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Title:
Growth and Resources in Space: Pushing the Final Frontier?*

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ABSTRACT
Growth models with resources and environmental externalities typically assume that planet Earth is a closed economy. However, private firms like Blue Origin and SpaceX have reduced the cost of rocket launches by a factor of 20 over the last decade. What if these costs continue to decline, making mining from asteroids or the moon feasible? What would be the implications for economic growth and the environment? This paper provides stylized facts about cost trends, geology and the environmental impact of mining on Earth and potentially in space. We extend a neoclassical growth model to investigate the transition from mining on Earth to space. We find that such a transition could potentially allow for continued growth of metal use, while limiting environmental and social costs on Earth. Acknowledging the high uncertainty around the topic, our paper provides a starting point for research on how space mining could contribute to sustainable growth on Earth.

JEL **classifications: Q32, E22, Q02**
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1 Introduction

The extraction of mineral resources increased more than 60 times over the last century, amid population growth and higher average living standards (Stuermer and Schwerhoff, 2015). While this trend could be weakened by recycling and a more efficient use of materials, the clean energy transition requires a strong increase in the use and production of critical metals such as copper, cobalt, and nickel (International Energy Agency, 2021b,a; Gielen, Dolf, 2021; World Bank, 2020). This could lead to upward pressures on prices, potentially delaying the clean energy transition Boer et al. (2021).

At the same time, negative environmental externalities from mining will likely increase. While output continues to rise, many high grade deposits have already been exhausted. Mining deposits of lower ore grades raises energy and water requirements, and produces more waste and carbon dioxide emissions (Azadi et al., 2020; International Energy Agency, 2021b).

Celestial bodies, such as asteroids, contain potentially high ore grades of metals. Technological advancement following R&D from private space companies has reduced the cost of rocket launches. This paper asks: to what extent could space mining help supply critical metals? What would be the environmental and economic impacts? We provide stylized facts about cost trends, geology, and the environmental impact of mining on Earth and potentially in Space. In line with integrated assessment models, we extend a neoclassical Ramsey growth model to investigate investment dynamics of a push towards mining in space. We finally lay out open research questions.

We find that a transition of mining from Earth to space could potentially allow for continued growth of metal use on Earth, while limiting environmental and social costs. At the same time, such a transition could require an upper limit on the environmental and social costs on Earth to incentivize investment into R&D for space mining.

Our results show that it is a possibility that space mining could contribute to sustainable growth on Earth in a distant future. Our simulations are stylized, but provide a starting point for a research agenda that could more closely investigate potential cost trends, including social and environmental costs of mining on Earth and space, and that could provide more micro-founded models to study incentives of firms under uncertainty.

We contribute to a small but growing literature on space economics (see Weinzierl, 2018, for an overview). While much of the academic literature focuses on the economics of satellites (see Grzelka and Wagner, 2019; Rao et al., 2020; Rouillon, 2020), there is also an increasing body on the feasibility of mining in space using net-present value calculations (see e.g., Kargel, 1994; Andrews et al., 2015; Calla et al., 2018). A few of these studies include more economic concepts. One study takes into account the exploration risk to show that public-private partnerships may generate better net-present value outcomes than a single private company Sommariva et al. (2020). Another study uses a model of firm entry to show that large amounts of minerals from space could depress mineral prices Dahl et al. (2020). Our paper is to our knowledge the first that introduces concepts of macroeconomics, growth, and endogenous investment.

We build on a literature of growth with resources and environmental externalities that typically assumes planet Earth to be a closed economy and technological change (TC) to be resource augmenting (Nordhaus et al., 1992; Weitzman, 1999; Acemoglu et al., 2012). We contribute to this literature by providing a simple growth model, but which lifts the assumption of a closed economy to include mining in space.

Sections 2 and 3 provide stylized facts, section 4 describes our model, and section 5 presents our theoretical results. We discuss our results in section 6 and provide guidance for futures research in section 7.

2 Context on Earth

Limiting climate change could substantially boost the consumption and production of metals like copper, nickel, cobalt, and lithium on Earth (World Bank, 2020; International Energy Agency, 2021b; Gielen, Dolf, 2021). For example, an electric car requires four times more copper than a conventional car (Singhi, 2021). The total consumption of lithium and cobalt, for example, could rise more than twenty-fold and sixfold, while nickel could see a fourfold increase of total consumption International Energy Agency (2021a). This scenario is based on the assumption that renewable energies become the leading source of electricity before 2030 and that 86 percent of the stock of cars being powered by electricity by 2050 International Energy Agency (2021a). Table 1 shows which minerals are required for each clean energy technology (Church and Crawford, 2020). Prices of metals such as copper, lithium, nickel and cobalt could reach previous historical peaks but

Clean Energy Technology	Minerals required
Solar	Bauxite, Alumina, Cadmium, Copper, Gallium, Germanium, Indium, Iron, Lead, Nickel, Selenium, Silicon, Silver, Tellurium, Tin, Zinc
Wind	Bauxite, Alumina, Chromium, Cobalt, Copper, Iron, Lead, Manganese, Molybdenum, Rare Earths, Zinc
Electric Vehicles & Storage	Bauxite, Alumina, Cobalt, Copper, Graphite, Iron, Lead, Lithium, Manganese, Nickel, Rare Earths, Silicon, Titanium

Table 1: Minerals for clean energy technologies. Source: Church and Crawford (2020)

for an unprecedented, sustained time period in a net-zero emissions scenario, potentially delaying the clean energy transition Boer et al. (2021).

While global metals supply will likely catch up in the medium to long-term, lower grade deposits will need to be exploited on Earth. The literature finds evidence for historical declines in ore grades for a broad set of metals Mudd (2007); Gerst (2008); Mudd (2009); Radetzki (2009); Crowson (2012); Mudd and Jowitt (2014). The underlying reason for lower ore grades is that minerals exhibit a log-normal grade-quantity distribution in the Earth's crust, implying a decided positive skewness, according to the Fundamental Law of Geochemistry Ahrens (1953, 1954); Wellmer (1998); Singer (2010).[1] In the past, innovation in extraction technology has offset the declines in ore grades to keep mining costs roughly stable Stuermer and Schwerhoff (2015). Many papers have even shown that the cumulative availability of many minerals has proven larger than previously anticipated throughout

[1]There is also the hypothesis of a discontinuity in the distribution due to the mineralogical barrier, the point below which atomic substitution traps metal atoms, which could make mining on Earth even more difficult (Skinner, 1979; Gordon et al., 2007)

history (Yaksic and Tilton, 2009; Tilton and Lagos, 2007). That's why the declining ore grades do not necessarily need to impact future mineral production (Northey et al., 2014; Radetzki, 2009).

At the same time, mining lower ore grades will likely lead to more negative environmental and social externalities due to higher consumption of water, energy, and the production of more mine tailings or waste Teseletso and Adachi (2021); Wellmer et al. (2019). The International Council of Mining and Metals has best practices for the environmental performance of mines, including plans for closures, water stewardship, effective tailings management, pollution prevention, and reduced energy use and greenhouse gas emissions (International Council on Mining and Metals, 2022). Overall, the literature suggests that environmental, social, and governance factors are likely the main source of risk to metal supply over the coming decades, more than direct depletion Jowitt et al. (2020); Wellmer et al. (2019).

3 Context in Space

Minerals are differently distributed in space compared to Earth. The average abundance of certain metals is higher in metallic asteriods than on Earth. There is evidence that this is the case for critical minerals like Cobalt and Nickel but also for Platium-Group Metals such as Iridium Cannon et al. (2023); Łuszczek and Przylibski (2021). Table 2 provides an overview of some of the metals that are in particularly high abundance on metallic asteroids. While there is good information about the availability and ore grades

Mineral	Asteroids Average Abundance g/mt	Earth's Crust Average Abundance g/mt
Iron (Fe)	893,000	41,000
Cobalt (Co)	6,000	20
Nickel (Ni)	39,000	80
Ruthenium (Ru)	22	<1
Rhodium (Rh)	4	<1
Palladium (Pd)	17	<1
Osmium (Os)	15	<1
Iridium (Ir)	14	<1
Platinum (Pt)	29	1
Gold (AU)	1	1

Table 2: Average Abundance of Minerals in Metallic Asteroids and on Earth. Source: Dahl et al. (2020)

of metal deposits on Earth, this is generally not the case in space. A search of one of the premier mineral exploration journals, *Economic Geology*, for work on minerals in outer space returns no articles. Karman+, one of the current asteroid mining companies, notes that we know little about near Earth asteroids other than their orbits and brightness Karman+ (2022). Our knowledge stock is expanding as numerous missions, including the Japanese Hayabusa missions, NASA's ongoing OSIRIS-REx mission, and NASA's 2023 Psyche, will provide more information on the geology of asteroids.

The main driver of increased interest in mining celestial bodies is the rapid decline in rocket launch costs. Bushnell and Moses (2020); Bushnell (2021) provide a technical overview of the quickening pace of progress in rocket launches. The move from cost-plus, government ownership contracting of rockets to fixed-price, purchase of service contracting by the National Aeronautics and Space Administration (NASA) incentivized cost reductions and innovation in rocket launching, as contractors keep gains from cost-saving innovation Weinzierl (2018); Holmstrom and Milgrom (1991). Main factors are reusable rockets, improved manufacturing, and optimization of launch operations Bushnell (2021). Data provided by Roberts (2022) on launch costs to low-earth orbit reveal that launch costs per kilogram have been decreasing since 2005, after increasing until that date. Bushnell (2021) cites current cost reductions of private companies by a factor of six, with factors up to 14 being worked compared to NASA space launch systems. The declining costs of space mining and internalization of environmental costs on Earth could spur metal production using space resources. While a first wave of space mining firms began in the late 2010s, with Deep Space Industries and Planetary Resources, these firms exited in 2018 and 2019 due to lack of funding (Foust, 2019). New firms have sprung up in the last year, such as TransAstra or Karmen+, but business activity remains limited.

The environmental costs of mining in space could be a fraction of those on Earth, as mining would occur in the vacuum of space and transportation of materials to Earth benefits from gravity (see e.g., Sivolella, 2019). However, the environmental impact would also depend on the number of rocket launches and the propellants used to the transportation of mining and processing equipment into space. Propellants have two main emissions concerns: greenhouse gas emissions and ozone depletion (Twiss, 2022). Some propellants emit black carbon into the stratosphere which trap heat and contribute to the greenhouse effect (Maloney et al., 2022). Rocket launches can have a large impact on the ozone layer in the stratosphere as launches are one of the only source of pollutants emitted directly into the stratosphere (Ross et al., 2009). These emissions lead to ozone depletion and limit gains made under the Montreal Protocol (Ross et al., 2009; Dallas et al., 2020).

The environmental impact differs significantly across propellants according to Dallas et al. (2020). Kerosene and hypergolic propellants as well as solid propellants have the highest negative impact in terms of toxidity, greenhouse gas emissions and effects on the ozone layer. At the same time, liquid hydrogen based propellants have only a low environmental impact due to Water vapour exhausts. Currently, most hydrogen is produced from fossil fuels, but investments in hydrogen derived from renewable energies are increasing (International Energy Agency, 2022). This could provide carbon-neutral propellants.

In addition to the environmental impact on Earth from rocket launches, there is a new field within the space literature on space sustainability, which focuses on space debris in the outer atmosphere and peaceful uses of space technology Secure World Foundation (2018); Grzelka and Wagner (2019); Rao et al. (2020); Rouillon (2020). The United Nation's Office of Outer Space Affairs is leading the discussion of space sustainability and argues that the UN Sustainable Development Goals are compatible with outer space activity (Simonetta di Pippo, 2018).

The remainder of the article details a growth model illustrating a potential transition path between Earth and space resources arising from these forces.

4 Model

We develop a stylized extension of the neoclassical Ramsey growth model Ramsey (1928); Newbery (1990); Cass (1965); Tc (1965) to illustrate savings and investment dynamics around the transition from mining metals on Earth to space. Modern Integrated Assessment Models (IAMs) of climate and the economy such as DICE and RICE also build on the Ramsey model Nordhaus (2017), and include endogenous technological change Nordhaus (2010). This simple approach allows us to simulate how economies make investments in R&D and capital, thereby reducing consumption today in order to increase future consumption. We extend the Ramsey model from Rutherford (2005) to include two metal producing sectors, one on Earth and one in space, a carbon externality, and endogenous R&D which augments productivity similar to Castelnuovo et al. (2005).

The central planner maximizes social welfare W of discounted consumption c_t where β_t is the discount factor, and η is the elasticity of substitution of consumption across time periods in Equation 1.

$$\max_{C_t} W = \sum_t \beta_t \frac{c_t^{1-\eta}}{1-\eta} \tag{1}$$

s.t.

$$Y_{z,t} = A_{z,t} * K_{z,t}^b * L_{z,t}^{1-b} \tag{2}$$

$$K_{z,t} = (1-\delta)K_{z,t-1} + I_{z,t-1} \tag{3}$$

$$A_{z,t} = \zeta + 1/(1 + e^{-V_{z,t}+\alpha_z}) \tag{4}$$

$$V_{z,t} = (1 - \delta_v)V_{z,t-1} + R_{z,t-1} \tag{5}$$

$$m_t = m_{t-1} - \gamma + \sum_z Y_{z,t} * e_z \tag{6}$$

$$m_t \leq \psi \tag{7}$$

$$C_t + \sum_z [I_{z,t} + R_{z,t}] \leq \sum_z Y_{z,t} \tag{8}$$

For simplicity, we assume that the economy only produces one metal Y (or a metal composite), but in two locations indexed by z, on Earth and in space. The metal is produced with a standard Cobb-Douglas production technology, combining capital K_t and labor L_t, as described in Equation 2. Labor increases at an exogenously specified growth rate, and is allocated with perfect elasticity between the two sectors. The capital stock grows endogenously through investment I_t and depreciates with factor δ in Equation 3. Capital is specific to Earth and space production, as mining and processing equipment must be designed to handle the inhospitable environment in space, e.g., vacuum, radiation, low gravity Sivolella (2019).

The production function implicitly assumes that mineral stocks, both on Earth and in space, will not be depleted within any relevant time-frame. Physical mineral stocks on

Earth and in space are sizable, while economically extractable reserves can be expanded through investment in exploration and new technologies Nordhaus (1974); Stuermer and Schwerhoff (2015); Wellmer et al. (2019). The model therefore does not feature a scarcity rent as in many growth models focused on exhaustible resources Stiglitz (1974); Heal (1976); Nordhaus et al. (1992); Weitzman (1999).

The production scalar $A_{z,t}$ (or total factor productivity) evolves with location-specific knowledge stocks $V_{z,t}$ in Equation 4. The relationship between these two variables is an s-curve, where $A_{z,t}$ is a function of $V_{z,t}$. The parameters ζ and α determine the height and slope of the s-curve, which governs the relative impact of R&D efforts on the production scalar. We choose this functional form based on the innovation literature Becker and Speltz (1983). It has been employed in learning-by-doing curves Yeh and Rubin (2012), and empirical evidence has been found supporting s-shaped innovation diffusion curves Griliches (1957). Initial R&D efforts have low returns, but returns start to increase rapidly as breakthroughs occur, and eventually level off as the frontier becomes more difficult to push. We assume that initial knowledge stocks for mining on Earth are higher than those for mining in space, yielding a higher initial production scalar. The location-specific knowledge stocks V_t are accumulated through R&D expenditures R_t and depreciate with factor δ_v in Equation 5.

Emissions are associated with output according to emissions intensity e_z, where production on Earth results in positive emissions, and production in Space does approximately not produce emissions. The central planner is assumed to have access to a carbon ceiling policy, limiting the stock of emissions m_t to a ceiling ψ following Rozenberg et al. (2020). Finally, the central planner allocates consumption as well as investment in capital and knowledge stocks under the budget constraint in Equation 8.

5 Results

This section presents results of the stylized growth model, depicting the transition of mining from Earth to space due to technological change in metal production in space and internalization of environmental damages on Earth.

Figure 1 illustrates the transition between investment in mining capital on Earth and in space. In the initial period, investment in mining capital is increasing on Earth as the cumulative history of R&D and higher initial productivity justifies continued investment.[2] Around period 30, the emissions ceiling starts to bind, and investment turns to space mining capital. This only occurs after some initial R&D has been conducted to increase the productivity of space mining. At one point there is no capital investment, as all resources that are not consumed are devoted to R&D in space mining, which is more valuable than capital investment.

Figure 2 illustrates the optimal time path for R&D investment in metal production on Earth and in space. There is initially some R&D conducted on Earth as there is room for

[2]Figure 1 initially shows zero capital investment on Earth. This is an artifact of the current model calibration, where the initial capital stock endowment is used for production, and investment is allocated to R&D which has a higher marginal benefit than that of capital investment. This could be revised to show positive initial capital investment on Earth.

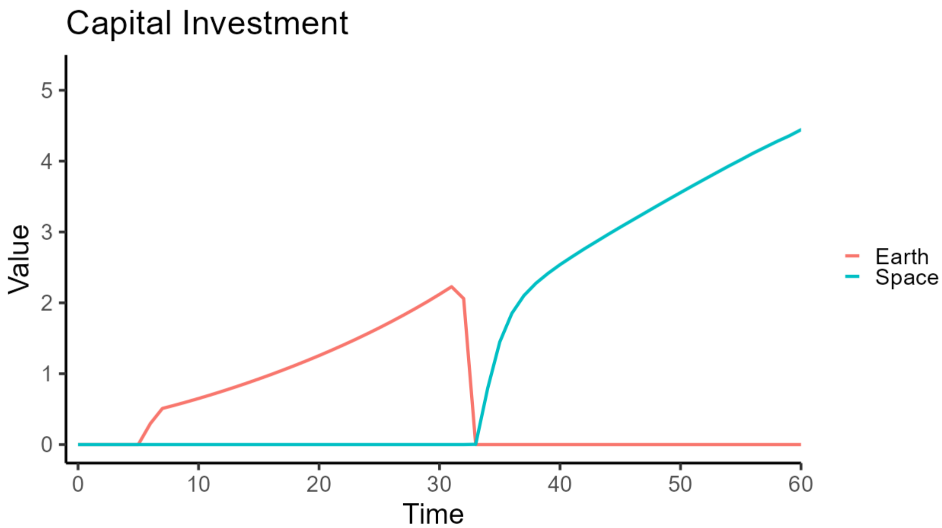

Figure 1: Evolution of capital investment on Earth and in space

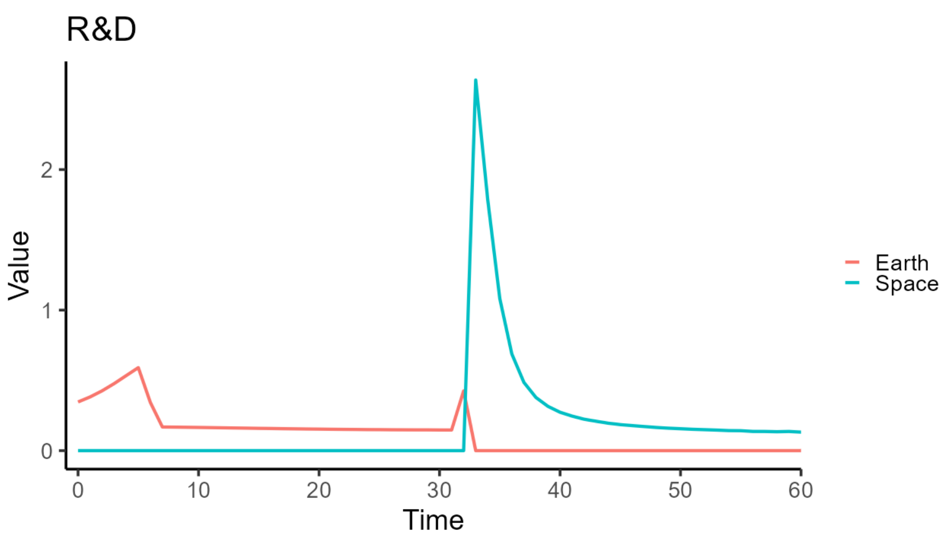

Figure 2: Evolution of R&D in mining on Earth and in space

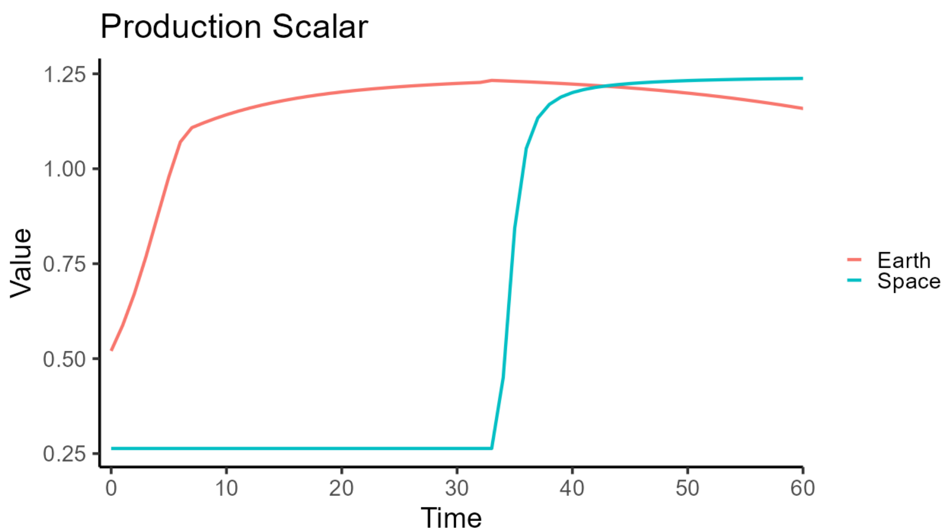

Figure 3: Scalar in the production functions for Earth and space

Earth metal production to expand relative to the emissions ceiling.[3] After period 30 there is a large push for R&D into space mining spurred by the emissions constraint, which rapidly increases the space production scalar.

The evolution of the production scalar in Figure 3 describes the increase in output associated with various combinations of labor and capital in space and Earth following R&D expenditures. On Earth, the production scalar increases initially as R&D still has positive returns below the emissions ceiling. As the ceiling binds, R&D increases the scalar for space production, and knowledge stocks for Earth production are allowed to depreciate, causing a decline in the Earth production scalar.

Figure 4 shows the resulting transition from metal production on Earth to space. Production initially occurs on Earth, due to the historical accumulation of R&D knowledge,

[3]The small spike in R&D in Earth mining around time 30 occurs as the remainder of Earth production depends on depreciating knowledge and capital stocks. This burst of R&D is optimal because it augments the remaining, depreciating Earth capital stocks.

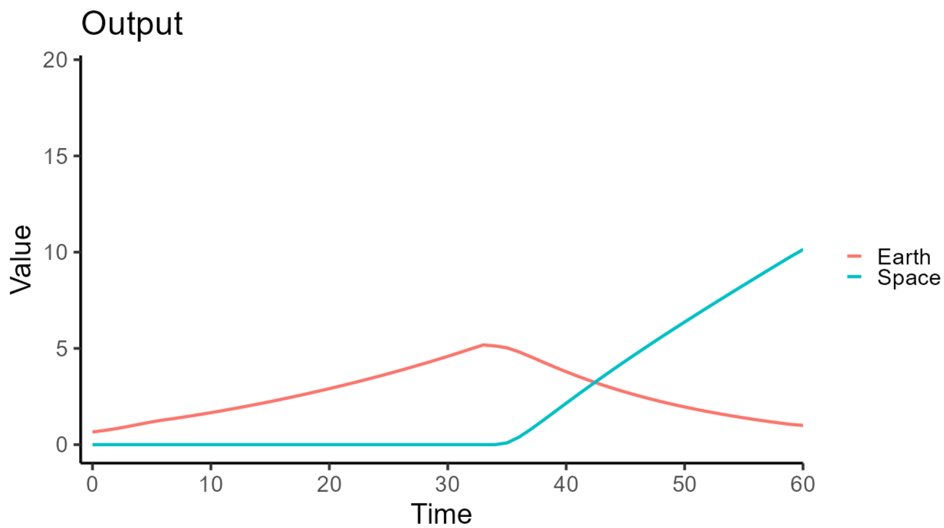

Figure 4: Evolution of metal output on Earth and in space

and the initially non-binding emissions constraint. Once the emission constraint begins to bind, metal output on Earth falls in accordance with declining capital investment, depreciating capital stocks, and labor allocation shifting to space. Metal output in space rapidly grows to exceed output on Earth following this space investment-intensive period.

The emissions stock in Figure 5 follows an s-shape as metal production switches from Earth to space. The planner optimizes production such as to just reach the emissions constraint. The steepest slope in emissions coincides with the peak in investment on Earth, capital stock, production scalar and output, as well as the spike in space R&D expenditures. From this point, Earth capital knowledge stocks are allowed to depreciate, and production shifts to space metal output. The net emissions intensity declines, and eventually results in the plateau of emissions at the ceiling.

Overall, the transition from Earth to space production is spurred on by the implemen-

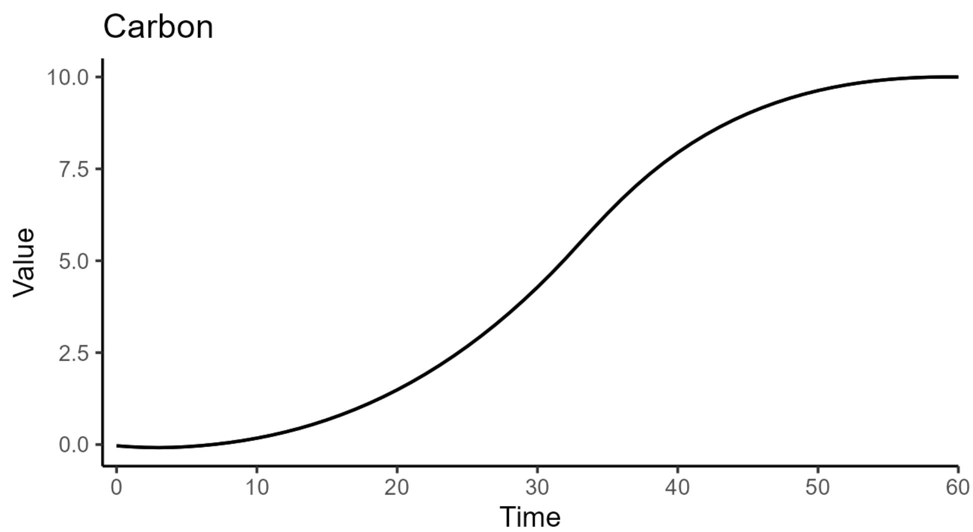

Figure 5: CO2 emissions stock on Earth

tation of the carbon ceiling and the functional form of the production scalar. The carbon ceiling limits production that is feasible using the Earth-bound production function, which has an initially high production scalar due to centuries of R&D accumulation. Initially, the production scalar for space is very low on the s-curve, resulting in inefficient mineral production in space. As Earth-bound production becomes more constrained, space becomes a more attractive option. R&D efforts are expended for space mining knowledge stocks, which augment the space production scalar. Over time, the binding policies on environmental damages combined with improved efficiency of production in space results in a transition to space mining.

6 Discussion

This section discusses implications of results and limitations of the model. We show that the combination of technological change and internalization of environmental damages can cause a shift in resource production from Earth to space. If future environmental damages cause a push for space mining, it is possible that such damages will reach the maximum allowable level given any policy constraint. While the model simplifies environmental damages, it exhibits the possibility for a policy to obtain the Pareto optimal time-path where production is distributed over time between Earth and space resource production.

The results also illustrate that substantial investment in R&D is necessary to achieve such an optimal time path. Without timely technological change, space mining would not provide a feasible route for increased consumption. The model assumes that the social planner has perfect foresight. Lacking foresight, scarcity of the consumption good might prevent adequate investment in R&D to cause a transition. Similarly, a lack of environmental policy would reduce pressure for R&D to occur, and space production would remain perpetually inefficient.

There are two components of the model which are introduced for the purpose of emphasizing and smoothing the transition path between Earth and space production - the emissions constraint, and the s-curve governing returns to R&D. The emissions constraint prompts the transition away from Earth production, as continued production would produce externalized costs in the form of emissions that are beyond what is deemed acceptable by the policy constraint. Without this constraint, ceteris paribus, there would be no transition as Earth production provides efficient production without R&D investments required for space production. The s-curves defined in Equation 4 governs the impact of knowledge stocks on the production scalar and thus the magnitude of the advantage of space mining over Earth. Without the initial period of lower returns to knowledge on the left side of the s-curve, we would see more immediate investment in R&D for space production, since marginal returns would be higher. In some scenarios, this results in a "bang-bang" solution, where the optimal time-path follows an immediate transition to space production, even without the presence of the emissions constraint (Clark, 1976). The upper asymptote of the s-curve prevents marginal returns to R&D from spurring infinite investment in R&D.

7 Future Research

To better understand the potential of space mining and its implications for sustainable growth on Earth, we suggest the following avenues of future research.

The goal of this paper was to develop a first, simple growth model. More sophisticated models should include a micro-founded space sector and allow for decentralized investment. A more detailed production structure, where resources are used as input to aggregate output would also allow to explicitly derive a growth path for the global economy. A challenge will be to develop growth models that allow for growth at the extensive margin. Current models typically work through the intensive margin. Technical change is assumed to be factor-augmenting, while factors of production are hold constant. A model that includes the effects of endogenous technological change on both cost of capital (see Huffman (2007)) and factor productivity would allow to compute the optimal mix of investment into resource augmenting and resource expanding technologies. The externality might be expanded to impact the utility function, as in other growth models and IAMs Nordhaus (2017) to more realistically project the timing of the transition and incentives for R&D. Ideally, models could also take the second moment into account, namely the uncertainty in technological change in the mining sector.

More careful modelling of the value chain of mineral mining and processing could also help a better understanding of the optimal sequencing for the development of mining in space. Is it optimal to first develop only mining in space and do the processing on Earth, or are a combination of both in space preferable?

To obtain a better sense of the potential costs of mining and processing in space, more subsidized prospecting missions and development of actual equipment for space mining would be helpful. In addition, empirical work could look more closely into historical experience from the development of similar frontier technologies and draw conclusions for future technology trends. Similarly, our model suggests a large ramp up in investment in space technologies is required. Data compiled by Capital (2022) suggest that equity investments in space are quite variable over time. Research into mechanisms that provide a steady flow of investments and research to the sector would help.

The property rights regime in outer space is unclear. Many authors have discussed the potential legal regimes and how the future decisions of government bodies would impact the incentives to mine celestial bodies (Steffen, 2022; Christensen et al., 2019; Hasin, 2020; Svec, 2022; Council of Economic Advisers, 2021). These issues will likely be settled in courts of law as more private entities push the legal frontier, such as the Breaking Ground Trust. However, the discussion would benefit from a combined law and economics perspective that allows for the optimal allocation of ownership rights to spur exploration in space.

The Outer Space Treaty states that the celestial bodies are the "providence of mankind", implying the benefits of space resources should be shared with all countries. It is unclear what is the best benefit collection mechanism (i.e., taxes, technology transfer, etc) that also encourages private investment.

Finally, the current market for space resource has a large amount of risk relative to other sectors. How can the government help "buy down" the risk to encourage private investment? What public-private partnerships provide all parties with a fair distribution of potential gains?

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