demand (Wellmer and Dalheimer, 2012).

Demand for the new technologies and perceptions of supply shortages are the triggers for prospecting and mining innovation (Renner and Wellmer, 2019). Fig. 2 shows that initial excitement about the new opportunities afforded by innovation is mostly driven by market hype. Disillusionment arises when early expectations are not met rapidly enough because the market is immature; expectations recover somewhat when a concept or market reaches maturity, leading to real value. The curve is not dissimilar to the Lassonde Curve that highlights risk in the protracted life cycle of a mineral discovery from pre-discovery and discovery through feasibility, development and start-up (LePan, 2019). LePan (2019) further describes the exit of speculative retail investors from the process and replacement by institutional investors who benefit from the income stream generated.

The companies *Planetary Resources* (launched in 2012; Abrahamian, 2019) and *Deep Space Industries* (in 2013) had the long-term goal of asteroid mining. However, the millions of dollars of business investment (e.g. Planetary Resources raised $50 million between 2012 and 2016; Abrahamian, 2019) that they raised were for development of propulsion systems and telescopes. The companies were both purchased for asset-stripping or merger in 2018–2019, thus ending the first asteroid-mining bubble (Abrahamian, 2019) and the peak of expectations (Fig. 2). The UK-based Asteroid Mining Corporation was founded in 2016, and in 2021 still carried a statement that it was competing with the two American '*major players in the field*' (AMC, 2021) despite the fact that they had ceased to operate. Fig. 2 demonstrates that Off-Earth extraction as a concept has very low maturity, particularly for asteroid mining, since the lack of geological certainty undermines any attempt to access resources.

Barker (2020) proposes that the marketing of space resources can be interpreted using the Prospect and Loss-aversion theories, where individuals make decisions based on perceived gains, rather than perceived losses. In this context, inadequate prospecting for extra-terrestrial resources highlights that Off-Earth extraction may be very little more than hype, such that it does not reach maturity as an industry in the near- to mid-term. Since there are no immediate options to produce commodities for trading, the start-up companies have cash flow that is dependant upon the enthusiasm of their investors, state sponsorship and/or service contracts with space industries. Disillusionment amongst high-risk investors may accompany recognition of the extreme challenges associated with commercialising off-Earth extraction, which may cause entry into the 'Valley of Death' of company failure even before operations have started.

We can consider that ICTs are not the only trigger in the Off-Earth extraction hype cycle and that technological innovation for energy provision that is not fossil-fuel based (e.g. from photovoltaic cells, Table 1) is also important. There is a very strong linkage between resource extraction, renewable energy provision and more wide-anging impacts in terrestrial mining (Beylot et al., 2021; Paneri et al., 2021). Players in the terrestrial mining industry variably engage in practices to dissociate themselves from, or to diminish, the negative impacts of mining, particularly in environmentally or culturally sensitive locations: investors reduce risks using environmental social and corporate governance (ESG) criteria; mining practitioners demonstrate JORC compliance and obtain social licence to operate (SLO). Dialogues about best practice in the terrestrial mining industries can shed new light on ambitions for off-Earth extraction, such that priority entanglement is perhaps the key to considering the relationship between the *out-of-this world* attractor and the hype cycle for off-Earth extraction.

Non-ISRU amounts to a dialogue about whether mining can be outsourced to space, i.e. a denial that consumption is limited to one planet based on an inflated expectation for technological solutions. If the peak of inflated expectations relates to hope for technological solutions, and the trough of disillusionment aligns with recognition that there is only one planet to provide our resources, then the slope of enlightenment is the reorientation of the modernization front that was suggested by Latour (2018). The slope of enlightenment is entered by recognition that risk is driven by environmental degradation on a planetary scale, i.e. the point at which society cooperatively recognises and implements effective real world solutions. New frameworks are emerging to reclaim and conserve existing materials (e.g. circular economy), to reduce demand by smart engineering and change behaviours, and to adopt cultures for environmental stewardship including those traditionally practiced by Indigenous Societies. However, technological advancement for space mining (prospecting and extraction) as an alternative solution to societal and environmental challenges may fuel complacency and hinder actions that preserve and reconstitute a liveable terrestrial habitat.

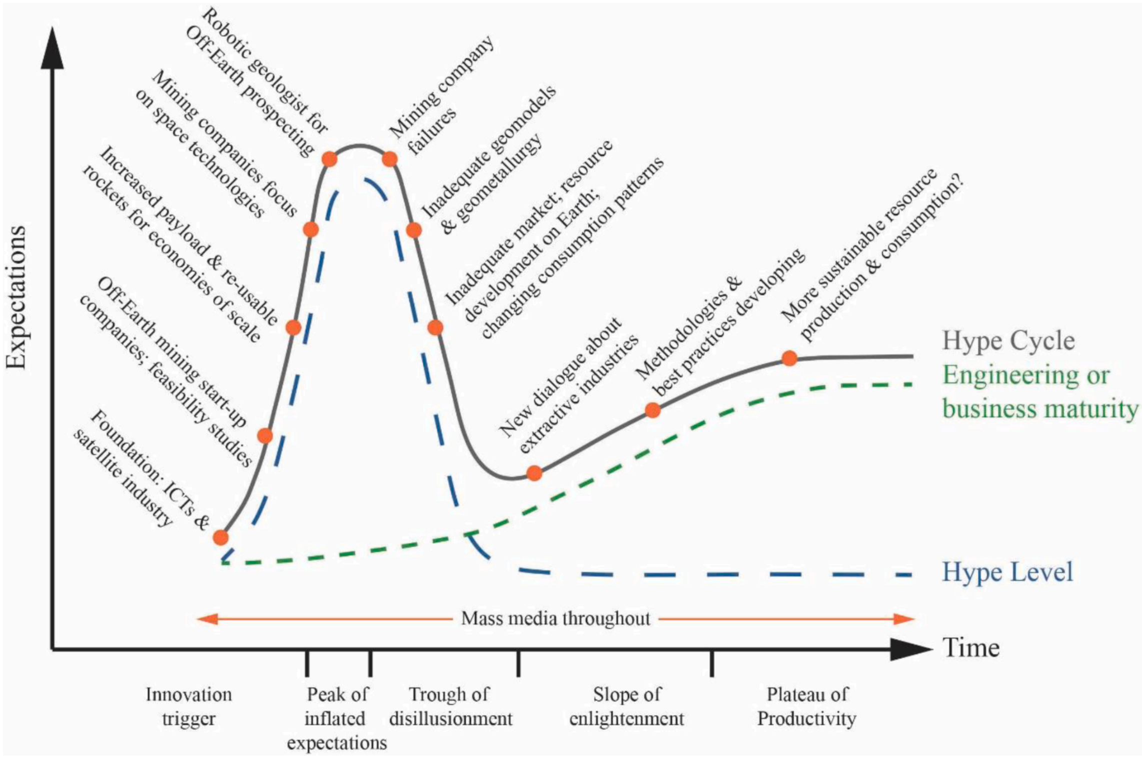

Fig. 2. The out-of-this-world mining Hype Cycle. Enthusiasm accompanies development of transportation and end-user infrastructure in the Hype Cycle for the Off-Earth extraction technology cluster, but disillusionment arises from both the time necessary to develop resource knowledge and the poor match between the economics of mining and the scale of the potential market. It differs from the Gartner Hype Cycle of Blosch and Fenn (2018) in that media interest exists prior to the peak of inflated expectations.

5. Martianist and counter-martianist narratives

The out-of-this-world mining Hype Cycle features intense and ongoing scrutiny by the media and public, since mining and space exploration are both *priority entangled* issues that evoke feelings of excitement, adventure, disappointment and anxiety (Tutton, 2021). Pollard (2015) assessed 20th century '*Martian*' literature, which is not about Mars, but uses metaphor to style the familiar at its most strange. In the Martian tradition of situational bizarrerie, Pollard's analysis both succeeds and fails as metaphor for uptake of *out-of-this-world* optimistic rhetoric and solutions for resource production. As successful metaphor, mundane mining is elevated to the fantastical by exciting narratives that suggest a solution to terrestrial challenges of production and consumption. Jeff Bezos, interviewed about the Blue Origin space-tourism business (Horizon, 2017), stated that the best way to protect this planet is to out-source heavy industry: '*In space you have 24/7 solar power. Resources in space are much vaster, in terms of mineral resources and so on. Every kind of element that you need is available in space in very large quantities. And so, over the next couple of hundred years, that will allow us to both continue to have a dynamic, expanding, growing, thriving, interesting civilisation, while still protecting this planet that we evolved on*'.

The promotional video of Deep Space Industries (who aimed to extract resources from asteroids) began with a series of images showing electricity generation and other industries, and people of different ethnicities representing a diverse human society. The images are accompanied by the words '*Our world is at its limits. And yet we all want more. And why not? Why shouldn't the future be better than today? But where will it come from? Simple. Our tiny planet sits in a vast sea of resources. It's time someone seized the opportunity*.' The statement echoes the perception that access to vast resources and deployment of mining (Andrews et al., 2015) is simple. Since Deep Space Industries was a high-risk start-up of short duration, it can be inferred that the solution to planetary limits by off-Earth extraction was not simple. The statement appears to be a complete reversal of Martianist narratives. It reduces the complex to the simple, in a counter-martianist dialogue that may create false expectations.

The Earth is not immediately likely to run out of resources (Herrington, 2021) and the hype cycle explains that investment will support the development of new ore deposits (Wellmer and Dalheimer, 2012): we access mineral and metal resources that have the highest available grade (concentration of metal in rock) and tonnage (volume) to serve a competitive economic climate, whether on- or off-Earth. The grade of an ore depends on the processes that operate to concentrate commodities of interest: plate tectonic activity and the extent of sedimentary reworking feature strongly in the Mineral Systems Concept (e.g. McCuaig and Hronsky, 2017). The Earth is the only planetary body in our inner solar system proven to have active plate tectonics and hydrous weathering. Mars is exceptional in that plate tectonics and hydrous erosion operated in its early planetary history (Breuer and Spohn, 2003; Kleinhans, 2005). Without such processes, most planetary bodies have less mineral diversity and ore deposits at lower grade than those on Earth (Hazen et al., 2008; Hazen and Ferry, 2010). Volatiles implanted by solar wind (Anand et al., 2012; Fa and Jin, 2007; Table 1) are an example of where potential commodities are concentrated to greater extent than on Earth. Overall, resources may be vaster in space but most commodities are less geologically available than on Earth.

Pollard (2015) explains how out-of-this-world (Martianist) styling aids in the self-promotional strategies of the narrators, where consumerist soundbites create public influence by engaging audiences, promoting an acceptance of ideas, and altering audience values. The issue of status, engagement and persuasion are not limited to Pollard's analysis of modern '*Martian*' literature. According to Simakova and Coenen (2013), visions and expectations of the far-reaching potential of emerging science and technology border on hype. They explain how the forward-looking statements of influential visionaries can act as prophecy, by producing scenarios that make futures. The status of the visionary narrator is significant, and it becomes important to establish motivation and context. In the context of off-Earth extraction, the 'someone' who drives development may cite curiosity-driven exploration/science, or a solution appropriate to a multi-ethnic society, while acting for personal economic benefit and entrepreneurial excitement.

Applied in the present context, there are celebrity billionaire businessmen that head or founded *Blue Origin, Space X* and *Virgin Galactic*. They state different drivers for backing innovation and development, including scientific endeavour and space exploration/colonization, but their business models are necessarily based on space tourism and/or provision of services to the satellite industry, governments or other organisations. Innovations are for smoother flight and landing, larger rockets to transport bigger payloads for less fuel consumption (Fig. 1), or smaller satellites with greater functionality for deployment from smaller payloads. SpaceX is contracted to land NASA astronauts on the Moon before the end of the decade, but it has a far more ambitious plan for inter-planetary space travel according to Elon Musk (Amos, 2021b; Sheetz, 2021). It includes building up to 100 Starships every year, and a self-sustaining colony on Mars by 2050 to ensure the continued survival of our species. Tutton (2021) describes the utopian and libertarian notion that living on other planets equates to positive change on Earth as evasion of global challenges, while Latour (2018) cites dreams of moving to Mars and post-humanistic hopes for virtual existence as examples of escapism.

Retelling narratives in a way that involves invention is likened to myth-making and it requires critical analysis. The leading visionaries (Simakova and Coenen, 2013) in the commercial space industries previously built a commercial platform, and achieved public status, by identifying techno-futures. By re-orienting towards the planetary, they have engaged the public audience, and achieved acclaim for their investment choices whether or not they are of widespread benefit. Kleine (2014) is sceptical of the motivations of visionaries and presents evidence that the actions of businesses to mitigate climate change while expanding climate-damaging practices are brand-building: a cynical ploy to reduce societal and political pressure for real change. Black (2021) explains that storytelling by experts, positioned as intermediaries between investors and publics, acts to perpetuate inequalities along lines patterned by race, gender and nationality. The credibility of post-humanist visions in any sector is therefore uncertain (Simakova and Coenen, 2013), particularly in a regime of rapid socio-environmental change since there is no 'escape' for the majority of the global population. Tutton (2021) concluded that spaceflight capability offers little to the flourishing of humans and the Earth, which draws into question efforts to market off-Earth extraction as a sustainable endeavour.

6. The abiotic dependence in an expanded resource base

To examine the sustainability and responsibility of off-Earth extraction, we will start by examining environmental ethics. Marshall (1993) stated that an anthropogenic-centred Conservation ethic governs the implementation of policies designed to protect extraterrestrial environments. The Conservation ethic (Fig. 3a) is shallow environmentalism, disinterested in the intrinsic value of the environment, instead seeing value in terms of an infinite supply of resources to be used by humanity (Marshall, 1993). There is extensive co-dependency between organisms in Earth (e.g. Lenton and Latour, 2018), and human consumers are dependant on ecosystem health. The Ecologic extension (Fig. 3a) of Conservation ethic is deep environmentalism that emphasizes the dependency of the biotic on the abiotic (Marshall, 1993; Rickaby, 2015). Since the urban industries are now considered to include space (Bélanger, 2016) and since lunar prospecting company iSpace views the Earth and Moon as one ecosystem (iSpace, 2021a), it is important to consider the impact of space industries from a deep environmentalism perspective.

Gupta and Schmeier (2020) examined the principle of 'no significant harm' as a way of addressing transboundary environmental challenges. Significantly, they described multi-directional, multi-actor/multi-level harm as creeping and cumulative, with growing spatial and temporal characteristics. They found that national prioritization of economic growth has led to externalizing the environment. To modernize the 1967 Outer Space Treaty for national appropriation, Wortman (2020) preferred a UN-enabled prospecting scheme '*rooted in the truest tradition of exploration and ownership*', despite concerns over environmental impacts and international conflict. This is poorly aligned with the *Cosmos 2030* Agenda for development, part of the 2030 Sustainable Development Agenda, which suggests that all members of the international community should equally enjoy the potential of astronautics and discussions around planetary sustainability (Galli and Losch, 2019; Gugunsky et al., 2020; UNOOSA, 2021). Losch (2020a), on the other hand, proposed adding an 18th Sustainable Development Goal called '*Space Environment*' to the United Nations 2030 Agenda as a political demand that could evolve into a '*Planetary Plan*'. While the US 2015 Space Act has stimulated discussions around national appropriation, there is currently no international consensus for the regulation of activities related to the exploitation of natural resources in space (Gugunsky et al., 2020).

If prospecting in space is rooted in the traditions of resource production (Wortman, 2020), then the constructs to manage terrestrial industries deserve attention. Segura-Salazar and Tavares (2018) reviewed sustainability in the regulated mining industry, which has arisen from a long history of needing to gain public acceptance and re-orientation towards the modernization front. They compared weak sustainability, where offsets are used to balance economic activity with environmental impacts, and strong sustainability that emphasizes nature as fundamental and sometimes irreplaceable by other capitals. Their perspective considered the local-global tension, the importance of time-scales, the natural environment as the Ecosphere (the geosphere (abiotic) plus the biosphere (biotic)), and its relations to society, economy, technology and governance (Fig. 3b). Modern visualisations place sustainable human practice in a whole system context of 'nature' (Segura-Salazar and Tavares, 2018).

The European Charter of Fundamental Rights promotes *the primacy of the interest and welfare of the human being*, whose health and wellbeing are dependent on its environment. However, global human-made mass now exceeds all living biomass (Elhacham et al., 2020) and the Ecologic Extension (Fig. 3a) is unbalanced in terms of consumption and the environment. The rebalancing of nature requires careful consideration of the abiotic-biotic relationship on vast planetary scales. Thus, the conceptualization of sustainability of terrestrial extractive activities proposed by Segura-Salazar and Tavares (2018) can be extended to a planetary scale (Fig. 3b) and serves as a basis for debates around an international consensus on the sustainable management of space mining activities. No schemes have been primarily designed to address the fundamental abiotic-biotic relationship as a means to describe human vulnerability on a planetary scale.

Multiple authors have considered human activities in space from either an anthropocentric, equating roughly to a Conservation ethic, or an ecocentric perspective, equating roughly to the Ecologic Extension (Table 2). The ecocentric perspectives dominate and variably assume that techno-optimistic visions of space colonisation and exploitation will be realised, or will create international tensions and increase inequalities. A recurring theme is that terrestrial and space development are linked, and that terrestrial frameworks form the basis of guidelines to manage extraction of resources off-Earth (Chrysaki, 2020; López, 2016; Newman, 2015).

In describing the movement of humankind into space, (Losch, 2020a) states that "Planetary Sustainability" implies understanding the limits of a planet facing the Anthropocene. The Anthropocene is not yet ratified as an epoch in the geological timescale (Luciano, 2022), but it describes an entangled abiotic-biotic relationship and the current imbalance in the Ecologic extension to ethics. The Anthropocene, in correlation with the Great Acceleration (Steffen et al., 2015), is a contested term because it

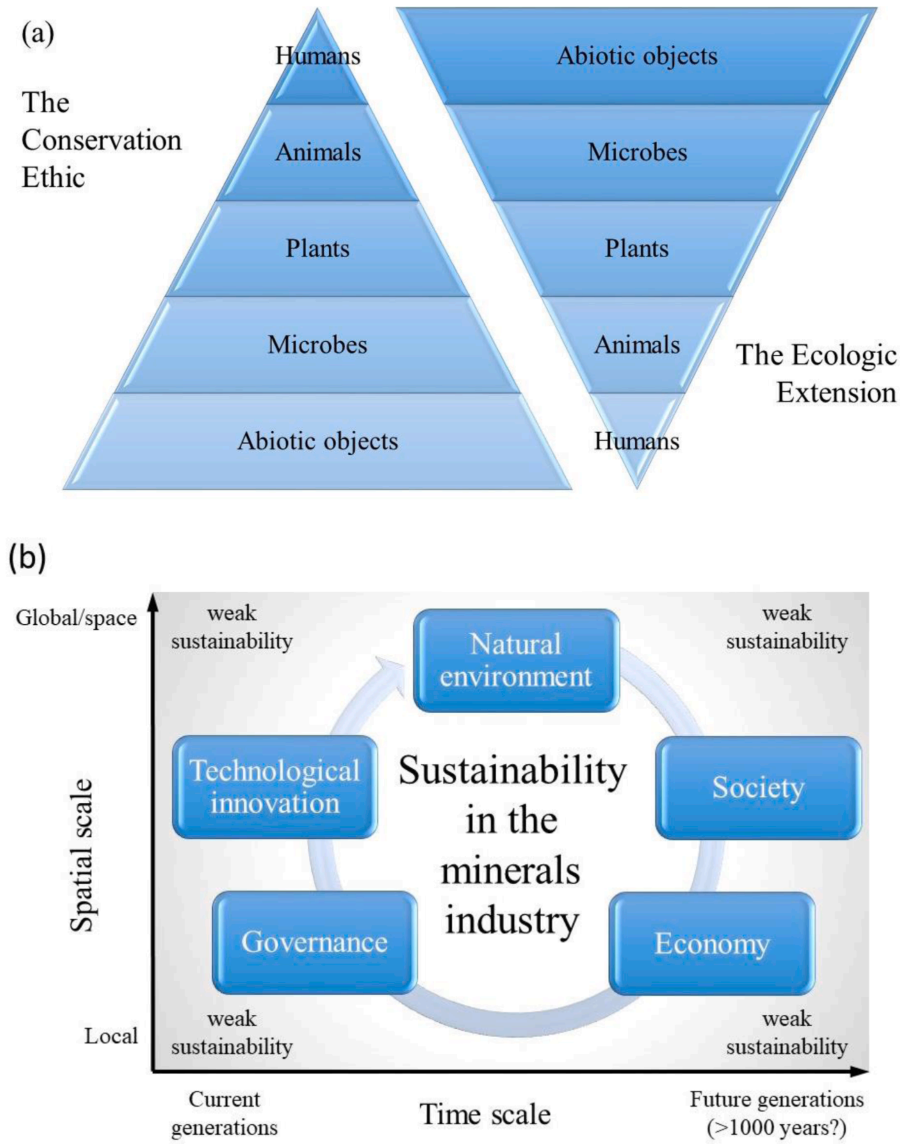

Fig. 3. Schematic representation of (a) The Conservation Ethic and its Ecologic Extension (Marshall, 1993) and (b) the five dimensions of the economic, social and environmental triple bottom line (Segura-Salazar and Tavares, 2018). Segura-Salazar and Tavares (2018) show that the natural environment supports the human constructs on the local to global, and intergenerational scales, and that consideration of any part of the system results in weak sustainability. Marshall (1993) demonstrates different perceptions of dependence and entitlement.

reinforces the human/nature dualism, central to modernisation theory (Whyte, 2018), and places the former above the latter. Latour (2018) suggests replacement of the term *human* with the term *terrestrial* that has the added advantage of not specifying species (Haraway, 2016), and emphasizes dependence of all organisms on the environment.

The current stage of the Holocene Epoch is the Meghalayan Age, the stratotypes of which mark a megadrought that coincides with the collapse of civilisations in the archaeological record (Sengupta et al., 2020; Walker et al., 2019). Thus timescales for different disciplines have converged and the coincidence of geological (abiotic) changes and human (biotic) flourishing are apparent. The abiotic planet persists through Meghalayan megadroughts that leave the civilisation of the biotic species populations in peril. Writers such as Haraway (2016) and Shoshitaishvili (2021) describe the Anthropocene as more a boundary event between times than an epoch, marking an era of coevolution between Earth's chemistry and life, where toxicity plays a role (Rickaby, 2015).

The stark abiotic-biotic and geological framings explain optimistic narratives of off-Earth escape but ultimately demonstrate the rate and scale at which societal, environmental and technological solutions at local and global scales are required. The triple bottom line of ESG for sustainable mining is a pragmatic framework in which to take action, where the stakeholders have the ability to design and create environments through the extraction-remediation life cycle in modern, responsible mining operations (Segura-Salazar and Tavares, 2018).

7. Extractivism in an expanded resource base

Not all stakeholders have equal influence in, or benefit from, space industries: Dallas et al. (2020) have demonstrated that a high proportion of countries based on mineral economies (on Earth) have low national incomes, while a high proportion of countries with spacefaring industries have high national income. Raw materials production in low-income countries underpins development of spacefaring industries in consumer-intensive nations, thus reinforcing patterns of global inequality. The relationship between consumer and producer is described as extractivism (e.g. Ye et al., 2020), an economic and social model in which raw materials are traded outside of the producing nation to more wealthy countries where value is added to the commodity and to community by manufacturing. Kleine (2014) writes that extractivism reflects a colonial mindset that '*there is always somewhere to go and exploit once the current site of extraction has been exhausted*'.

Bélanger (2016) describes the altitudes of urbanisation stretching from 10 km below to 35,000 km above sea level. Devezas et al. (2012)

Table 2
Contemporary views on sustainable development (SD) related to Space Resource Utilisation.

Reference	Reasoning regarding space activities and sustainability	Main conclusions
System valuation: Anthropocentric		
(Iliopoulos and Esteban, 2020)	Assumption that humanity will inevitably migrate to space. There is marginal attention to space environment preservation & controversy over the moral line on the commercialisation of space resources. Sustainability is about minimizing human extinction & environmental space degradation risks; improving human welfare on Earth.	Private space activities may bring direct & indirect benefits to society in the long term; provide humanity with appreciable sustainable value by establishing efficient and profitable operations, tax revenue to the United Nations. Requires unambiguous regulations concerning property rights
(Barker, 2020)	The relatively low population growth off-Earth justifies ISRU to support establishing self-sustained human colonies in the long-term. Sustainability has four components: operational, political, engineering, and logistics.	The 'Planetary Resources Management System' model, inspired by the petroleum industry and still under development, supports extra-terrestrial resource prospecting and landing site selection for ISRU.
(Palmroth et al., 2021)	A notable environmental concern is space debris. Mitigation involves encouraging the participation of new commercial players. Sustainability: the current use of space should not impair its future use.	Continue developing the concepts of 'satellite sustainability footprint' and 'orbit capacity' and embed these in legal frameworks. Binding & voluntary frameworks can contribute to multi-stakeholder sustainability.
System valuation: Ecocentric		
(Hofmann and Bergamasco, 2020; Losch, 2020a; Ursul and Ursul, 2020[a])	Assumption: humanity will inevitably migrate to space. Space mining technologies may differ from those on Earth, be potentially more cost-effective and environmentally friendly, and less resource-intensive. Space mining is a path to achieve global SD; it will support the increasing human needs & ensure the continuity of human existence on a planet with limited resources and environmental issues, but may trigger future conflicts.	Space resource extraction will have a remarkable impact on human civilization, may create a new way of interaction between humans and the extra-terrestrial environment & new technologies may contribute to developing more sustainable mining on Earth. A new 18th UN SDG "Planetary Plan" is preferred but domestic laws can guarantee the sustainability criteria of a project in the absence of an international regulatory regime.
(Newman, 2015; Williamson, 2005)	Space activities to support a self-sufficient colony on the Moon and contribute to the economy of the Earth-Moon system. The concept of SD in space allows for a balance between protection and exploitation. SD issues of the Moon are unique compared to other celestial bodies and require a modern policy framework.	Lunar activities must be based on SD, as they may generate greater impacts in the future - or - Commercial resource extraction from the Moon is an unnecessary burden considering the high uncertainty of economic viability and associated environmental impacts. Terrestrial environment legislation might serve as inspiration for policy guidelines.
(Aganaba-Jeanty, 2016; Dallas et al., 2020; López, 2016)	Engagement with the new space actors (Brazil, Mexico, Colombia) & more established stakeholders is key to foster more responsible practices in space. Space sustainability relates to shared benefits & shared risks of the space environment, since the 'governance for global security' view is more aligned with the needs of the present space actors and conflicting with the Outer Space Treaty (OST). Access to space increases inequality between spacefaring and non-spacefaring countries ('Space Gap').	Space sustainability has analogous issues in terrestrial sustainability. Concerns: limiting space debris, safeguarding equal access to space, continuing multilateral engagement and agreement, enforcement of environmental regulations. International frameworks needed to facilitate cooperation between emerging and well-established space actors, & to benefit non-spacefaring countries. Space mining ventures should share information with scientists to benefit humanity.
(Chrysaki, 2020; Deva Prasad, 2019)	SD implies using natural resources responsibly to protect the environment, respecting current and future needs, acknowledging the responsibility of each actor, using the precautionary and polluter pays principles: Industrial space activities are an integral part of the Fourth Industrial Revolution & may cause potentially irreversible impacts on Earth and space. The environmental impact assessment process is appropriate.	The legal concept of SD is compatible with international space regulations for peaceful use and non-appropriation of space. Major gaps are related to space debris, extraction of space resources, access to space, space tourism and settlement. A voluntary Code of Conduct for the private space industry is proposed, aiming to strengthen the self-regulation and governance based on ethics and the 'do not harm' notion.
(Martinez, 2021)	Space sustainability: '*the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations*'. UN COPUOS LTS Guidelines	Although the non-binding LTS Guidelines are likely to be revised in the future, they started establishing an internationally accepted collection of best practices for space sustainability, which has been agreed upon by 92 States. Successful implementation of the guidelines will require collective efforts from all space actors and capacity-building amongst countries.

[a] focussed on the Earth environment.

describe space as an extension of the Earth (the fourth frontier). Such viewpoints can be explained by the concept of *satellite planetarity* (DeLoughrey, 2014), which explains visions of the globe that have emerged from satellite-based expansion of empire into extraterritorial space. Thus, mining in low Earth orbit provides a potential extension of business opportunities through the expansion of the resource base. The implication is that the contemporary economy is subject to, and may create, a wider range of environmental forces, impacts and inequalities than previously encountered.

The global inequality in participation in spacefaring industries (Dallas et al., 2020) is demonstrated by investment and benefit patterns. Davis Cross (2019) cites that governments now spend over US$80 billion annually on space programmes; that the total global space economy, including private companies, is worth over US$387 billion; that each US $ invested by government generates US$5 to global economies. The United States accounts for approximately one quarter of the global spend on space programmes, with every US$ spent on NASA purported to add more than US$8 to the national economy (Amadeo, 2020), such that more value is added to the US economy by the space programme than to the economies of other countries.

The distribution of benefit within nations that have spacefaring industries is also unequal (e.g. Karlis and Spencer, 2018), where public investment ends in business oriented towards the wealthiest portion of society, such as space-tourism. As an example, the tax-payers of New Mexico paid two-thirds of the >$200 million to build Spaceport America, completed in 2011, but the daily flights by a fleet of Virgin Galactic (lead tenants) spaceships did not commence until 10 years later due to the challenging nature of the development programme (Horizon, 2017). Kleine (2014) describes how market fundamentalism generally operates at the expense of public spending through privatization, corporate deregulation and reduced taxation of multinational corporations, to little benefit to all humanity.

A minimum global business tax rate is currently under negotiation to help support public spending (Parker et al., 2021; Politi et al., 2021) and the space industries investment choices of individuals are publicly challenged when they are perceived to be at the expense of Earth-bound societies and environments (Colson, 2021). The public and shareholders are growing in frustration at inequality and poor ESG in businesses (e.g. Hume, 2021; Wang and Wang, 2021). Shareholders in the mining giant Rio Tinto rejected excessively unequal remuneration packages following the destruction of Aboriginal heritage (Hume, 2021; Wahlquist, 2020). Extra-terrestrial environments are also variably valued by different global communities beyond the intrinsic value of abiotic materials, including for Aboriginal heritage and spiritualism (Hamacher, 2021; Hertzfeld and Pace, 2013; Lee et al., 2020).

The question of whether off-Earth mining constitutes extractivism is valid where resources are associated with a planetary body over which any nation could claim to be a stakeholder, because it arises from national prioritization of economic growth, because it may be culturally sensitive and because there is currently insufficient protection of the externalized environment. Indeed, the national appropriation enabled by prospecting in space (Wortman, 2020) is a colonial claim-staking process for mining that removes rights from, and is opposed by, Indigenous Peoples (Gignac, 2020). Indigenous communities are under-represented in nation state global decisions, such as how to govern off-Earth mining, which has the potential to affect their way of life (UN, 2018).

The ESG risks for new types of mining in extreme environments are poorly-defined, and require an alternative governance model (Kung et al., 2021). If only rich nations are engaged in active off-Earth mining activities, then the foundation of ESG regulations will not adequately account for the needs of Indigenous/local communities, perpetuating the new form of post-colonial imperialism (Vidaurri et al., 2020). It calls for an additional recognition of the need for due diligence in raw material sourcing for off-Earth extraction and to build the space industry infrastructure. Exclusion of raw materials producers from the advantages of space industries reinforces corrosion of social, environmental and cultural lands of vulnerable Indigenous/local communities. Such a recognition calls into further question the narratives that off-Earth extraction is somehow an endeavour to increase the sustainability of terrestrial, including human (Haraway, 2016; Latour, 2018), habitats.

8. Moderation of techno—optimism

Asayama and Ishii (2017) discussed how storylines enhance broader learning, and that plural, balanced and critical narratives are required to sustain sound balance between uncertainty and optimism surrounding emerging technologies. Technological innovation is coupled to maintenance of global population (e.g. the need for intensive agricultural practice), clean energy supply that is not founded on fossil fuels, and remediation of damaged environments, such that it is key for collective human wellbeing (Segura-Salazar and Tavares, 2018). However, techno-optimism is defined as the belief that science and technology will provide the solutions to modern-day challenges without impacting the lifestyles of developed societies (Alexander and Rutherford, 2019; Allwood, 2018; Banister and Hickman, 2009), thereby endorsing global inequalities.

The fabrication of modern innovative technologies is dependent upon mining for feedstocks so that there is a feedback loop of raw material extraction from the environment, in order to protect the environment from past economic activity. The narratives of off-Earth extraction are also circular: the notion that non-ISRU can remove damaging activities from the Earth requires innovation of an extensive automation-robotics-prospecting-extraction-processing-storage-use technology cluster, which then requires more resources. Research into techno-optimism largely concludes that it is at best a double-edged sword and ultimately that it delays action to address global environmental change, postponing adaptive behavioural change in society (Gardezi and Arbuckle, 2020).

Asteroid Mining Corporation (AMC, 2021) state that moving polluting industries into Space will enable the Earth to become '*the garden of the Solar System*' but do not consider that full removal of automated mining removes livelihoods and increases vulnerability in global socio-economic structures. The image of distant off-Earth resource production as clean and environmentally beneficial reflects a global-scale nimbyism: a global outsourcing of environmental degradation to the detriment of local terrestrial economies and cultures, in a new form of post-colonial imperialism that fails to address the pressing need to improve terrestrial practice.

Haraway (2016) states '*we need a hardy, soiled kind of wisdom*' to develop a new relationship with the planet. The implication for off-Earth extraction is that learning can be created by investigating the way in which mining operations involve engineering of the environment: preparation of landscapes for extraction; materials handling; separation of useful and deleterious elements from the environment. At the end-of-life of mine, operators have the ability to return landscapes to their former status, or create environments of greater biodiversity than existed at the outset of mining. "Product life extension" is also a consideration for the end of the mine life cycle, where mining infrastructure can be reutilized to create other social, economic, or environmental opportunities (Caven and Johnson, 2022; K2fly, 2020; Lacy et al., 2020).

The prospect of off-Earth extraction is as, or more, exciting than the prospect of deep-sea extraction because it more visibly relates to the possibility of human civilisations in alternative environments (Carlyle, 2013; Dahl et al., 2020). It constitutes extreme techno-optimism since it involves a belief system that innovation will be rapid enough to contribute meaningful socio-environmental solutions, and an assumption that all terrestrial communities will benefit. It also requires that the decrease in grade of easily-accessible terrestrial ore deposits will create a conducive economic climate and that an economic credit system including carbon offsets (e.g. Day, 2021) will include both off-Earth and terrestrial extraction. Most significantly, such extreme techno-optimism requires that there are fewer ethical and environmental hazards overall.

The underpinning concept of asteroid mining is that asteroids are 'captured' and secured in Earth orbit by continual manoeuvres at unstable Legrange points to account for reducing mass, with capture of material that is lofted from the surface (Gertsch et al., 1997; McInnes, 2016). This increases the potential for debris to limit the Earth's space environment for much sought-after orbits (Losch, 2020b). It is already the case that less than 9.6% (using data from ESA, 2022) of the human-made objects > 10 cm in size are working satellites, and the likelihood of collisions will be increased by SpaceX's ambitious 'Starlink' constellation of satellites for high-speed global internet connectivity (Cao, 2020). The potential for the SpaceX Starship to gather decommissioned satellites and other space debris from low earth orbit to mitigate the overaccumulation of space clutter is considered possible (Tangermann, 2020) but it remains to be proven. Ultimately, the vast scale of the challenges facing modern society and environments inspires optimism that the extreme risks associated with some 'big' innovation are acceptable, and/or that solutions will emerge to manage any negative consequences.

9. Towards a mature safety culture

Kleine (2014) describes examples of geo-engineering projects to reverse or mitigate climate change as examples where rapid change and uncertainty increases the acceptance for innovation and investment in experiments on too large and high risk a scale for environmental control. Off-Earth resource extraction could usefully be included in a similar debate due the potential for severe negative consequences arising from the failure of extreme critical control management. To avoid inconsistent implementation of learning from the past within the modernisation paradigm (Whyte, 2018), the potential exists to think more widely about learning from the terrestrial mining industry for space industries.

Mining practice has evolved through millennia of (including contemporary) environmental and social misadventure, being recorded in historical narratives since the Medieval period (e.g. Agricola, 1556). Perturbation of the environment by responsible and highly regulated mining is tightly constrained to the site and life-of-mine, but the risks of widespread damage increase with poor practice. The safety culture maturity model (Anglo American, 2010; Foster and Hoult, 2011, 2013; University of Queensland, 2008) summarises criteria that describe increasing maturity from reactive, through preventative and enhanced, to resilient safety cultures and behaviours. Applied to off-Earth extraction (Fig. 4), the safety culture maturity model provides a framework in which to reject high-risk technological solutions, which might otherwise be promoted by visionaries with economic/political influence.

Many of the concepts in this manuscript are framed in binary positions but the step-wise progression of the safety maturity model (Fig. 4) embraces the space between and it provides an alternative mechanism for reorientation of modern practices. The model places safety culture in mining in a rhetoric of responsibility, and it describes the multiple styles of mining operation that currently coexist on Earth (e.g. Sidorenko et al., 2020). Reactive culture is one where remediation of impacts prevails, following ill-informed development of economic opportunity. Any proposed mining experiment in space without due diligence of the potential for damaging consequences would fall within the remit of Reactive culture.

Preventative culture focuses on licencing, observation, enforcement and regulation: safety culture is imposed; enforcement may be required depending on the ethos of the operator. Since there is no international consensus for the regulation of activities related to the exploitation of natural resources in space (Gugunsky et al., 2020), the model describes the safety of off-Earth mining culture as immature. Inadequate data is a challenge for the development of a Preventative culture, since licencing and regulation of responsible mining operations requires knowledge of geology and metallurgy, mining methods and processing flowsheets, which are insufficient for off-Earth extraction. Enhanced culture is also strongly data dependent, since the feedback loops and external consequences of actions may be modelled and thereby predicted using the Life Cycle Thinking paradigm as a tool (Beylot et al., 2021; Maury et al., 2020).

It is imperative that visions of off-Earth extraction have a high-level ethical and safety maturity from the outset, following development and agreement of mining regulations and best practice that recognise the fragility of extra-terrestrial environments, and sites with special scientific significance. Hence, a sufficient period of time should be allocated for geological and/or palaeobiological exploration prior to irreversible in-situ extraction, reflecting the approaches taken by mature mining companies on Earth. This ideology converges with that of Vidaurri et al. (2020), who advocate for '*barring non-scientific human settlement… until proper governance and methods of human settlement are discussed and*

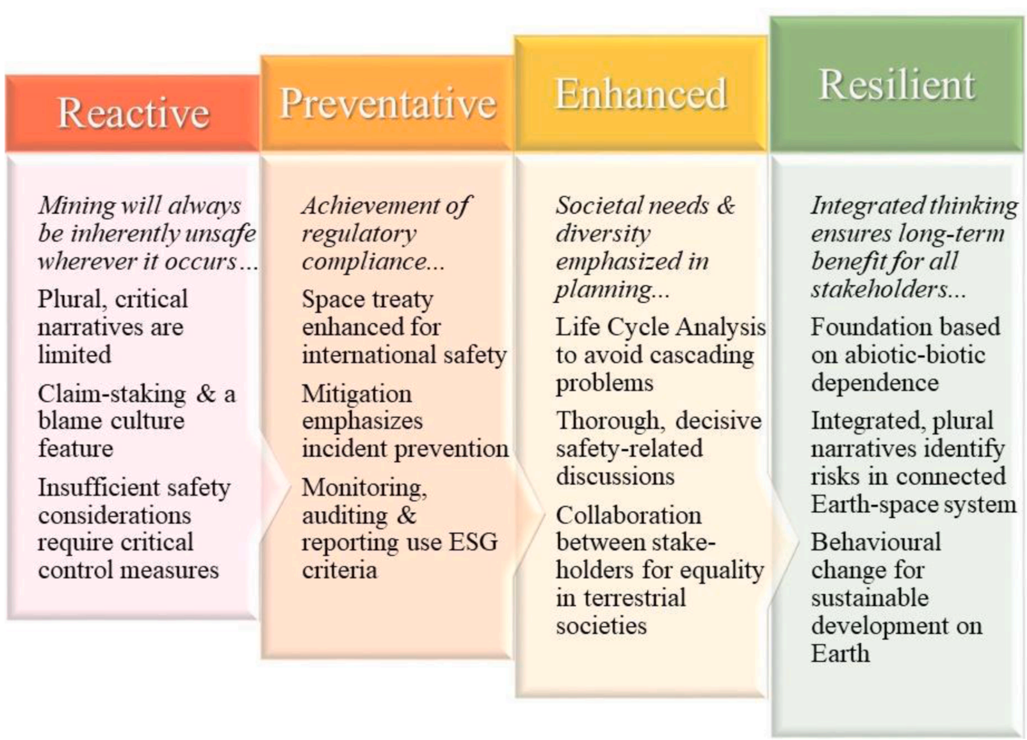

Fig. 4. Summary of the safety culture maturity model applied to off-Earth extraction, comprising 4 stages of increasing maturity with associated criteria that contribute to the overall occupational safety culture. After (Foster and Hoult, 2011, 2013; Moore et al., 2021; Anglo American Plc, 2010; University of Queensland, 2008).

adopted internationally with all global communities that do not explicitly represent the will of one government or community'.

The acquisition of data through prospecting in space is a time-intensive process that will be incomplete prior to international targets for reaching Net Zero Goals. Seventy years of space research have, with modern image processing and ICT capabilities, resulted in a detailed geological map of the surface of the Moon (Fortezzo et al., 2020). Contrary to the messaging of headlines in the media ('*Want to Mine the Moon? Here's a map of all its minerals*'; Williams, 2020), a geological map does not describe mineral variations, nor the economic viability of mineral and ore deposits. A data-supported Resilient global safety culture for off-Earth extraction, which appreciates imbalances in the abiotic-biotic relationship, uses pragmatic sustainability approaches that emphasise more equal access to benefits and quality of life, and does not result in significant harm, is a distant prospect. The timescale of development raises questions whether the majority of the Terrestrial population will have an ability or an appetite to benefit from off-Earth extraction, by the time that knowledge and technologies are developed.

10. Terrestrial solutions: reducing inertia for behavioural change

International co-operation in the space industry has helped bring together disparate interests including: an anthropocentric desire to further scientific knowledge and technological innovation; a strategic mechanism to acquire and display military and political might; and an entrepreneurial quest to develop a leading position in the industries of the next economic K-wave (Davis Cross, 2019; DeLoughrey, 2014; Devezas et al., 2012). Citing evidence from Brown et al. (2014) that the 1978 peak in Genuine Progress Indicator per capita occurred at the same time as biocapacity was exceeded, Segura-Salazar and Tavares (2018) state that the only certainty is that continuous exponential growth is not possible.

Human population growth is already effectively slowing (Dorling, 2020) while between country and within country inequality is unambiguously increasing (Gradín, 2021). Patterns and rates of consumption will change and affect political prioritization of economic activities and societal interventions. For example, various government efforts to maintain working-age populations to fuel economic growth, and support aging populations, are failing where it impacts quality of life (Gallagher, 2020; Hegarty, 2021; Lowen, 2021; McDonell and Allen, 2020; Wang and Wang, 2021). A strategy to reduce consumption of non-essential goods and services might increase the quality of life of a population, but it is challenging due to the strong correlation between the GDP and development (Armenta et al., 2014; Brown et al., 2014; Nicholas, 2021; Segura-Salazar and Tavares, 2018).

Alexander and Gleeson (2019) propose that a post-carbon urban future will be an energy descent future with reduced mobility suburbia and increased localization of economy. However, the global mining industry is required to continue to supply the growing and diversifying feedstocks for infrastructural demands of post-carbon futures, though shipping is increasingly an environmental and economic challenge (Allwood et al., 2019). The carbon footprint is just one of many challenges that threaten a secure supply of feedstock to manufacturers and consumer populations, so that there is movement to strengthen trade relations and increase regional raw materials production (e.g. EC, 2013, 2008).

Since the impacts of climate change are now being realised, the complexity of local and global tensions can be placed within the context of different shared socio-economic pathways (UNEP, 2021) and diverse, tiered mining industries. The global mining industry has multiple levels of technological sophistication, automation and remote operation, depending on micro-political context (Sidorenko et al., 2020). Full automation removes workers from dangerous environments but is too costly for some small-scale operations and it is sometimes inappropriate for local social sustainability (Moore et al., 2021). An audit of NASA found that the first four SLS missions would each cost an unsustainable $4 billion to execute (Amos, 2022), such that both timeframes and the economics of development of extra-terrestrial solutions will fail to address the issues facing society now.

Brand et al. (2017) suggest that inclusive development needs to build on ideas of degrowth and post-extractivism, and '*critique sustainable development or green growth that remain within the corridors of existing economic, political and cultural logics… and the exploitation of natural capital*'. However, the majority of degrowth and reduced carbon footprint debates have variable global relevance due to the stark contrasts in consumption patterns per capita that accompany the Plantationocene and the disparities between participating and affected communities (Haraway, 2016; Segura-Salazar and Tavares, 2018; Toussaint and Martínez Blanco, 2020). In this light, the notion that off-Earth extraction is in some way beneficial to all humanity and constitutes green growth is undermined, and the emphasis remains on promoting better practice at all parts of the supply chain, from international mining to consumption.

Mining is used to epitomise economic progress at the expense of the environment and society in the media, popular culture and literature, including interplanetary scenario (e.g. Otto, 2003; Mitchell et al., 2012). McFarlane et al. (2020) highlights the paradox that, '*at a time of modern civilization's greatest dependence on mining, societal acceptance and the portrayal of mining is at its lowest, most critical juncture*'. Visionary dialogues about off-Earth escapism utilise popular and negative perceptions of mining to promote new economic interests, and effectively neglect the challenges facing humanity (Colson, 2021; Latour, 2018; Tutton, 2021). However, debates and ripostes serve to highlight that terrestrial solutions are already available to address challenges, if they can be supported by appropriate and visible societal, legal, financial and political actions. Positive actions by mining companies are rarely celebrated since they do not meet societal expectations (RMI, 2020) and because the proponents of best practice in mining rarely, if ever, have an equal media or commercial profile to the Martianist visionaries.

Responsible practice (Goodland, 2012) by multiple mining operators (using site-specific, community- and environment-centred solutions) is reported and audited through programmes such as the Initiative for Responsible Mining Assurance (IRMA) and the Extractive Industries Transparency Initiative (EITI). Moreover, the mining industry engages in and reports voluntary sustainability initiatives in response to regulation, or to influence policy development. Potts et al. (2018) explain that voluntary sustainability initiatives are fundamentally instruments of the market, subject to private, individual preferences and market forces. Where companies pay the economic cost of good mining practice for the creation of lasting, sustainable development outcomes (Caven and Johnson, 2022), the dialogues that arise have the potential to be transformative. In a parallel dialogue about the highly complex economic, social and environmental risks of off-Earth extraction, champions of solutions to terrestrial challenges have a real opportunity to implement positive change.

The main benefit arising from off-Earth extraction might be for scientific knowledge-gain purposes. Fundamental science arising from curiosity-driven research in any context may not have an application at the time of discovery (McGuigge, 2018), but it may yet create significant benefit for human society or find an application other than that originally intended. There is evidence that investment in space research does contribute to technological development for improved data collection and innovation for greater sustainability (UNOOSA, 2021). There are obvious examples in satellite detection of Ozone layer depletion and melting of polar ice sheets, but there is also transfer of knowledge into the prospecting and mining industries. For example, advances in mineral analysis arose from development for the NASA Mars curiosity rover (automated loading and testing of Martian soil by X-Ray Diffraction; Wright, 2017) and satellite imagery is used to monitor global environmental change, including mining activities (e.g. Gallwey et al., 2020). However, appropriation of space technologies for terrestrial applications may arise more from a need to derive economic benefit by commercialisation, than whether it accompanies the path of enlightenment towards a plateau of productivity (Fig. 2).

The potential benefit of innovation to enhance Earth-bound resource prospecting is recognised by iSpace, with cited applications in post-blasting analysis and tailings/waste analysis (Espejel, 2019). But there is a paradox between terrestrial and off-Earth extraction, as the terrestrial mining industry is "*embarrassingly slow at adopting new technologies*" (O'Kane, 2019) and innovation for any and all space industries is rapid. It is highly likely that a combination of slow-to-innovate and 'dirty' industry rhetorics contribute to the shortage of mining professionals in both the terrestrial and the off-Earth extraction industries (AMC, 2021; Rolfe, 2022; Sánchez and Hartlieb, 2020). It is also very likely that pragmatic mining professionals do not see a future in off-Earth extraction since non-ISRU is implausible in modern-day economics, and scientific-technological capability. However, high speculative investment for Martianist innovation coupled with counter-Martianist pragmatism might result in disruptive change by knowledge transfer: encouraging safe behaviours amongst visionary innovators and improving terrestrial extraction practices and dialogues.

DeLoughrey (2014) draws particular attention to the physical encirclement of the planet by imperialistic technologies, which naturalize militarization to the ends of the Earth's gravity field. The materials of the new technologies and the growing urban mine in space inhabit the techno-sphere (Steinbach and Wellmer, 2010). The urban mine may become available as a secondary resource but debris from orbiting waste is known to fall to Earth or to the Moon (Helmore, 2021; Rannard, 2022). Life inhabits and is interconnected to the abiotic but responsive spheres of Earth/Cosmos, such that the techno-sphere is nested in the Noosphere. The Noosphere is the sphere of thought emerging among human beings to envelop the planet and '*implicate themselves deeply into the materials of the planet*' (Shoshitaishvili, 2021). It could be argued that the Noosphere is itself an innovation for greater sustainability, an innovation of thought with the potential to reconfigure the ways that we think about the future of mining as terrestrial.

By a forward-looking and hopeful reorientation towards technological and cultural interconnection, the Noosphere concept interrogates techno-optimism in an interconnected, entangled, non-heirarchical and anti-colonial philosophy. The Noosphere undermines the proposition that space offers safe and sustainable access to bountiful resources for all residents of planet Earth. It provides a concept in which to find nuanced, grounded real-world solutions to negative impacts and *solastalgia*, the distress caused by environmental change (Albrecht et al., 2007; Nicholas, 2021). By encouraging dialogues about mining impacts and practices relative to technological futures, there is great potential to excite the public to reconsider individual practices, to ground aspirations for out-of-this-world solutions, and to focus attention on the Terrestrial.

11. Concluding comments

The justification that space colonization is necessary to gather more raw materials and/or as an insurance policy for humanity to survive the climate and environmental crises is not new (e.g. Hartmann, 1984; Marshall, 1993). However, the suggestion that extreme solutions offer a way out of environmental crises on Earth is flawed for multiple reasons. (1) Other planets are not life-supporting and artificially-supported life might be more vulnerable than on a contaminated planet Earth. (2) The time-frame for geological (or any) exploration of other planetary bodies is greater than the time-frame of extreme environmental change on Earth. (3) The intrinsic value of extra-terrestrial environments is marginalised in favour of anthropocentric concerns. (4) There is no legal, ethical or societal consensus as to how to share or value other planetary bodies, or to decouple off-Earth extraction from colonial patterns of extractivism. The result is tension between the ecocentric perspective of planetary sustainability and anthropocentric visions of multi-planetary resource acquisition for Earth-based societies. This reinforces the human/nature dualism that Latour (2018) rejects in his conceptualisation of the Terrestrial.

The key to a mature off-Earth safety culture perhaps lies in recognition that urban industries extend into space in a physical structure of nested spheres that overlap with the metaphysical noosphere, which encompasses regulation, conversation and transformation. In this sense, there is no *out-of-this-world* location. Instead, there is anthropocentric expansion into the cosmos and continued productivity at the expense of environmental progress, such that the same fundamental risks arise from viewing the abiotic as unresponsive and endlessly available to support the biotic (humans). The implication is that there should be no diminution of standards of protection for either off-Earth environments or the international community of stakeholders, relative to those used in best practice extractive operations on Earth. The cumulative risks of negative impacts arising from off-Earth extraction, for all terrestrials, trouble the notion that the Terrestrial actor can be circumnavigated by expanding consumerist patterns dependent on techno-futuristic fixes.

Many of the challenges facing humanity have binary framings: the global versus the local; the out-of-this-world visionaries versus the Earth-bound Terrestrial champions; the economy versus the environment. In Latour's (2018) critique, the global represents a scientific, rational, objective mode of modernity. The Terrestrial, in contrast, is local, material, subjective, felt – it is the critical zone that creates, sustains and gives meaning to life. The Global, and the political rhetoric of globalisation, is an abstraction and obscuration. For the proponents of modernity, infinite progress and economic growth, the Global aligns with colonialism and extractivism. The political economy of the Global works to support expansionist technological innovation that will further create the means of resource production whether on land or deep sea, or in space. The mining industry is multi-faceted, operating in globalised and local economies, and at different levels of safety culture maturity. The reality is that the space in between binary positions is fully occupied by conversations to manage hype and expectations, and structures or frameworks that enable interventions for practical improvements in responsible best practice and sustainability.

We examined the challenges associated with, and limitations of, off-Earth resource extraction as a means to focus attention on the multi-layered and sophisticated Earth-bound industry (mining) that cannot be readily outsourced or by-passed. In so doing we have tried to excite the narratives that will accelerate behavioural changes for the creation of an ethical, sustainable and liveable future. By taking a multi-layered plural approach, we have aimed to avoid discretization of data and concepts.

Off-Earth extraction operations would necessarily be remotely automated, but safety culture extends beyond removing workers from directly-hazardous environments. The development of a mature safety culture is necessary to focus on the potential for damage on planetary scales rather than the excitement of adventure and new horizons, which act as drivers along the modernisation front. Such progress rests upon notions of empty space waiting to be colonised and utilised. Debris build-up in space may self-limit the satellite industry. Thus, the extended Earth system intervenes in the space industries, and human agency in space cannot operate in a stable and indifferent framework for modernisation, as described by Latour (2018).

Duty of care to the planet arises from the ecologic extension to conservation ethics using sustainability agendas as a pragmatic means to deliver. By comparison to terrestrial mining activities, a potential off-Earth extraction operation has an immature and high-risk safety culture. Safety culture maturity in mining is tied to responsible practice for environmental and social sustainability: the mining industry has evolved the ability, however inconsistently used, to engineer environments during and following the life of mine. The Terrestrial champions who focus on improving local conditions on Earth operate both within and without the mining sector, but have less apparent global business and social influence than the Martianist visionaries.

The narratives may have a modern and exciting context, but they reinforce the interaction between the Terrestrial Actor and earth-bound stakeholders who are affected by climate change and environmental degradation. In an era of modern communications, the abiotic and multi-species terrestrial stakeholders can have a measurable impact and may be reassured that there are Earth-based ways in which to effect transformation, aided by the dialogue and debate that is inspired by the out-of-this-world hype cycle. The transformation requires behavioural change within the raw materials production industries, within the manufacturing sectors, within the end-user communities and within the regulation/governance communities. Societal objection to the concept of mining may ignite excitement at the prospect of off-Earth extraction as an *out-of-this-world* solution. However, a direct and practical dialogue with the mining industry may serve to refocus attention on the implementation of the real world solutions that are possible in an economic climate that is engineered for socio-political and environmental outcomes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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