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DISCUSSION PAPER

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ABSTRACT This study explores possible futures of the mining industry through numerical analysis of a conceptual mineral extraction problem with two resource stocks - terrestrial and marine. The model is inspired by the manganese mining industry. We consider four model scenarios. The first two consider a principal representing a cartel that invests and extracts to maximize the net present value of extraction from the onshore and offshore reserves. The second two consider two principals, each representing one cartel, that invests and extracts to maximize the net present value of extraction from their respective reserves subject to the decisions of the other cartel. The scenarios include several realistic features such as convex demand, operating costs, capital dynamics including irreversible investments, reserve-dependent capital efficiency, and capacity constraints. We present associated extraction paths and industry transformations. The results indicate that reserve-dependent capital efficiency and cross-sector competition can drive transition. Moreover, our results and discussion indicate that a transition to an industry with both onshore and offshore mining may be near, and that once the transition sparks, it may happen quickly.

KEY WORDS: Terrestrial minerals, marine minerals, industry transition, monopoly, duopoly.

JEL CODES: C61, D24, D25, Q30, Q32, Q33, Q34, Q37, Q40, Q50.

INTRODUCTION

Access to critical minerals is of high economic and strategic importance for economies in growth and on a path towards increased digitalization, electrification, and de-carbonization (Buchholz & Brandenburg, 2018; Coulomb, Dietz, & Godunova, 2015; Henckens, 2021; International Energy Agency (IEA), 2021; Kalantzakos, 2020; Toro, Robles, & Jeldres, 2020; Watari et al., 2019)

Today, critical minerals are almost exclusively mined on land (Kaluza, Lindow, & Stark, 2018; United States Geological Survey (USGS), 2020). However, onshore reserves are in decline, and extraction costs are increasing (International Energy Agency, 2021). Although fear of mineral scarcity is nothing new (Schmidt, 2019), one cannot deny that future supply will be increasingly restricted without additional mineral reserves, and that extraction costs may continue to rise. Consequentially, there may be lack of access to critical minerals in near future, which in turn may slow economic growth and give rise to challenges regarding green transitioning (Calvo & Valero, 2021; Herrington, 2021).

To make matters more challenging, many minerals are unevenly distributed across countries and interest-spheres (Henckens, 2021; Toro et al., 2020). Certain countries dominate the global supply of several critical minerals. This introduces additional supply risk challenges, partly as countries may prioritize to supply their own industries, and partly as the dominance of given commodities markets may be wielded as a strategic tool (Childs, 2020; HAO & LIU, 2011).

While the future prospects of the onshore mining industry appears scarce, marine mineral resources are pointed to as a possible source of future supply (Hein, Mizell, Koschinsky, & Conrad, 2013; Petersen et al., 2016; Rona, 2003). Yet, the challenges of mining the seabed are plentiful – spanning economic, technical, social, and environmental dimensions (Carver et al., 2020; Hoagland et al., 2010; Niner et al., 2018; Toro et al., 2020; Van Dover et al., 2017; Volkmann & Lehnen, 2018). Thus, it is unclear whether, how and when, the mining industry will transition into commercial extraction of marine mineral resources.

Existing research literature has been highly focused on the opportunities and challenges of offshore mining (Carver et al., 2020; Hein et al., 2013; Hoagland et al., 2010, 2010; Petersen et al., 2016; Rona, 2003; Toro et al., 2020; Volkmann & Lehnen, 2018; Watzel, Rühlemann, & Vink, 2020).

However, the literature is limited in conceptual, explorative studies on how a transition from onshore to offshore mineral extraction may unfold. This paper intends to fill parts of that gap, and spark research further in that direction.

Specifically, we set out to shed light on the following: ***(I)*** *What describes today's situation with critical minerals, in general, and manganese in particular?* ***(II)*** *Where is the mining industry at regarding marine mineral extraction?* ***(III)*** *What role can we expect marine mining to play in the future mining industry?* ***(IV)*** *What role do factors such as reserve-independent vs. reserve-dependent unit efficiency of capital and cross-sector competition play in and for a potential future transformation process?* To answer these questions, at least in part, we provide an explorative literature review and a conceptual model and analysis.

The model draws upon theory and research on optimal exploitation of nonrenewable resources, e.g. Herfindahl (1967), Solow and Wan (1976), Amigues et al. (1998), Holland (2003) and Meier and Quaas (2021) who all focus on optimal order to extract different deposits, and Campbell (1980) and Cairns (2001) who focus on extraction under capacity constraints and investments, and Hotelling (1931), Salant (1976), Reinganum and Stokey (1985), Lewis and Schmalensee (1980), Loury (1986), Hartwick and Sadorsky (1990), and Salo and Tahvonen (2001) who partly discuss and partly focus on oligopoly models of nonrenewable resources. We also let us inspire by Clark and Munro (1979) and Sandal et al. (2007) who consider irreversible investments and capital dynamics, but in a renewable resource context.

Moreover, the model is inspired by the manganese mineral industry. This is done to afford the reader a rudimentary grasp of the parameters and dynamics at play. Manganese is a critical mineral with no proper substitutes. Further, all commercial manganese mining currently happens onshore (Kaluza et al., 2018). However, the onshore reserves are scarce, and will run out in approximately 40 years at today's production rate. Centralization of current reserves makes the outlook even more concerning (National Minerals Information Center, 2020; Schulz et al., 2017). Meanwhile, abundances of manganese have been identified offshore, and pointed to as a possible source of future supply (Schulz, Seal, Bradley, & Deyoung, 2017). As such, it serves as a representative motivational case for mining transition between terrestrial and marine resources.

We solve the model with and without reserve-dependent unit efficiency of capital to investigate the effects of reserve-dependence on a potential transformation to offshore mineral extraction. We solve for monopoly (one cartel) and duopoly competition (two cartels) to investigate the effects of competition. Furthermore, we use sensitivity analysis to study the effects of various factors on optimal extraction paths. The sensitivity analysis is motivated by the lack of knowledge about key factors and uncertainty tied to the future potential of a marine mining industry.

CRITICAL MINERALS

Since the early onset of human society – access to minerals and metals has been a critical factor in societal, technological, and economic advancement. Seven thousand years before the common era, humanity started working with copper – since then, it is fair to establish that minerals and metals have been closely tied to human advancement (Radetzki, 2009). Population- and economic growth is a significant driver for increasing demand for minerals (Petersen et al., 2016; Vidal, Rostom, François, & Giraud, 2019). More people doing more things require additional tools, transportation, and infrastructure – minerals and metals are crucial inputs to these sectors. In high-tech societies, the array of different minerals required for growth is significant. For example, high-tech consumer goods such as smartphones comprise several critical minerals (He et al., 2020) – and such consumer goods are becoming widespread with economic growth.

Climate Change is quickly emerging as an additional demand driving factor for minerals. In the 1850s, in response to electricity becoming more utilized, the global demand for copper surged (Radetzki, 2009). In 2021, global demand for critical minerals is projected to increase significantly, also this time on account of new technologies and electrification, partly in response to climate change (Campbell, 2020; Coulomb et al., 2015; International Energy Agency, 2021; Toro et al., 2020).

Minerals and metals are crucial components in several technologies required for electrifying and de-carbonizing industry, energy, and transportation (Herrington, 2021; Kaluza et al., 2018; Watari et al., 2019). The term "Minerals" circumference a plethora of different metals and elements utilized in a wide array of different applications. Copper, cobalt, nickel, lithium, rear earth elements (REEs), chromium, zinc, platinum group metals (PGMs), manganese and aluminum are all examples of minerals that are critical to different green technologies (International Energy Agency (IEA), 2021; National Minerals Information Center, 2020).

As already implied, access to critical minerals is a complicated issue. Minerals are finite resources, and when extracted, their abundance declines. In recent years, growth in mineral consumption has started depleting many established sites (Petersen et al., 2016). As a result, high-grade concentration ore is becoming increasingly difficult to locate, and miners turn towards lesser deposits to meet demand (Humphreys, 2018, 2020). Moreover, minerals are unevenly distributed across countries and interest-spheres. Also, certain countries dominate the global supply of several critical minerals. As mentioned, this introduces supply risk challenges, partly as countries may prioritize to supply national industries in growth, and partly as the dominance of given commodity markets may be wielded as a strategic tool in the geopolitical landscape (Childs, 2020; HAO & LIU, 2011; Humphreys, 2018). Indeed, significant powers such as the US and the European Union have compiled lists of critical materials and closely monitor stockpiles and the supply situation to avoid potential disruption of productivity (Kalantzakos, 2020).

Recycling of minerals is an integral part of the mineral economy. The rate of recycling is dependent on element properties, utilization, infrastructure, and cost. Recycling rates differ significantly between elements; e.g., gold is recycled at 86%, copper at 45%, molybdenum at 20%, while boron, bismuth, and indium have a 0% recycling rate (Henckens, 2021; Herrington, 2021). In some instances, such as for lithium-ion batteries for electric vehicles, recycling can generate significantly higher emissions and energy consumption than the initial extraction and refinement of the elements (Golroudbary, Calisaya-Azpilcueta, & Kraslawski, 2019). From a cost-efficiency and sustainability perspective, it may, in some cases, hence, be preferable to extract new minerals rather than recycling them, while from a supply-strategic perspective having the ability to recycle may be important. Furthermore, considering projected global economic growth and technology shifts, it may be questionable if there are currently sufficient mineral resources in circulation to sustain growth and tech transformation as projected – even with significant improvements to the rates of recycling or circular resource utilization (Coulomb et al., 2015; Herrington, 2021; International Energy Agency (IEA), 2021; Watzel et al., 2020).

With the above said, technological innovation and paradigm shifts can lead to substitution, and reduced demand, of any given mineral as well as increased recycling rates (Coulomb et al., 2015; Henckens, 2021; International Energy Agency (IEA), 2021). This represents a significant uncertainty for any modeling exercise involving minerals, technology, and innovation, especially those dealing with long time horizons.

ONSHORE AND OFFSHORE MANGANESE MINING

This model and analysis, is inspired by the manganese industry, including Ferromanganese and Silicomanganese ore. Manganese is considered essential in conventional industry and green-shift technologies, cannot be recycled (at least not with today's technology) and has no adequate substitutes (Schulz et al., 2017).

Today's supply of manganese is purely based on onshore mining (Kaluza et al., 2018). The onshore extraction is executed either as open-pit or underground mining. Open-pit or surface mining involves the removal of overburden with excavators, bulldozers, and explosives and removing ore and waste rock. Underground mining is often executed on higher grade concentration ore – and involves less removal of waste rock. Upon retrieving the ore, the mineral is extracted through a series of chemical and thermal processes (Westfall, Davourie, Ali, & McGough, 2016).

Further, the onshore reserves are centralized and scarce, and offshore resources are pointed to as a potential source of future supply (Martino & Parson, 2013; Schulz et al., 2017). South-Africa, Brazil, and Ukraine currently sit on 63 % of the globally identified onshore reserves (Schulz et al., 2017, Chapter L1). These deposits have been formed through a process occurring in marine sedimentary rocks and environments and presently located onshore through tectonic uplift and erosion (Schulz et al., 2017, Chapter L1). The current onshore Manganese reserves are estimated at 810 000 thousand tons in 2020, with a yearly production just shy of 20 000 thousand tons (National Minerals Information Center, 2020)

– indicating that the current identified onshore reserves will be depleted in approximately 40 years at today’s extraction rate.

Centralization of onshore reserves and scarcity make professionals point to the sea for alternative sources of ore. Marine mineral deposits have been known for more than a century but focused exploration and scientific research into these deposits is more recent, dating back to the 1960s (Hein et al., 2013; Rona, 2003). Known marine mineral deposits are located both with different countries' exclusive economic zones and in international waters. The International Seabed Authority governs mining licenses in international waters, while EEZ's resource licensing is governed by the individual nation-state (Toro et al., 2020).

The marine deposits of Manganese are primarily identified as nodules and crusts (Lusty & Murton, 2018). The ore concentration or gehalt of both nodules and crusts is high relative to observed concentrations in remaining deposits on land; both categories of deposits are laden with other metallic elements beyond Manganese, such as cobalt and REEs (Hein et al., 2013; Petersen et al., 2016). The deposits are located in deep water (Lusty & Murton, 2018; Rona, 2003; Volkmann & Lehnen, 2018) – and as such, they are typically located far out at sea. Nodules are distributed across large geographic regions, and crusts are very hard entities located typically on steep subsea mountains (Hein et al., 2013; Lusty & Murton, 2018; Sharma, 2017). To extract these types of ore requires heavy and advanced robotic machinery.

Since the 1960s, many attempts have been made to extract marine minerals (Glasby, 2000; Mccullough & Nassar, 2017; Sparenberg, 2019; Toro et al., 2020; Volkmann & Lehnen, 2018). However, as already implied, marine manganese mining has yet to be established on an industrial or commercial scale. But several experimental and pilot mining activities have been launched (Sharma, 2017; Toro et al., 2020). So far, there has been very little return on investment (Alvarenga, Pr, Duhayon, & Dewulf, 2022; Childs, 2020; Glasby, 2002). Yet, these projects offer useful knowledge. These projects have shown that marine mining technology is costly and exposed to significant strain from the environment and nature of operations (Boomsma & Warnaars, 2015; Volkmann & Lehnen, 2018). Although no projects have been economically successful so far, increasing demand, onshore scarcity, centralized supply, technological innovation, etc. are all factors that intuitively may contribute to a transformation to offshore extraction.

MODEL SCENARIOS AND SOLUTION APPROACH

Table 1 Model and scenario overview (see in-text for a detailed and elaborative description)

Model	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Competition	MONOPOLY		DUOPOLY	
Objective / Approach	$\max_{u_{i,t}\geq 0, I_{i,t}\geq 0} \sum_{t=0}^{T} e^{-rt}\left(P_t(u_{i,t})\sum_{i=1}^{2} u_{i,t} - \sum_{i=1}^{2} c_t(u_{i,t}, I_{i,t})\right)$		Dynamic Cournot Nash Equilibrium[1]	
Control Variables	Principal Agent: $u_{i,t}, I_{i,t}$		Principal Agent 1: $u_{1,t}, I_{1,t}$ Principal Agent 2: $u_{2,t}, I_{2,t}$	
Production Constraint	$u_{i,t} \leq A_i k_{i,t}$	$u_{i,t} \leq A_i k_{i,t} x_{i,t}$	$u_{i,t} \leq A_i k_{i,t}$	$u_{i,t} \leq A_i k_{i,t} x_{i,t}$
Capital Dynamics	$k_{i,t+1} = k_{i,t} - d_i k_{i,t} + I_{i,t}$			
Reserve Dynamics	$x_{i,t+1} = x_{i,t} - u_{i,t}$			
Demand Function	$P(u_{i,t}) = \frac{P_{max}}{1 + P_c \sum_{i=1}^{2} u_{i,t}}$			
Cost Function	$c_t(u_{i,t}, I_{i,t}) = \sum_{i=1}^{2}(\alpha_i u_{i,t} + \beta_i I_{i,t}^{\gamma_i})$		$c_{i,t}(u_{i,t}, I_{i,t}) = \alpha_i u_{i,t} + \beta_i I_{i,t}^{\gamma_i}$	
r	0.05	0.05	0.05	0.05
P_{max}	0.01	0.01	0.01	0.01
P_c	0.001	0.001	0.001	0.001
A_1	250	0.0003	250	0.0003
A_2	125	0.0001	125	0.0001
d_1	0.2	0.2	0.2	0.2
d_2	0.3	0.3	0.3	0.3
α_1	0.0005	0.0005	0.0005	0.0005
α_2	0.0005	0.0005	0.0005	0.0005
β_1	0.01	0.01	0.01	0.01
β_2	0.01	0.01	0.01	0.01
γ_1	2	2	2	2
γ_2	2	2	2	2
$x_{i=1,t=0}$	820 000	820 000	820 000	820 000
$x_{i=2,t=0}$	1 640 000	1 640 000	1 640 000	1 640 000
$k_{i=1,t=0}$	80	80	80	80
$k_{i=2,t=0}$	0	0	0	0

[1] Each agent makes decisions to maximize the net present value of extraction from their respective reserves, taking the other agent's decisions as given, until neither agent can improve its decisions given the other agent's decisions.

Table 1 gives an overview of the modeled scenarios, which we present in detail in the following. We consider four model scenarios. Common for all model scenarios is that we consider one or two agents that aim to maximize the net present value of resource extraction from reserves at their disposal by choosing production and capital investment rates, subject to a set of constraints, in which two of the constraints determine the upper limits on extraction in each sector based on relevant states in the system, while other constraints deal with the dynamics of the system. The only interaction between the two sectors is observed through the demand function, in which extraction from either reserve influences the common price that both sectors receive for their production in the end-market.

In scenario 1, we consider a monopolist (cartel) facing reserve-independent capital efficiency. Scenario 2 considers a monopolist facing reserve-dependent capital efficiency. In scenario 3, we consider a duopoly (two cartels), in which one principal agent is responsible for the terrestrial reserves, and another is responsible for the marine reserves – both facing reserve-independent capital efficiency and competing against each other in the same end-market. Scenario 4 considers a duopoly, as in scenario 3, but with reserve-dependent capital efficiency. All in all, we consider scenarios that allow for investigation of the effects on possible industry transition of reserve-dependent capital efficiency and competition.

In scenario 1 and 2, the objectives are written as:

$$\underset{u_{i,t}\geq 0, I_{i,t}\geq 0}{\text{Max}} \sum_{t=0}^{T} e^{-rt}\left(P_t\left(u_{i,t}\right)\sum_{i=1}^{2} u_{i,t} - \sum_{i=1}^{2} c_{i,t}\left(u_{i,t}, I_{i,t}\right)\right),$$

where e^{-rt}, $P_t\left(u_{i,t}\right)$, $\sum_{i=1}^{2} u_{i,t}$, and $c_{i,t}\left(u_{i,t}, I_{i,t}\right)$ is the discount factor, demand function, total production decision and cost function, respectively. As indicated, both types of controls are constrained to be nonnegative. Moreover, $i = (1, 2)$, where 1 represents the terrestrial sector, and 2 represents the marine sector. The time horizon is defined in years as $t = (0,1, \dots, 200)$. However, we will assume that the agents are mainly interested in what happens in the first 100 years. In other words, we will assume the agents are not interested in the end-phase, where the incentive for conservation goes to zero.

In scenario 3 and 4, things are a bit more complicated regarding objectives and solution approach. Here we are interested in the dynamic Cournot Nash equilibrium, which we obtain through an iterative and repetitive optimization process, in which each agent makes decisions to maximize the net present value of extraction from their respective reserves, taking the other agent's decisions as given (Cournot), until neither agent can improve its decisions given the other agent's decisions (Nash).

In scenarios 1 and 3, the total production is $\sum_{i=1}^{2} u_{i,t}$, where $u_{i,t} \leq A_i k_{i,t}$, where A_i is the total factor productivity of capital in sector i, while $k_{i,t}$ is the capital available in sector i, measured in billion USD, i.e., in monetary value. In words, the production decision cannot exceed the production capacity determined by the total factor productivity and available capital. In scenarios 2 and 4, where the unit efficiency of capital is reserve-dependent, the total production is written in the same manner $\sum_{i=1}^{2} u_{i,t}$, but with $u_{i,t} \leq A_i k_{i,t} x_{i,t}$. We consider the reserve-dependent scenarios more realistic than the reserve-independent scenarios due to the observed onshore development regarding extraction costs.

We assume $A_i = (250, 125)$ in scenarios 1 and 3. Further, we assume $A_i = (0.0003, 0.0001)$ in scenarios 2 and 4. The numerical values are chosen to reflect that marine extraction is more capital-intensive than onshore extraction (Volkmann & Lehnen, 2018). We use different values for scenarios 1 and 3, and scenarios 2 and 4 to make the results more comparable. As we shall return to, the initial capital level for the terrestrial sector is set such that all scenarios are initialized with a terrestrial production capacity in the ballpark of today's actual production level.

The dynamic equations governing the most essential parts of the system are defined as $x_{i,t+1} = x_{i,t} - u_{i,t}$ and $k_{i,t+1} = k_{i,t} - d_i k_{i,t} + I_{i,t}$, where d_i represent the depreciation rates. Worth noting regarding the capital dynamics is the assumption of irreversible, or quasi-reversible investments, i.e., capital is highly specialized, and excess capital can therefore not be sold, and as such, investments can only be diminished through depreciation. In all scenarios, we define $x_1(0) = 820\,000$, roughly equivalent to actual estimates on current onshore manganese reserves (National Minerals Information Center, 2020). Further, we define $x_2(0) = 1\,640\,000$, the double of the initial onshore reserve, reflecting that marine deposits are abundant relative to remaining onshore reserves (Schulz et al., 2017). However, it should be noted that the initial value for the marine reserves is highly uncertain. There are currently no proper estimates on offshore resource abundances.

We define $d_i = (0.2, 0.3)$ for all scenarios to reflect that marine capital is subject to significant environmental strain relative to terrestrial capital (Schulz et al., 2017). Further, we set $k_1(0) = 80$, measured in billion dollars, which is about twice the value of yearly revenue at today's manganese production rate and trading price (2000 USD/ton * 20 000 thousand tons = 40 billion USD). The initialization value for terrestrial capital ensures that the terrestrial sector starts out with a production capacity that roughly equates today's production rate in all scenarios. We set $k_2(0) = 0$ to reflect that the marine sector is in its infancy. Finally, to ensure integrity, all stocks are constrained to be non-negative, i.e., $x_{i,t}, k_{i,t} \geq 0 \; \forall \; i \in (1,2) \; and \; t \in (0, \dots, T)$.

The demand function is $P\big(u_{i,t}\big) = \frac{P_{max}}{1+P_c q(u_{i,t})}$ in all scenarios, where P_{max} is the willingness to pay when supply is non-existent, and P_c is a curvature parameter. In our scenarios, we assume $P_{max} =$ 0.01 billion USD per thousand tons of the mineral resource, equivalent to 10 000 USD per ton, about 5 times higher than today's price per ton of ferromanganese and silicomanganese (www.metals-hub.com/data/). Moreover, we assume $P_c = 0.0002$. Thus, the demand functions are downward sloping convex curves starting at (0, P_{max}) $and \lim_{q(\dots)\to\infty} P(\dots) = 0$ – indicating that the willingness to pay for the resource becomes progressively higher for lower supply, reflecting that the mineral resource has some precious use cases and that there are no viable substitutes for application in said use cases (United States Geological Survey, 2020). Worth noting is that the price curvature parameter is set such that the modeled price is in the ballpark, but slightly higher than the recent average trading price at recent average production level (0.01 billion USD per ton / (1 + 20000 thousand tons) * 1 billion USD = 2500 USD/Ton). We choose to err on the positive side due to the projected growth in demand.

We consider two types of direct costs: operating costs and capital investment costs. The operating costs are tied to the production decisions $u_{i,t}$, while the capital investment costs are tied to the investment decisions $I_{i,t}$. We assume a constant unit cost associated with $u_{i,t}$. Moreover, we assume the supply-industries prefer workloads distributed over time to heavy workloads over short time intervals. Since we assume a constant and short delay from investment to employment, regardless of investment magnitude, we impose increasing marginal costs of investments in any single period to reflect the preferences of the supply-industries. When compared to constant marginal costs of investments, this gives incentives to spread orders over wider time intervals rather than ordering a large magnitude of capital for delivery at the next time step. Moreover, it makes it relatively more expensive to build up capital in a sector when compared to maintaining capital in a sector, all else equal. The cost functions are formally defined as: $c_{i,t}(u_{i,t}, I_{i,t}) = \alpha_i u_{i,t} + \beta_i I_{i,t}^{\gamma_i}$, where $\alpha_i = 0.0005$, $\beta_i = 0.01$ and $\gamma_i = 2$ are cost parameters. We note that any $\gamma_i > 1$ would infer increasing marginal cost of capital acquisition with respect to investment decision.

It is worth highlighting that the cost functions infer a possible discrepancy between the costs of acquiring a unit of capital and the subsequently independent valuation of that unit of capital – more precisely, the cost of acquiring an additional unit of capital may be both higher and lower than the subsequent valuation of that unit of capital. This makes sense in situations where for example the supply-industry has excess capacity to deliver capital to the extractive industries, but no orders, and vice versa.

In addition to the direct costs, there are obvious indirect costs tied to idle capacity. Not utilizing the full capacity means there is overcapacity, i.e., that excessive investments has been made, or that the capital is initialized at a level higher than what is optimal. At the same time, it means that a trade-off is made between increasing production at low cost today and postponing production, which involve discounted revenue, and may involve costs tied to maintenance and/or re-accumulation of capital.

We solve all optimization problems numerically by use of GAMS and the KNITRO solver. The solver is well-suited for dynamic nonlinear problems. Moreover, it has a fast method for finding a first feasible solution well suited for models with few degrees of freedom, such as the model scenarios presented here. For the interested reader, we have made our codes available on GITHUB (*link will be provided upon acceptance of the paper*). The codes also contain instructions on how to solve the scenarios presented in this study.

MONOPOLY: RESERVE-INDEPENDENT VS. RESERVE-DEPENDENT RESULTS

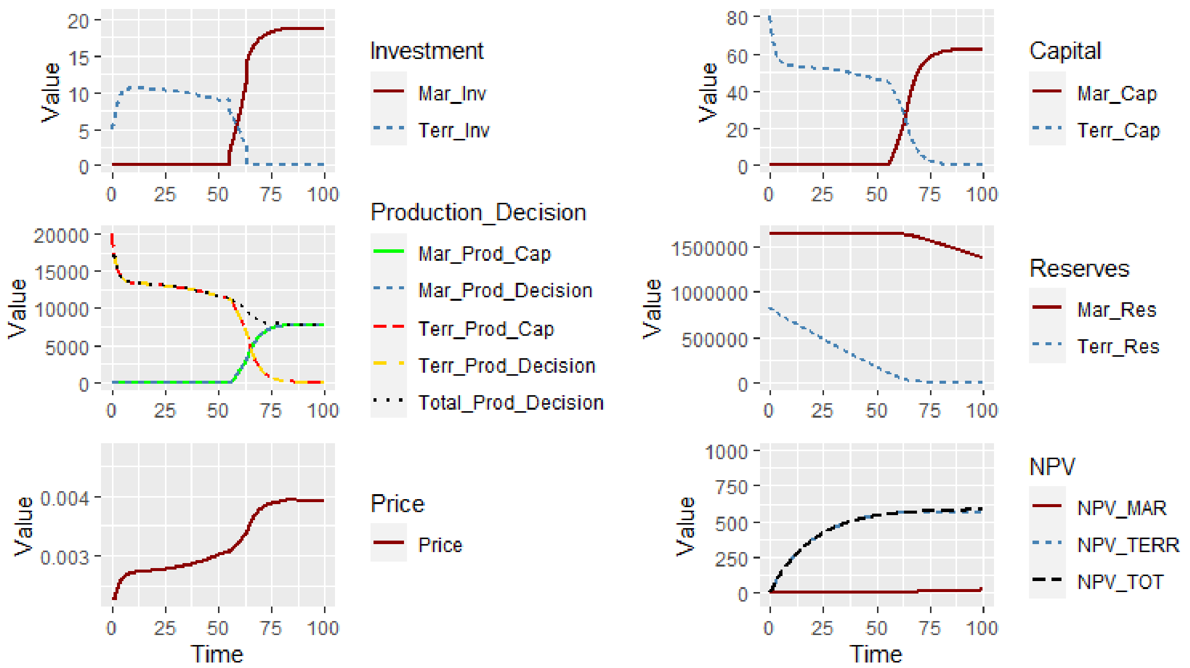

Fig. 1 Results from scenario 1: Monopolist facing reserve-independent capital efficiency

Fig. 1 provides an overview of the results from scenario 1, i.e., the monopoly case with reserve-independent capital efficiency (described in table 1). First, regarding the structure of the panel: The principal chooses investment rates (top left panel), which leads to accumulation of capital (top right panel), which allows for positive production decisions resulting in production/extraction (second to top left panel), which further leads to decline in mineral reserves (second to top right panel). Total production determines price (bottom left panel). Based on the previous information, and information about the discount rate, the net present value is calculated (bottom right panel).

Aligned with Herfindahl (1967), Solow and Wan (1976) and others, the results from scenario 1 indicate it is optimal to extract in order of increasing extraction cost. First, it is optimal to begin by investing in terrestrial capital, which has the highest unit efficiency and lowest maintenance costs (due to lower depreciation rates). When the terrestrial reserves near depletion, it is optimal to start investing in marine capital, which has lower unit efficiency and higher maintenance costs.

On the one hand, the results from scenario 1 are unsurprising, in that it resonates theory and common sense. On the other hand, it is useful to know that the core part of the model produces reasonable results before moving into more complex scenarios.

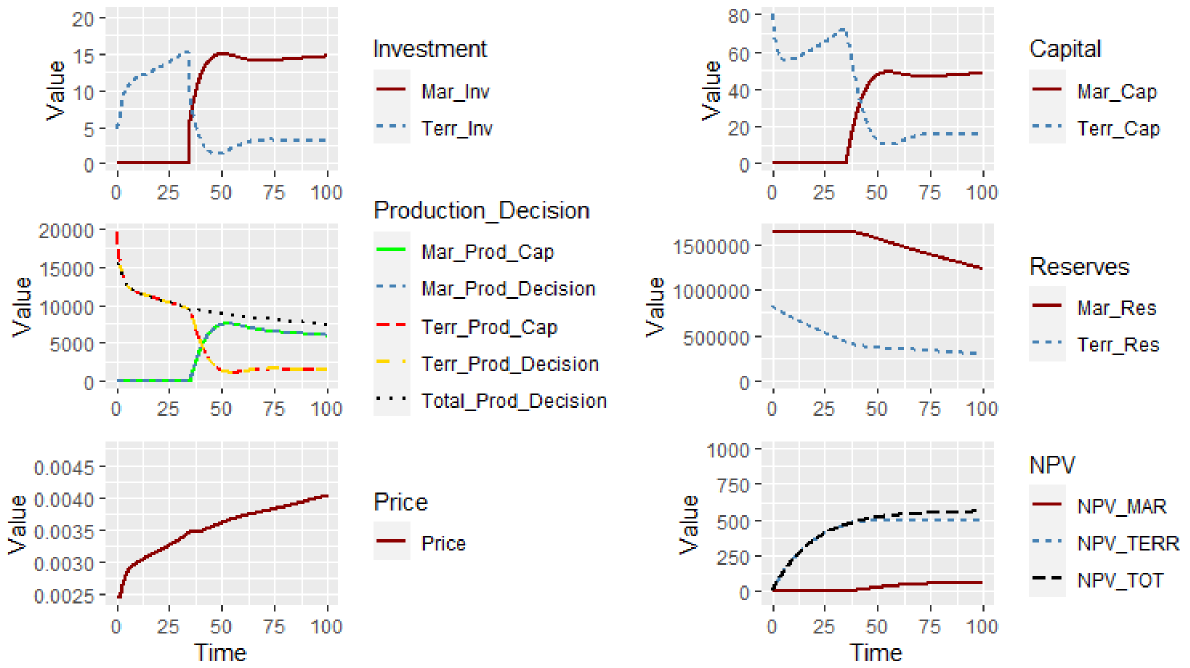

Fig. 2 Results from scenario 2: Monopolist facing reserve-dependent capital efficiency

Fig. 2 provides an overview of the results from scenario 2, i.e., the monopoly case with reserve-dependent capital efficiency. The optimal behavior is quite different when compared to optimal behavior in the monopoly scenario with reserve-independent capital efficiency (Fig. 1 vs. Fig. 2).

In the monopoly scenario with reserve-independent capital efficiency, the deposits were extracted in order of increasing extracting costs - aligned with Herfindahl (1967), Solow and Wan (1976) and others. We witness the same behavioral phenomenon in the monopoly scenario with reserve-dependent capital efficiency. However, now the output per unit capital is increasing with positive changes in the reserves, i.e., decreasing with negative changes in the reserves. Thus, the unit extraction costs are partly and indirectly dependent on the size of the reserves. As such, the reserve-dependent model allows for switching between what resource stock has the highest extraction cost. Such switching plays a crucial part role in explaining the behavior seen in Fig. 3. The unit extraction costs depend not only on the unit efficiency but also the depreciation rates, which says something about capital maintenance costs, which is also of relevance.

Like in the monopoly scenario with reserve-independent capital efficiency, the principal begins by investing in terrestrial capital (see Fig. 1 vs. Fig. 2). This continues until the transformation phase is initiated. The transformation phase begins with a sharp drop in terrestrial investment and sharp commencement of marine investments. This leads to a reduction in terrestrial capital through depreciation and an accumulation of marine capital. As a result, terrestrial production decreases while marine production increases. The phase ends as the two investment rates transition to steady trajectories. Through the steady trajectory phase, terrestrial and marine production coexist, although at different levels. This is fundamentally different from scenario 1, where there was no coexistent terrestrial and marine capital investment.

To elaborate, the initial marine reserves are abundant relative to terrestrial reserves, while initial marine capital is low relative to terrestrial capital. Moreover, the marine total factor productivity is lower than the terrestrial total factor productivity, and the marine depreciation rate is higher than the terrestrial depreciation rate. The relative abundance of marine reserves has an indirect positive effect on the relative attractiveness of marine investment, while the relative abundance of terrestrial capital exists as a competitive disadvantage for the marine sector. Finally, the lower marine total factor productivity and higher marine depreciation rate have negative effects on the relative attractiveness of marine investment. And the results in Fig. 2 clearly shows that the additional abundance of marine reserves does not fully compensate for the lower marine total factor productivity and higher marine depreciation rate, and its disadvantage of no initial capital. Overall, the initial relative attractiveness of marine investment is low, and the principal chooses to invest in terrestrial capital. Through terrestrial extraction and reduction in terrestrial reserves, the terrestrial unit efficiency goes down. This continues until the relative attractiveness of marine investment reaches a level where the principal reduces investment in terrestrial capital to build up marine capital through marine investment while letting the terrestrial capital depreciate. The principal then seeks to enter investment paths that ensure terrestrial and marine extraction are equally attractive.

DUOPOLY: RESERVE-INDEPENDENT VS. RESERVE-DEPENDENT RESULTS

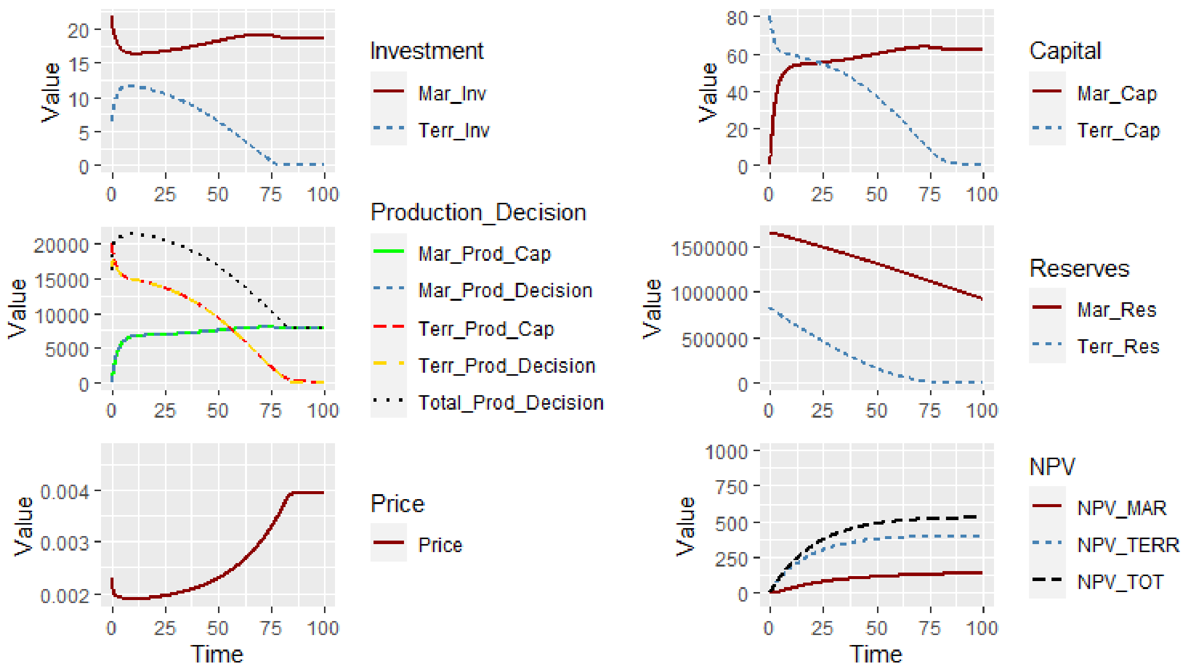

Fig. 3 Results from scenario 3: Duopoly and reserve-independent capital efficiency

Fig. 3 provides an overview of the results from scenario 3, i.e., the duopoly case with reserve-independent capital efficiency. The results from this scenario sketches out an entirely different behavior than the one observed in the monopoly case with reserve-independent capital efficiency.

Key things to note when comparing the duopoly scenario with reserve-independent capital efficiency to the monopoly scenario with reserve-independent capital efficiency include: **(I)** In line with what to expect from an increase in competition, total production is higher in the duopoly scenario with reserve-independent capital efficiency through the period where both reserves are positive when compared to the monopoly scenario with reserve-independent capital efficiency – consequentially, the price is also lower through this period; **(II)** More surprisingly, the transition to an industry with marine production starts already at time zero; **(III)** The depletion of terrestrial resources happens at a later stage; **(IV)** Once the terrestrial reserves are depleted, the marine sector enter the same production trajectory as seen in the monopoly scenario with reserve-independent capital efficiency, which to some extent validate the numerical results because the marine principal agent becomes a monopolist once the terrestrial reserves have been depleted; **(VI)** As one should expect in a situation with competition, the overall NPV is lower in the duopoly scenario with reserve-independent capital efficiency when compared to the monopoly scenario with reserve-independent capital efficiency; **(VII)** Per expectation, the marine NPV is much higher in the duopoly situation when compared to the monopoly situation.

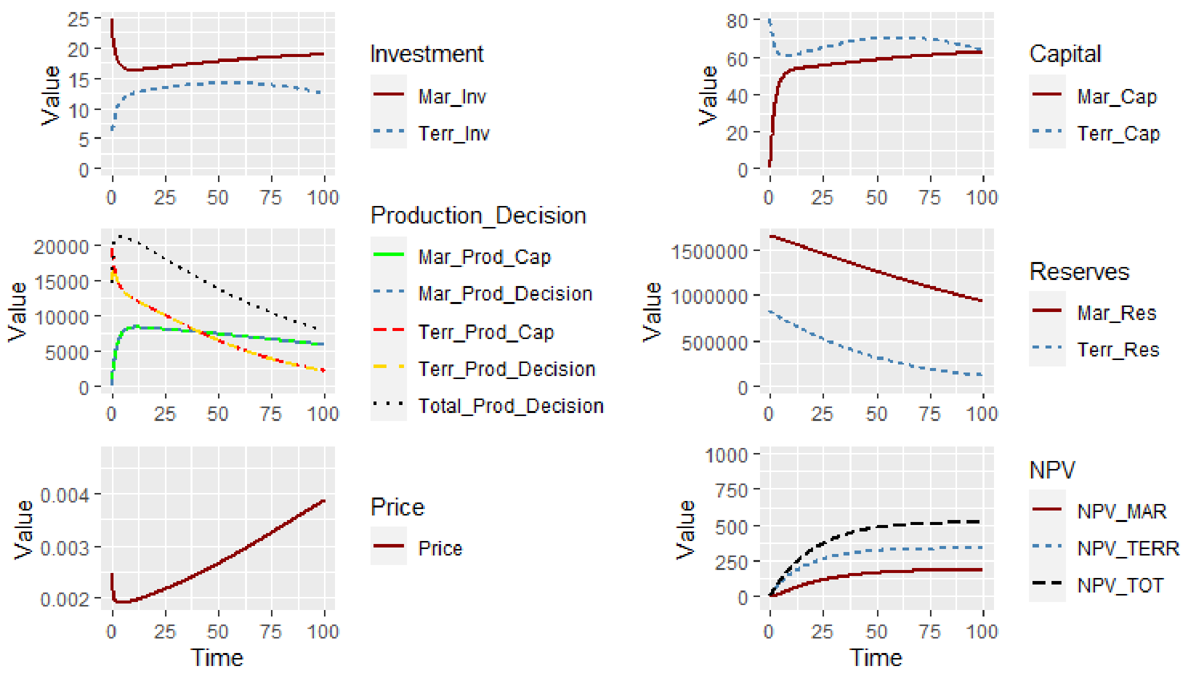

Fig. 4 Results from scenario 4: Duopoly and reserve-dependent capital efficiency

Fig. 4 provides an overview of the results from scenario 4, i.e., the duopoly case with reserve-dependent capital efficiency. The results from this scenario sketches out a different behavior than those observed in the monopoly scenarios. However, the observed transitional behavior is quite similar to the observed behavior in the duopoly scenario with reserve-independent capital efficiency. This is somewhat surprising considering there were significant differences between the monopoly scenario with reserve-independent capital efficiency and the monopoly scenario with reserve-dependent capital efficiency.

Key things to note regarding the duopoly scenario with reserve-dependent capital efficiency, and when comparing that scenario to the monopoly scenario with reserve-dependent capital efficiency, and the duopoly scenario with reserve-independent capital efficiency include: **(I)** Total production is higher in the duopoly scenario with reserve-dependent capital efficiency, when compared to the monopoly scenario with reserve-dependent capital efficiency, through most of the time horizon, but lower towards the end, likely explained by the lower reserves, increase in unit extraction costs and a resulting desire of a higher price. **(II)** As in the duopoly scenario with reserve-independent capital efficiency, the transition to an industry with marine production starts already at time zero; **(III)** As opposed to the duopoly scenario with reserve-independent capital efficiency, co-existence of terrestrial and marine extraction occurs throughout the entire time horizon; **(IV)** Per expectation, the overall NPV is lower in the duopoly scenario with reserve-dependent capital efficiency than in the monopoly scenario with reserve-dependent capital efficiency; **(VI)** The marine NPV is much higher in the duopoly scenario with reserve-dependent capital efficiency than in the monopoly scenario with reserve-dependent capital efficiency; **(VII)** The marine proportion of total NPV is higher in the duopoly scenario with reserve-dependent capital efficiency than in the duopoly scenario with reserve-independent capital efficiency – highlighting the marine benefit of abundant reserves.

SENSITIVITY ANALYSIS

Results from sensitivity analysis provide further insight into optimal behavior in the various scenarios. Although we will focus on the sensitivity of the density-dependent duopoly results, some comments can be made based on tests for sensitivity in the monopoly scenarios: **(I)** An increase in P_{max} yields a more aggressive extraction approach in both reserve-independent and -dependent scenarios (see appendix A1-A2). A decrease in P_c has similar effects as an increase in P_{max}; **(II)** Reducing the depreciation rate of marine capital makes it more attractive to invest in the marine sector in both reserve-independent and -dependent scenarios (see appendix A1-A2); **(III)** Increasing the total factor productivity of marine capital relative to terrestrial capital naturally makes marine investment more attractive in both type of scenarios (see appendix A1-A2); **(IV)** In the reserve-independent monopoly scenario, an increase in the discount rate leads to a slightly more aggressive terrestrial extraction and slightly delayed but more aggressive transition to marine extraction in reserve-independent monopoly scenario, with overall less aggressive marine extraction (see appendix Fig. A1). In the reserve-dependent monopoly scenario, an increase in the discount rate leads to slightly more aggressive terrestrial extraction and earlier transition, with overall less aggressive marine extraction (see appendix Fig. A2); **(V)** Even when the terrestrial capital stock is initialized at zero, the transitional behavior is the same as when it is initialized at 80, in terms of extraction order (see appendix Fig. A3-A4).

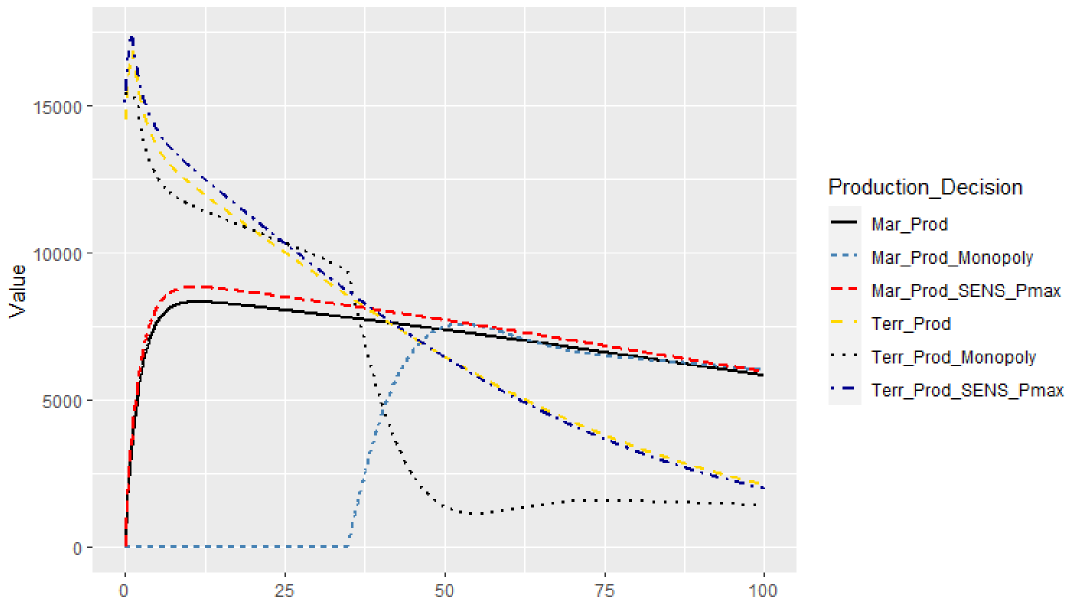

Fig. 5 The effects on the results from the *reserve-dependent duopoly scenario* of increasing P_{max} by 10%. The baseline results from reserve-dependent duopoly and monopoly scenarios are included for reference.

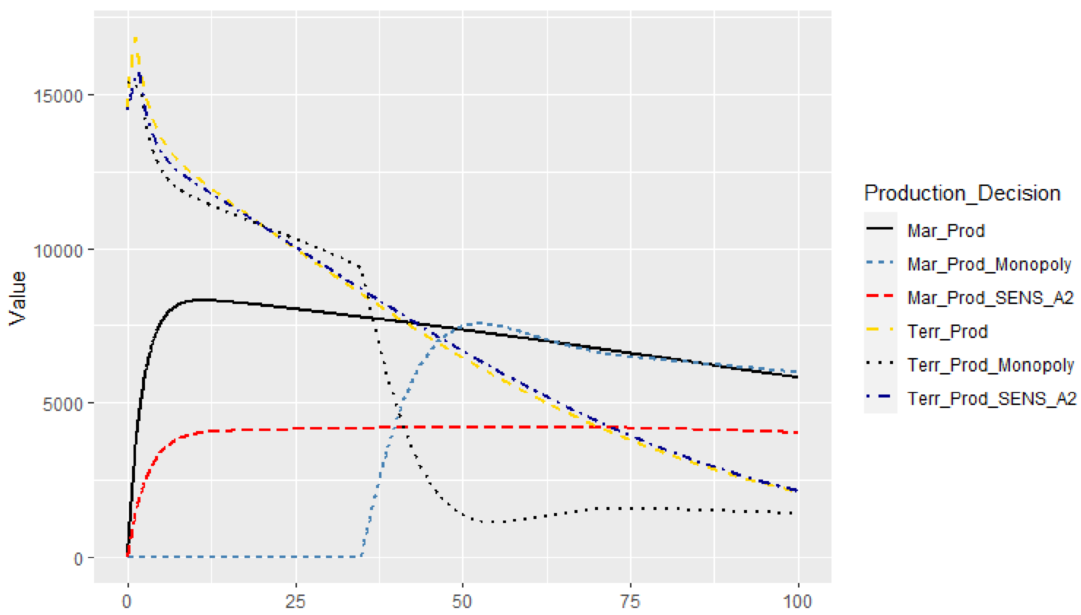

Fig. 6 The effects on the results from the *reserve-dependent duopoly scenario* of reducing A_2 by 50%. The baseline results from reserve-dependent duopoly and monopoly scenarios are included for reference.

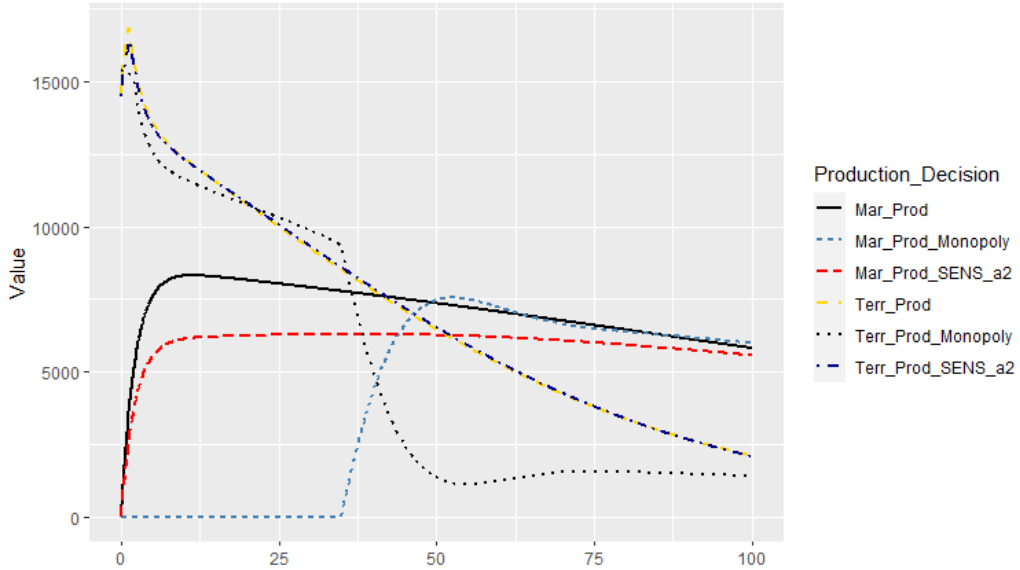

Fig. 7 The effects on the results from the *reserve-dependent duopoly scenario* of doubling α_2. The baseline results from reserve-dependent duopoly and monopoly scenarios are included for reference.

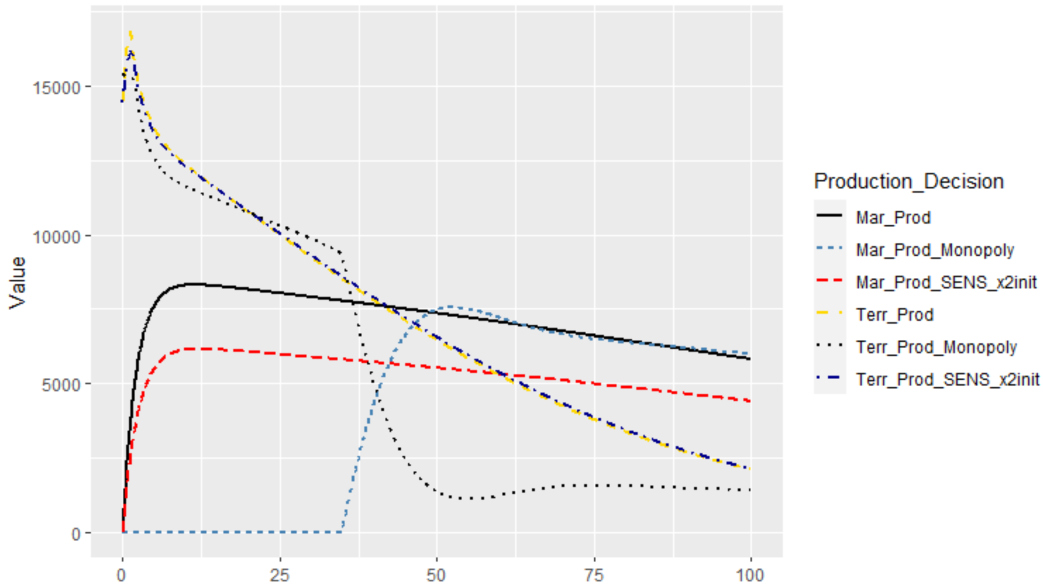

Fig. 8 The effects on the results from the *reserve-dependent duopoly scenario* of reducing the initial marine reserves by 410 thousand tons. The baseline results from reserve-dependent duopoly and monopoly scenarios are included for reference.

Fig. 5-8 show the effects of increasing P_{max} by 10%, reducing A_2 by 50%, doubling α_2, and reducing the initial marine reserves by 410 thousand tons in the *reserve-dependent duopoly scenario*.

The baseline results from reserve-dependent duopoly and monopoly scenarios are included for reference. The increase in P_{max} increases the extraction in both sectors, but relatively more in the marine sector when compared to the terrestrial sector. A reduction in the capital efficiency of the marine sector naturally leads to reduced marine extraction. Interestingly, the terrestrial sector does not respond to this by increasing its extraction, but rather choose to reduce it slightly. The increase in marine operation costs leads to reduced marine extraction. However, no significant response is seen in the terrestrial production, albeit the small response seen is in the negative direction. The reduction in initial marine reserves also leads to reduced marine extraction, and as before, there is no strong response in the terrestrial sector, but a slight response to produce less. The weak negative extraction response in the terrestrial sector is easily explained by the fact that it gains more market power, and work to push the production schedule towards the monopoly solution, which is best seen in Fig. 6, where the reduction in marine extraction is most significant.

DISCUSSION

In summary, the results presented in the previous sections indicate that a transition to marine mining is likely. However, the results from the various scenarios sketches out different transitional behavior.

In the monopoly scenario with reserve-independent capital efficiency, our results indicate that a transition will take place when the terrestrial reserves near depletion, far out in time. However, knowing that onshore costs are increasing due to depletion of high-grade reserves, we can conclude that this scenario is not realistic. In the monopoly situation with reserve-dependent capital efficiency, the results indicate that a transition will take place well before the terrestrial reserves near depletion, at an earlier stage. Moreover, the results indicate a transition to an industry with co-existing terrestrial and marine mining. However, the monopoly scenarios may be considered unrealistic, no matter the assumptions regarding capital efficiency. Marine resources have been identified in the deep-sea across the globe, mostly in international waters governed by the International Seabed Authority, but also within a few national EEZs. This may imply competition, for example between a cartel representing the current onshore industry and a cartel representing a future possible marine industry, or several agents in each sector.

In the duopoly situation with reserve-independent capital efficiency, the results indicate an immediate and powerful transition to an industry with co-existing terrestrial and marine mining, in which the relative extraction of terrestrial reserves to marine reserves is decreasing over time until the terrestrial stock is fully depleted. Now, this scenario is interesting because it truly shows the effect of competition on transition in a profitable resource-based and resource-scarce industry.

In the duopoly scenario with reserve-dependent capital efficiency, which we consider the most realistic scenario of the four, the results indicate an immediate transition to an industry with co-existing terrestrial and marine mining, like in the duopoly scenario with reserve-independent capital efficiency. The relative extraction of terrestrial reserves to marine reserves is decreasing over time, just as in the duopoly situation with reserve-independent capital-efficiency. However, in the duopoly scenario with reserve-dependent capital efficiency, the onshore reserves are never depleted, and there is co-existing terrestrial and marine extraction throughout the time horizon.

We consider the above interesting. The results and discussion indicate that a transition to an industry with both onshore and offshore mining may be near, and that once the transition sparks, it may happen quickly. However, we must remind the reader that our model and analysis is mainly conceptual, and there are limitations. First, the model and many of its parameters are uncertain. Second, the model does not consider exploration, costs tied to innovation, delays, nor externalities. A more realistic model should consider all these things. And a model that incorporate these factors may sketch out a somewhat different transitional behavior. As such, our results should not, and cannot, be considered precise forecasts. However, what can be synthesized from the results is the understanding of how two key factors, namely reserve-dependent capital efficiency and competition, can affect a future transition. And we think that these insights hold some practical value.

Regarding the missing factors, we can only speculate how they would affect a transition. For example, significant effort must be put into exploration and identification of potential marine mining sites. This could be costly in terms of both money and time, and as such, push a transition further out in time. Moreover, it is possible that inclusion of delays and costs tied to innovation would push a transition further out in time, and change the behavior seen during the build-up of marine capital, for example from a concave development to a convex development, i.e., a capital-development that is initially slow, and then shoots speed through time (until reaching some desired level, and thereafter possibly decline). This seems reasonable because, for example, investment-delivery delays mean that costs occur today, while the benefits are pushed further out in time, and as such, discounted harder. Furthermore, it seems reasonable to argue that the costs of acquiring one unit of production capital is high when the technology is not yet invented, because money and time must be invested in research and development. Future studies could investigate how such factors can affect transition in a similar framework to the one presented here.

From a societal point of view, externalities are also important to consider. Many studies have investigated the potential ecological impact of marine mining, and it is apparent that the risks are significant. Such considerations could also be built into models for future research on mineral industry transition. In such a case, one must not forget to ask the question whether the potential immediate environmental costs associated with marine mining can be offset by the potential contribution of minerals as input factors to green-tech technologies. This is a complex discussion, but nevertheless, an interesting one.

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APPENDIX

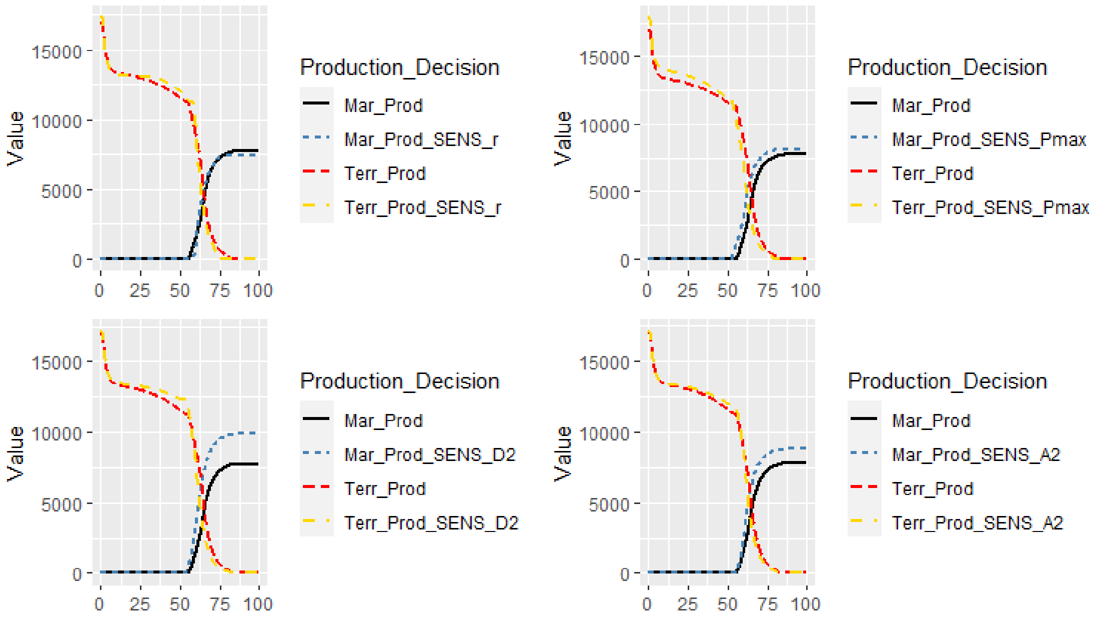

Fig. A1 The effects of increasing the discount rate r to 0.1 (upper left), increasing P_{max} by 10% (upper right), reducing d_2 from 0.3 to 0.2 (lower left), and increasing A_2 from 125 to 150 (lower right), in the reserve-independent monopoly scenario.

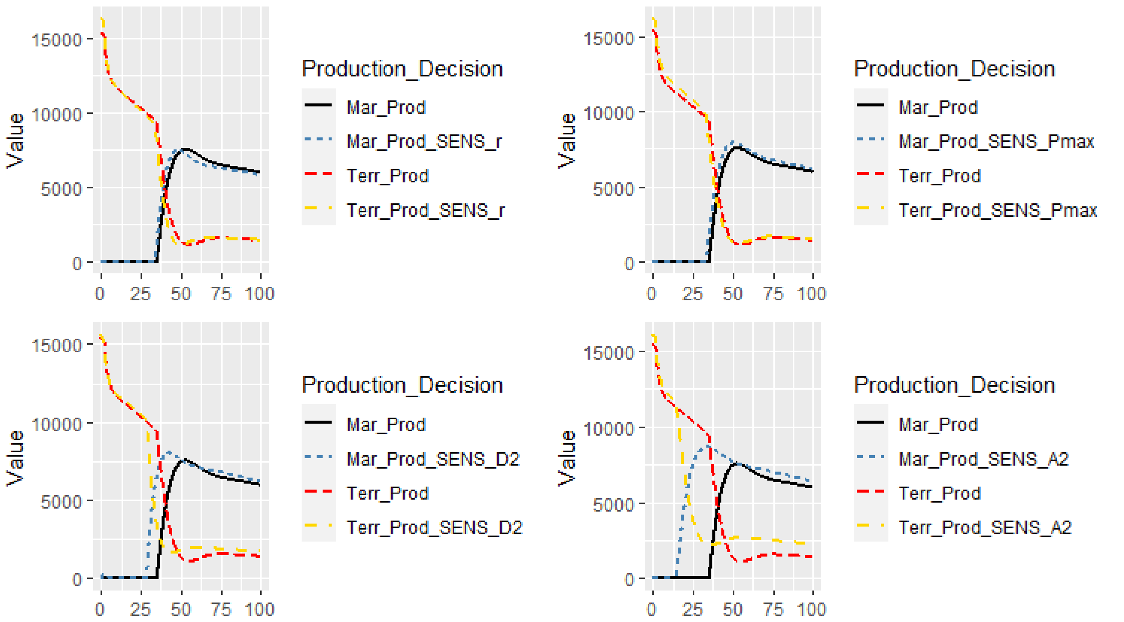

Fig. A2 The effects of increasing the discount rate r to 0.1 (upper left), increasing P_{max} by 10% (upper right), reducing d_2 from 0.3 to 0.25 (lower left), and increasing A_2 from 0.0001 to 0.00015 (lower right), in the reserve-independent monopoly scenario.

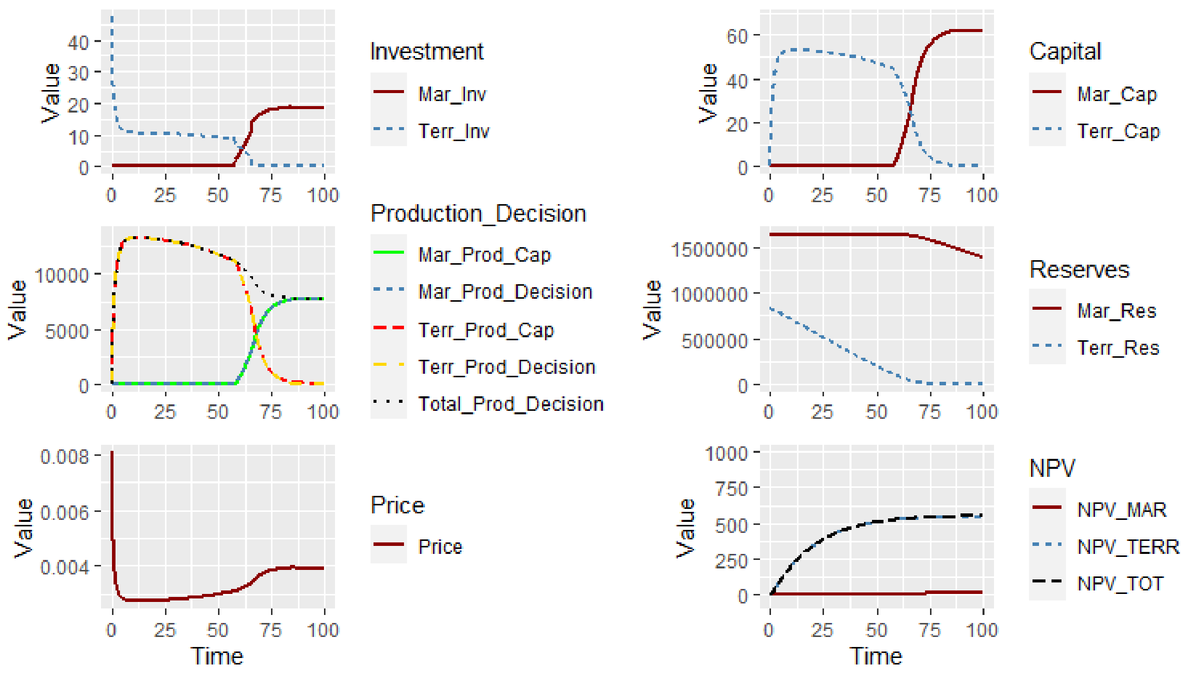

Fig. A3 Results from the reserve-independent monopoly scenario where the capital stock is initialized at zero.

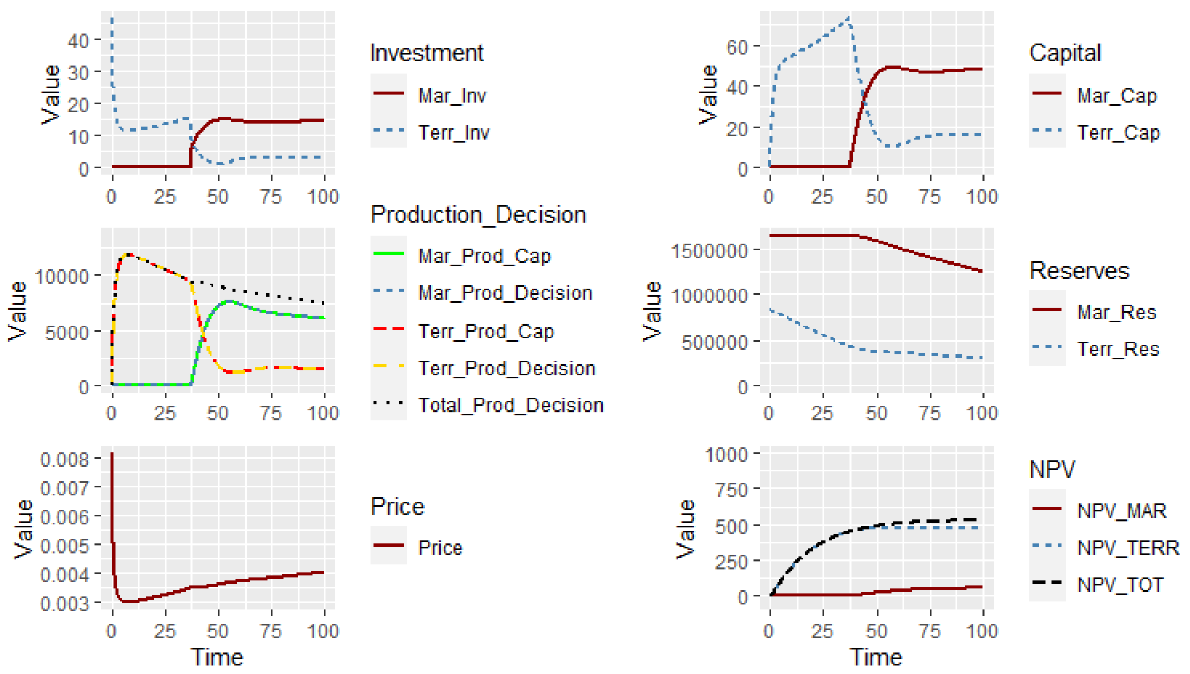

Fig. A4 Results from the reserve-dependent monopoly scenario where the capital stock is initialized at zero.

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