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Reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations in mineral industry transition

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Abstract
This study pinpoints three current factors that could be momentous in a possible transition to marine mining, namely reserve-dependent capital efficiency (accessibility and grade-dependent output per unit capital), cross-sector competition (competition between two separate mining sectors), and asymmetric mineral security considerations (e.g., the resource owner(s) and government(s) tied to a sector desires production for profit *and* security reasons). Moreover, four *conceptual* optimization problems are explored to specify the potential roles of said factors in a possible transition. The first problem considers a principal agent, who make decisions on behalf of resource owner(s), government(s) and producer(s), and invests and extracts to maximize the net present value of extraction from onshore and offshore reserves while facing reserve-independent capital efficiency. The second problem considers the same as the first, except here, the principal meets reserve-dependent capital efficiency. The third problem considers two principals, each representing resource owner(s), government(s), and producer(s) tied to a sector, who invest and extract to maximize the net present value of extraction from the respective reserves subject to the decisions of the other principal. Finally, the last problem considers a duopoly setting in which the marine principal values both financial gain and mineral security. The results illustrate that reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations can, in different ways, drive a possible transition to marine mining. Possible counter effective factors are highlighted and discussed.

Keywords Terrestrial minerals · Marine minerals · Industry transition · Monopoly · Duopoly · Geopolitics

JEL codes C61 · D24 · D25 · Q30 · Q32 · Q33 · Q34 · Q37 · Q40 · Q50

Introduction

Critical non-fuel minerals are compounds of elements that are crucial to growing economies on a path towards increased digitalization, electrification, and decarbonization (Buchholz and Brandenburg 2018; Coulomb et al. 2015; Henckens 2021; International Energy Agency (IEA) 2021; Kalantzakos 2020; Toro et al. 2020; Watari et al. 2019). Restricted access to such minerals can result in a range of short and long-term challenges, for example, challenges regarding green transitioning and sustainable economic growth (Calvo and Valero 2021; Herrington 2021).

Today, critical non-fuel minerals are exclusively mined on land (Kaluza et al. 2018; United States Geological Survey (USGS) 2020). However, increasing demand, declining onshore resources, falling ore grades, increasing extraction costs, and centralized supply raise worries about future access to critical minerals, especially for non-producing import economies.

Marine minerals may possibly alleviate concerns and contribute to the future supply of critical minerals (Hein et al. 2013; Petersen et al. 2016; Rona 2003). However, marine mineral exploration and mining involve technical, economic, environmental, and social challenges (Carver et al. 2020; Hoagland et al. 2010; Niner et al. 2018; Toro et al. 2020;

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Van Dover et al. 2017; Volkmann and Lehnen 2018). Thus, it is unclear whether, how, and when the industry will transition into commercial extraction of marine non-fuel mineral resources.

Existing 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; Petersen et al. 2016; Rona 2003; Toro et al. 2020; Volkmann and Lehnen 2018; Watzel et al. 2020). However, the literature is limited in conceptual, aggregate, and explorative studies on how a transition from onshore to offshore mineral extraction may unfold. This study intends to fill parts of that gap and spark research further in that direction.

Inspired by the ongoing development in the mining industry and geopolitical landscape, and considering existing research gaps, this study sets out to investigate the roles of reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations in a possible transition from onshore to offshore mining.

Reserve-dependent capital efficiency means that output per unit capital depends on the deposits in terms of their accessibility and ore grade. Cross-sector competition refers to possible competition between terrestrial and marine mining. In relation to settings without cross-sector competition, the industry, including both sectors, should here be understood as an entity consisting of resource owner(s), government(s), and producer(s), represented by a principal, with no competition from the outside—i.e., a monopoly cartel. In relation to settings dealing with cross-sector competition, each sector should here be understood as an entity consisting of resource owner(s), government(s), and producer(s), represented by a principal, and competing against the other sector—i.e., each sector represents a cartel that is part of a duopoly. While the monopoly and duopoly configurations represent abstractions from reality, in which there is more competition, these simplified perspectives allow clear focus on the effects of cross-sector competition.

Mineral security considerations mean that at least one sector desires production for profit *and* security reasons. In relation to this, one can imagine that the principal in charge of a sector makes a decision on behalf of the resource owner(s) and government(s) to provide extraction licenses and subsidies to the producer(s)—the subsidies to reflect the mineral security considerations, which could, e.g., be geopolitically motivated. In the real world, mineral security considerations may directly affect both onshore and offshore mining. However, we shall here focus on the simplified case where mineral security considerations only directly affect the marine sector. This is motivated by the fact that mineral security considerations may have an asymmetric effect—potentially benefiting the possibly emerging offshore sector more than the existing onshore sector (in a global perspective).

Specifically, we present four conceptual dynamic optimization problems to achieve the objectives. We present problems with reserve-independent and reserve-dependent capital efficiency to investigate the effects of reserve-dependent capital efficiency on a potential transformation to offshore mineral extraction. Furthermore, we present problems with monopoly and duopoly competition (terrestrial vs. marine) to investigate the effects of cross-sector competition. Finally, we present problems where both sectors value only financial gain and a problem where the marine sector values both financial gain and mineral security. This is done to investigate the effects of asymmetric mineral security considerations.

Although this study is conceptual, it offers practical value by pinpointing factors that are highly relevant to a possible transition to marine mining. Furthermore, it contributes by providing an understanding of how those factors can affect a possible transition. Hopefully, the model framework and approach can also serve as a venture point for future studies and thereby contribute to building further insight and eventually indicating whether, how, and when a transition will occur.

The three following sections provide background on the demand and supply of critical minerals, and the relevance of supply risks and mineral security considerations. The subsequent sections outline the optimization problems, solutions, and sensitivity analysis. Then, the results are discussed. Finally, conclusions are drawn.

Demand for critical minerals

Seven thousand years before the common era, humanity started working with copper—since then, it is fair to establish that access to minerals have been closely tied, even critical, to human advancement (Radetzki 2009).

Mineral contents are crucial inputs in several vital technologies, such as those required for electrifying and decarbonizing industry and transportation (Herrington 2021; Kaluza et al. 2018; Watari et al. 2019). Copper, cobalt, nickel, lithium, rare earth elements (REEs), chromium, zinc, platinum group metals (PGMs), manganese, and aluminum are all examples of elements that are critical to different green technologies (International Energy Agency (IEA) 2021; National Minerals Information Center, U. 2020).

In the 1850s, new technologies and electrification led to a surge in demand for copper (Radetzki 2009). In 2022, 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 and partly in response to geopolitical development (Campbell 2020; Coulomb et al. 2015; International Energy Agency

(IEA) 2021; Kalantzakos 2020; Toro et al. 2020). As such, access to minerals is becoming increasingly important.

Supply of critical minerals

Today's commercial supply of critical non-fuel minerals is based on onshore mining and recycling (Kaluza et al. 2018). Onshore mining is mainly executed as open-pit and underground mining from mineral reserves unevenly distributed across countries, economies, and interest spheres. Open-pit mining involves the removal of overburden with excavators, bulldozers, and explosives. Upon retrieving the ore, the valuable elements are extracted through mechanical, chemical, and thermal processes (Hein et al. 2013; Westfall et al. 2016). Underground mining is often executed on higher-grade ore—and involves less removal of waste rock.

The rate of recycling is dependent on several factors, including element properties and their recycling potential, the recycling costs, and the alternative costs of recycling. 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). In some cases, such as for lithium-ion batteries for electric vehicles, recycling can generate significantly higher costs, energy consumption, and emissions than the initial extraction and refinement of the elements (Golroudbary et al. 2019). In such cases, it may be preferable to extract new minerals rather than recycling.

In recent years, the mining industry has started depleting many established sites (International Energy Agency (IEA) 2021; Petersen et al. 2016). Moreover, easily accessible, high-grade ore is becoming increasingly difficult to locate. As a result, miners turn towards lesser deposits to meet demand, increasing the unit extraction costs (Haugan and Levin 2020; Hein et al. 2013; Ragnarsdóttir 2008; Toro et al. 2020). Moreover, there are insufficient mineral resources in circulation to sustain technological development and economic growth through recycling—even with significant improvements in the rates of recycling and circular resource utilization (Coulomb et al. 2015; Herrington 2021; International Energy Agency (IEA) 2021; Watzel et al. 2020). This makes it interesting to consider alternative sources of supply—perhaps by exploring marine minerals.

The HMS Challenger identified marine mineral deposits already in the 1870s. However, focused exploration and scientific research is more recent, dating back to the 1960s (Hein et al. 2013; Rona 2003). Since the 1960s, marine mineral deposits have been identified in international waters and within different countries' exclusive economic zones—also in economic zones where there is little or no onshore mining, which can indicate future cross-sector competition.

Several attempts have been made to extract marine minerals (Glasby 2000; Mccullough and Nassar 2017; Sparenberg 2019; Toro et al. 2020; Volkmann and Lehnen 2018). So far, there has been no positive return on investment (Alvarenga et al. 2022; Childs 2020; Glasby 2002; International Energy Agency (IEA) 2021). However, increasing demand for critical minerals, increasing onshore mineral scarcity, increasing onshore extraction costs, and geopolitical polarization and security considerations may point towards a future with commercially viable offshore mining.

Supply risks and mineral security

Today, certain countries dominate the global supply of several critical non-fuel minerals. This induces supply risks for importing nations, partly because current exporting countries may prioritize supply to their own industries in events of increased scarcity, or wield their dominance as a strategical tool in the geopolitical landscape; also, supply can be disrupted by stand-alone events such as natural disasters and conflicts (Childs 2020; Hao and Liu 2011).

When Russia launched a full-scale invasion of Ukraine in February 2022, western nations rallied to sanction Russia. However, western dependence on Russian oil and gas inhibited sanctions on Russia's most significant exports—at least up until the moment of writing in early May 2022. The European costs of imposing an oil and gas embargo on Russia have so far been considered too high for implementation. This safeguards significant revenue for Russia, which in turn enable Russia's continued offensive in Ukraine, which is expensive. This has rendered Russia's geopolitical advantage of controlling supply of oil and gas to Europe conspicuous. At the same time, from a European perspective, it has demonstrated the strategic perils of not controlling supply of oil and gas.

The war in Ukraine and the European Union's dependence on Russian oil and gas highlight the importance of secure access to oil, gas, and energy. In principle, they also highlight the importance of secure access to other critical raw materials such as critical minerals. And in March 2022, the European Council released a declaration emphasizing the importance of securing the supply of critical raw materials (European Council 2022).

The European Union and European Economic Area are net importers of many critical minerals (Dominish et al. 2019; European Commission 2020; Herrington 2021; International Energy Agency (IEA) 2021; Kaluza et al. 2018). At the same time, some of the countries within this area have access to marine minerals (Hoagland et al. 2010; Pedersen et al. 2021; Sharma 2017). That, together with an increasing focus on securing access to critical raw materials, makes it interesting to investigate the effects of mineral security considerations in a possible transition to marine mining.

The war in Ukraine and the European Union's dependence on Russian oil and gas are also relevant in a more intricate way. The newly strengthened European desire to reduce dependence on Russian oil and gas has led the European Union to send signals about doubling down on renewable energy transition, electrification, and digitalization. This represents an acceleration in the already increasing demand for renewable energy, electrification, and digitalization in Europe, which will undoubtedly further increase the demand for minerals in Europe. This makes secure access to critical minerals even more crucial for Europe than it otherwise would have been.

If Europe does not secure access to critical minerals, it will risk swapping dependence on Russian oil and gas for dependence on possibly non-desirable interest sphere's critical minerals—a situation it seems reasonable to conclude the European Union prefer to avoid.

Strategic considerations and increasing European demand for minerals may indicate an increase in support schemes to advance the European mining industry, including the existing onshore sector and a possible marine mining sector.

Conceptual optimization problems

This study presents four conceptual dynamic optimization problems. The problems draw upon ongoing real-world development, as well as theory and research on optimal exploitation of nonrenewable resources. The problems are inspired by 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. They are further inspired by Campbell (1980) and Cairns (2001) who focus on extraction under investments and capacity constraints. Finally, the problems draw upon 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.

The problems start out with some simplifying assumptions. This is done to isolate the focus on the roles of reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations in mineral industry transformation. First, it is assumed that all commercially interesting resources have been identified both onshore and offshore. Hence, the problems do not consider the process of converting resources to reserves, which includes exploration and more. Instead, the problems start out with the assumption of given reserves in each sector, which cannot be added to. Moreover, the problems disregard the full scale of competition in the mining sector, recycling, and the projected increase in demand. These simplifications represent abstractions from the real world but allow clear focus on the objectives of the study.

All problems consider one or two agents that aim to maximize the net present value of extraction from the reserves at their disposal by choosing capital investment and production rates. The agents maximize the objective function(s) 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 direct interaction between the two sectors is observed through the demand function, in which onshore and offshore production influence the price that both sectors receive for their production in the end-market.

The first problem considers a principal who invests and extracts to maximize the net present value of extraction from onshore and offshore reserves while facing reserve-independent capital efficiency. This scenario is far from realistic. However, it allows isolated study of the effects of reserve-dependence by establishing a baseline for comparison. The second problem considers the same as the first, except here the principal faces reserve-dependent capital efficiency, which is more realistic.

The third problem considers two principals, each representing one cartel, that invest and extract to maximize the net present value of extraction from their respective reserves subject to the decisions of the other cartel. For intuitive purposes, the reader can think of the two sectors as separated by ownership and geographical location while competing in the same well-functioning and stable international market. The terrestrial sector starts out as dominant, while the marine sector starts out as subordinate, or basically nonexistent.

The last problem considers a duopoly setting in which the principal responsible for the marine sector values both financial gain and mineral security. For intuition, the reader can think of the two sectors as separated by ownership and geographical location while competing in the same functioning but unstable and nervous international market, where the owner of the marine sector wants to hedge against possible future market disruptions to make sure it can satisfy a certain demand without supply from the terrestrial sector. The terrestrial sector starts out as dominant, while the marine sector starts out as subordinate, or basically nonexistent, just like in the third problem.

The following sections give detailed descriptions of the problems and their numerical specifications.

Problem 1: reserve-independence

Problem 1 is written as follows: $\underset{u_{i,t}\geq 0, I_{i,t}\geq 0}{\text{Max}} \sum_{t=0}^{T}\sum_{i=1}^{I} e^{-rt}\left(\frac{P_{max}}{1+P_c\sum_{i=1}^{2}u_{i,t}}u_{i,t} - \frac{\alpha_i u_{i,t}}{A_i} - \beta_i I_{i,t}^{\gamma_i}\right)$ subject to $x_{i,\ t+1}=x_{i,\ t}-u_{i,\ t}$, $k_{i,\ t+1}=k_{i,\ t}-d_i k_{i,\ t}+I_{i,\ t}$, $u_{i,\ t}\leq A_i k_{i,\ t}$,

$x_{i,t} \geq 0$, $k_{i,t} \geq 0$, given positive values of all parameters, and given initial values of all state variables. We define time $t=(0,1,\ldots,T)$ with T=200 years. However, the study assumes that the agents are mainly interested in what happens in the first 100 years. In other words, the agents are not interested in the end-phase, where the incentive for conservation goes to zero. Sector $i=(1,2)$ represents the terrestrial and marine sector, respectively. $u_{i,t}$ and $I_{i,t}$ denote the production and investment decisions, respectively. Furthermore, e^{-rt} is the discount factor, while P_{max} and P_c are price parameters, and α_i, β_i, and γ_i are cost parameters. $k_{i,t}$ and $x_{i,t}$ denote the capital levels and mineral reserve levels, respectively. Finally, d_i denote the depreciation rates, while A_i is a parameter that describes the factor productivity of capital in each sector.

The component $\frac{P_{max}}{1+P_c\sum_{i=1}^{2}u_{i,t}}$ represents the demand function, where P_{max} is the willingness to pay when supply is non-existent, and P_c is a curvature parameter. The demand function is a downward sloping convex curve starting at (0, P_{max}) with $\lim_{q(\ldots)\to\infty} P(\ldots)=0$—indicating that the willingness to pay for the resource becomes progressively higher for lower supply.

The component $\frac{\alpha_i u_{i,t}}{A_i}$ represents the operation costs, which are independent of the reserves. Although not directly visible, the operation costs are directly related to the employment of capital. The factor $\frac{u_{i,t}}{A_i}$ represents the level of capital needed to execute the production decision $u_{i,t}$. As such, the term $\frac{\alpha_i u_{i,t}}{A_i}$ is equal to $\alpha_i k_{i,t}$ when the production capacity constraint is binding, that is, when $u_{i,t}=A_i k_{i,t}$. However, since it is allowed for utilizing less capital than what is available, $u_{i,t} \leq A_i k_{i,t}$, the operation costs is represented by $\frac{\alpha_i u_{i,t}}{A_i}$, which means that the principal only pays operating costs proportionally to the capital in use, not the capital available for use. Relating to this, it is worth highlighting that the production constraint is reserve-independent in problem 1. This is the explanation as to why the operation costs are reserve-independent.

The term $\beta_i I_{i,t}^{\gamma_i}$ represents the investment costs, and $\gamma_i >$ 1 is imposed such that there are increasing marginal costs of investment in each sector. When compared to constant marginal costs of investment, 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.

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.

Although there are no direct costs relating to idle capacity, there are obvious indirect costs. 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 relatively low cost today and postponing production, which involve discounted revenue, and may involve costs tied to maintenance and/or re-accumulation of capital.

Problem 2: reserve-dependence

Problem 2 is similar to problem 1, except here $x_{i,t}$ affects the production capacity and amount of capital needed to execute a production decision. That is, the principal meets reserve-dependent capital efficiency. The problem is written as: $\underset{u_{i,t}\geq 0, I_{i,t}\geq 0}{\text{Max}} \sum_{t=0}^{T}\sum_{i=1}^{I} e^{-rt}\left(\frac{P_{max}}{1+P_c\sum_{i=1}^{2}u_{i,t}}u_{i,t}-\frac{\alpha_i u_{i,t}}{A_i x_{i,t}}-\beta_i I_{i,t}^{\gamma_i}\right)$ subject to $x_{i,t+1}=x_{i,t}-u_{i,t}$, $k_{i,t+1}=k_{i,t}-d_i k_{i,t}+I_{i,t}$, $u_{i,t}\leq A_i k_{i,t} x_{i,t}$, $x_{i,t}\geq 0$, $k_{i,t}\geq 0$, given positive values of all parameters, and given initial values of all state variables. Note that the model does not consider accessibility and ore grade explicitly. Instead, it assumes that the principal extracts the deposits in each sector in order of their attractiveness such that there is correlation between the size of the reserves in each sector, and the attractiveness of the current-best deposit. This is a common assumption in theoretical non-renewable resource economics (see, e.g., Chapter 5.6 Reserve-dependent Cost in Conrad (2010)).

Problem 3: cross-sector competition

Problem 3 is more complex than problem 1 and 2. Problem 3 involve both reserve-dependent capital efficiency *and* cross-sector competition. When dealing with cross-sector competition, we are interested in dynamic Cournot Nash equilibria (OECD 2013), which are obtained 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). The algorithm for problem 3 is outlined as follows:

- $\underset{u_{1,t}\geq 0, I_{1,t}\geq 0}{\text{Max}} \sum_{t=0}^{T} e^{-rt}\left(\frac{P_{max}}{1+P_c\sum_{i=1}^{2}u_{i,t}}u_{1,t}-\frac{\alpha_1 u_{1,t}}{A_1 x_{1,t}}-\beta_1 I_{1,t}^{\gamma_1}\right)$ subject to $x_{1,t+1}=x_{1,t}-u_{1,t}$, $k_{1,t+1}=k_{1,t}-d_1 k_{1,t}+I_{1,t}$, $u_{1,t}\leq A_1 k_{1,t} x_{1,t}$, $x_{1,t}\geq 0$, $k_{1,t}\geq 0$, given positive values of all parameters, and given initial values of all state variables, and given values for all variables relating to sector 2.
- Store the solutions relating to sector 1 and treat them as given in the next optimization step.
- $\underset{u_{2,t}\geq 0, I_{2,t}\geq 0}{\text{Max}} \sum_{t=0}^{T} e^{-rt}\left(\frac{P_{max}}{1+P_c\sum_{i=1}^{2}u_{i,t}}u_{2,t}-\frac{\alpha_2 u_{2,t}}{A_2 x_{2,t}}-\beta_2 I_{2,t}^{\gamma_2}\right)$ subject to $x_{2,t+1}=x_{2,t}-u_{2,t}$, $k_{2,t+1}=k_{2,t}-d_2 k_{2,t}+I_{2,t}$,

$u_{2,t} \leq A_2 k_{2,t} x_{2,t}$, $x_{2,t} \geq 0$, $k_{2,t} \geq 0$, given positive values of all parameters, and given initial values of all state variables, and given values for all variables relating to sector 1.
- Store the solutions relating to sector 2 and treat them as given in the next optimization step.
- Calculate the difference between newly obtained decision vectors and previously given decision vectors.
- If there is no significant difference between newly obtained decision vectors and previously given decision vectors, then report the last obtained decision vectors and exit the algorithmic procedure, else repeat the steps above.

Problem 4: mineral security considerations

Problem 4 is like problem 3 but with a key difference—in problem 4, the marine principal does not only value financial gain but also mineral security. This is incorporated by the inclusion of a new term $m_2 u_{2,t}$ in the objective function of the marine principal, in which m_2 is a parameter that adds a constant value to each unit of production. For the sake of intuition, this can be interpreted as a unit subsidy on production in the marine sector. The algorithm for problem 4 is:

- $\underset{u_{1,t}\geq 0, I_{1,t}\geq 0}{\text{Max}} \sum_{t=0}^{T} e^{-rt}\left(\frac{P_{max}}{1+P_c \sum_{i=1}^{2} u_{i,t}} u_{1,t} - \frac{\alpha_1 u_{1,t}}{A_1 x_{1,t}} - \beta_1 I_{1,t}^{\gamma_1}\right)$ subject to $x_{1,\ t+1} = x_{1,t} - u_{1,t}$, $k_{1,t+1} = k_{1,t} - d_1 k_{1,t} + I_{1,t}$, $u_{1,t} \leq A_1 k_{1,t} x_{1,t}$, $x_{1,t} \geq 0$, $k_{1,t} \geq 0$, given positive values of all parameters, and given initial values of all state variables, and given values for all variables relating to sector 2.
- Store the solutions relating to sector 1 and treat them as given in the next optimization step.
- $\underset{u_{2,t}\geq 0, I_{2,t}\geq 0}{\text{Max}} \sum_{t=0}^{T} e^{-rt}\left(m_2 u_{2,t} + \frac{P_{max}}{1+P_c \sum_{i=1}^{2} u_{i,t}} u_{2,t} - \frac{\alpha_2 u_{2,t}}{A_2 x_{2,t}} - \beta_2 I_{2,t}^{\gamma_2}\right)$ subject to $x_{2,\ t+1} = x_{2,t} - u_{2,t}$, $k_{2,t+1} = k_{2,t} - d_2 k_{2,t} + I_{2,t}$, $u_{2,t} \leq A_2 k_{2,t} x_{2,t}$, $x_{2,t} \geq 0$, $k_{2,t} \geq 0$, given positive values of all parameters, and given initial values of all state variables, and given values for all variables relating to sector 1.
- Store the solutions relating to sector 2 and treat them as given in the next optimization step.
- Calculate the difference between newly obtained decision vectors and previously given decision vectors.
- If there is no significant difference between newly obtained decision vectors and previously given decision vectors, then report the last obtained decision vectors and exit the algorithmic procedure, else repeat the steps above.

Numerical specifications

So far, the problems have been described in general notation—very little has been said about the numerical specifications of the problems. The numerical specifications represent fabricated values. However, they are chosen to articulate the units and values at play in parts of the mineral industry, e.g., the manganese mineral industry. Table 1 provides an overview of the parameters, their unit of measure, and their numerical specifications. Most important to note is that $x_{i=1,t=0} < x_{i=2,t=0}$, and $k_{i=1,t=0} > k_{i=2,t=0}$, and $A_1 > A_2$ are imposed in all problems.

The study assumes that the onshore reserves are smaller than the offshore reserves based on the fact that marine mineral deposits are thought to be abundant relative to remaining accessible onshore mineral deposits (Schulz et al. 2017, pp. F13, L10, L12).

Onshore capital is initialized at a positive level to make sure the onshore mining sector starts out with a significant production capacity. Marine capital is initialized at zero to reflect that the marine sector is in its infancy.

Onshore capital efficiency is set higher than marine capital efficiency to reflect that the marine mining sector is thought to be more capital-intensive than the onshore mining industry. In other words, all else equal, the onshore mining sector will have higher output per unit capital than the marine mining sector.

Finally, the reader should note that the numerical specification of the factor productivity parameters in problem 1 differ from the numerical specification of said parameters in problems 2, 3, and 4. The factor productivity parameter values are specified such that the onshore mining sector starts out with the same production capacity in all scenarios. This makes the solutions more comparable.

Results

The optimization problems are solved by use of GAMS and the KNITRO solver (GAMS 2022a). KNITRO implements both state-of-the-art interior point and active-set methods for solving non-linear dynamic optimization problems (GAMS 2022b). This makes it well suited for solving the problems presented here. For the interested reader, we have made our code available on GITHUB (Bang and Trellevik 2022). The GITHUB repository also contains instructions on how to solve the scenarios

Table 1 Numerical specifications of the dynamic optimization problems

Parameter	Units	Problem 1	Problem 2	Problem 3	Problem 4
$x_{i=1,\,t=0}$	Thousand tons	2,000,000	2,000,000	2,000,000	2,000,000
$x_{i=2,\,t=0}$	Thousand tons	3,000,000	3,000,000	3,000,000	3,000,000
$k_{i=1,\,t=0}$	Capital units	40	40	40	40
$k_{i=2,\,t=0}$	Capital units	0	0	0	0
r	Dimensionless	0.05	0.05	0.05	0.05
P_{max}	Billion USD per thousand tons	0.006	0.006	0.006	0.006
P_c	Dimensionless	0.0001	0.0001	0.0001	0.0001
m_2	Billion USD per thousand tons	-	-	-	0.0005
α_1	Billion USD per unit employed capital	0.3	0.3	0.3	0.3
α_2	Billion USD per unit employed capital	0.3	0.3	0.3	0.3
β_1	Billion USD per unit investment raised by the power of γ_1	0.5	0.5	0.5	0.5
β_2	Billion USD per unit investment raised by the power of γ_2	0.5	0.5	0.5	0.5
γ_1	Dimensionless	1.1	1.1	1.1	1.1
γ_2	Dimensionless	1.1	1.1	1.1	1.1
A_1	Production per unit employed capital/production per unit employed capital per size of reserves	600	0.0003	600	0.0003
A_2	Production per unit employed capital/production per unit employed capital per size of reserves	300	0.0001	300	0.0001
d_1	Dimensionless	0.1	0.1	0.1	0.1
d_2	Dimensionless	0.1	0.1	0.1	0.1

presented in this study. In the following, we present the solutions to the problems.

Figure 1 provides an overview of the solution to problem 1, i.e., the monopoly case with reserve-independent capital efficiency. 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).

The solution to problem 1 indicates that it is optimal to extract in order of increasing unit extraction costs, aligned with Herfindahl (1967), Solow and Wan (1976), and others. However, since the terrestrial reserves do not get depleted within the first 100 years, there is no transition to marine mining. Problem 1 is solved with a doubling of the factor productivity parameters to confirm that the characteristics of the solution align with existing theory and research. The solution is shown in Appendix Fig. 9 and illustrates what a transition would look like in the monopoly-case with reserve-independent capital efficiency. The solution clearly confirms what was already indicated by the solution in Fig. 1.

On one hand, the solution to problem 1 is 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. Moreover, the solution to the problem helps identifying the ceteris paribus effects of reserve-dependent capital efficiency by serving as a baseline solution for comparison.

Figure 2 provides an overview of the solution to problem 2, i.e., the monopoly case with reserve-dependent capital efficiency. The optimal behavior is different to the behavior witnessed 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. However, since the terrestrial reserves did not get depleted within the first 100 years, we witnessed no transition to marine mining within the given time horizon. In the solution to problem 2, we witness extraction in order of increasing extracting costs, just like in the solution to problem 1. However, in problem 2, 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 dependent on the size of the reserves. As such, the reserve-dependent model allows for switching between what resource stock has the highest unit extraction costs.

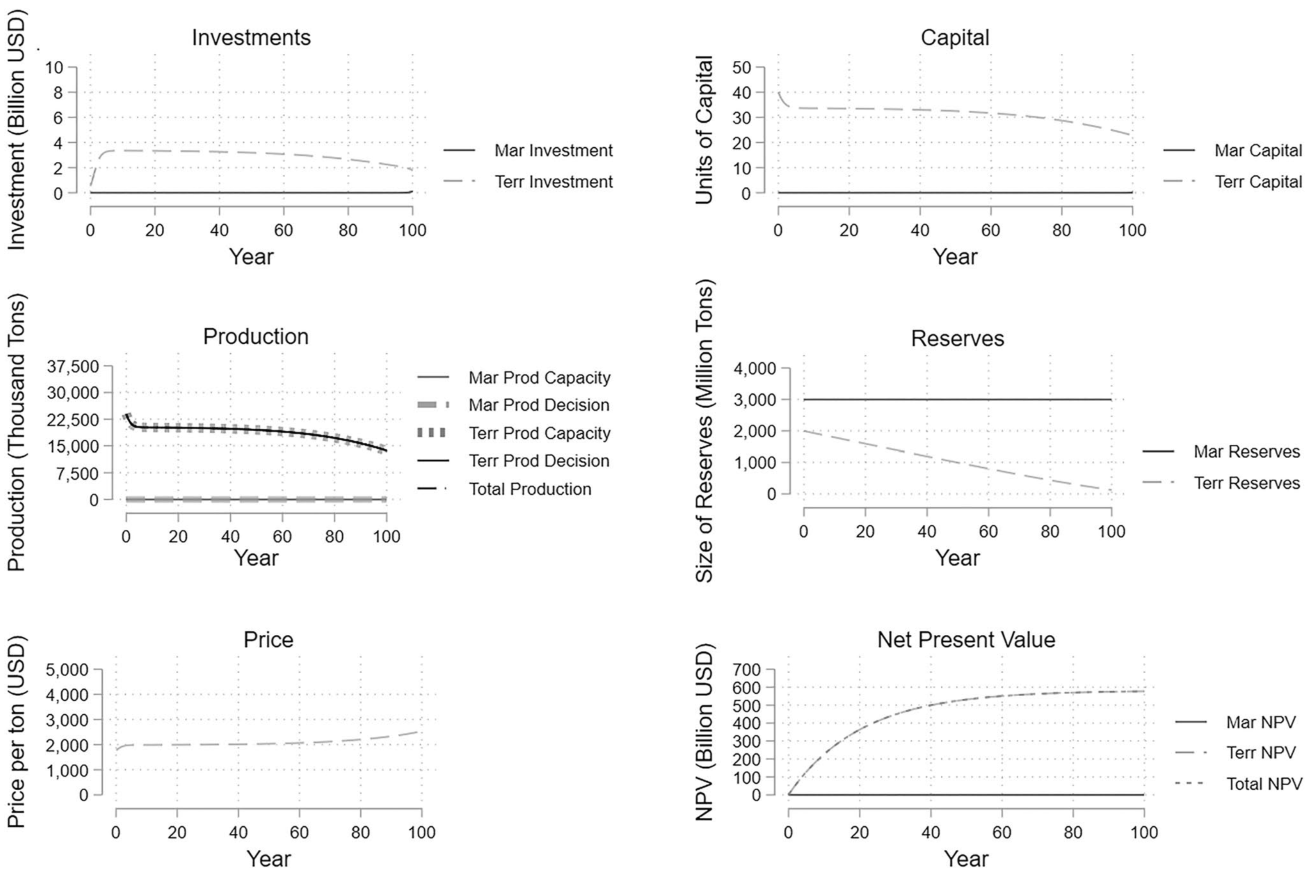

Fig. 1 Solution to problem 1: reserve-independent capital efficiency, no competition, and no mineral security considerations

The initial marine reserves are abundant relative to terrestrial reserves, while initial marine capital is low relative to terrestrial capital. 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. Moreover, the marine total factor productivity is lower than the terrestrial total factor productivity. The lower marine total factor productivity has negative effects on the relative attractiveness of marine investment.

Figure 2 clearly shows that the additional abundance of marine reserves does not fully compensate for the lower marine total factor productivity and the marine disadvantage of no initial capital. Therefore, the principal begins with onshore extraction, just like in the monopoly scenario with reserve-independent capital efficiency (see Fig. 1 vs. Fig. 2). However, 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.

Figure 3 provides an overview of the solution to problem 3, i.e., the duopoly case with reserve-dependent capital efficiency. The solution to this problem sketches out a different behavior than those observed in the monopoly scenarios.

In line with what to expect from an increase in competition, total production is higher in the duopoly scenario with reserve-dependent capital efficiency when compared to the monopoly scenario with reserve-dependent capital efficiency. Consequentially, the price is also lower through this period (Fig. 2 vs. Fig 3). Consistent with 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. And the marine NPV is much higher in the duopoly scenario with

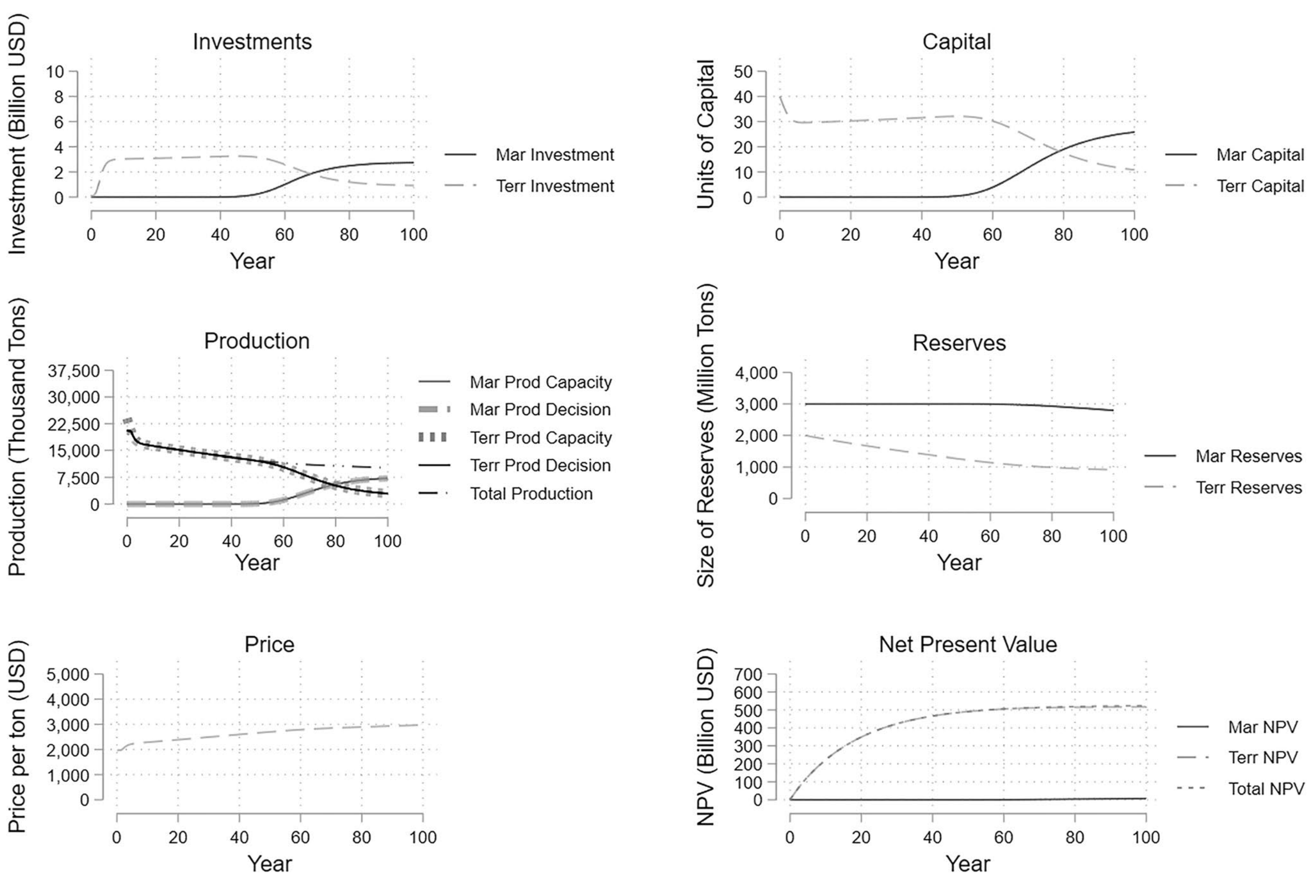

Fig. 2 Solution to problem 2: reserve-dependent capital efficiency, no competition, and no mineral security considerations

reserve-dependent capital efficiency than in the monopoly scenario with reserve-dependent capital efficiency. More surprisingly, the transition to an industry with marine production starts already at time zero.

Figure 4 provides an overview of the solution to problem 4, i.e., the duopoly case with reserve-dependent capital efficiency and marine mineral security considerations.

The solution to problem 4 is similar to the solution to problem 3. However, when compared to the solution to problem 3, the introduction of marine mineral security consideration leads to a significant increase in the marine investments and production, resulting in an overall much higher production.

Sensitivity analysis

Several changes can be considered in a sensitivity analysis here—ranging from changes in the initial values of the state variables, to changes in the discount rate, price parameters, cost parameters, productivity parameters, and the depreciation rates of capital, across all four scenarios. However, the analysis concentrates on how changes in P_{max}, γ_2, A_2, and m_2 affect the solutions to problem 3 and 4. Together, these changes offer broad insight to how changes in various types of parameters affect the optimal solutions in the cross-sector competition scenarios.

Specifically, we consider the following questions. How does the solution to problem 3 respond to a 20% increase in the price parameter P_{max}? How does the solution to problem 3 respond to a doubling of the investment cost exponent γ_2? How does the solution to problem 3 respond to a doubling of the factor productivity of marine capital A_2? And how does the solution to problem 4 respond to a doubling of the mineral security consideration parameter m_2?

Figures 5, 6, and 7 show the solutions to problem 3 with a 20% increase in P_{max}, a doubling of γ_2, and a doubling of A_2, respectively. Figure 8 shows the solution to problem 4 with a doubling of m_2.

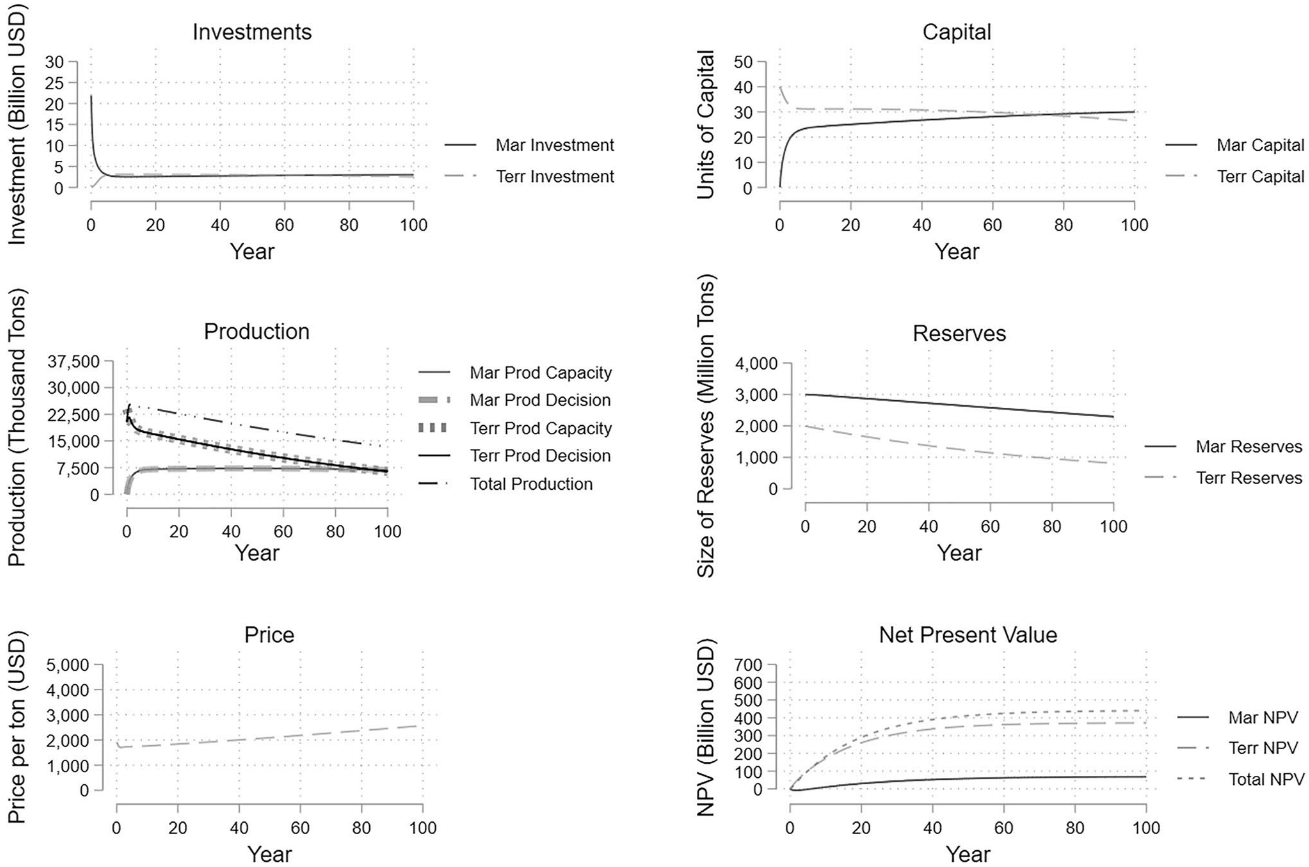

Fig. 3 Solution to problem 3: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

The sensitivity results show that an increase in P_{max} increases the extraction in both sectors, but relatively more in the marine sector compared to the terrestrial sector, which is interesting, as it indicates that the marine sector has more to gain from an increase in demand than the terrestrial sector (Fig. 5). The increase in γ_2 weakens the competitive ability of the marine sector, and prolongs the build-up time of marine capital, both of which lead to different behavior and overall reduced marine extraction (Fig. 6). Interestingly, the terrestrial sector does not respond to this by increasing its extraction, but rather choose to reduce it slightly. The weak negative extraction response in the terrestrial sector is explained by the fact that it gains more market power and works to push the production schedule towards the monopoly solution (Fig. 6 vs. Fig. 2). A doubling of the marine factor productivity turns the marine sector into the dominant producer, even though it starts out with no initial capital and must take on large investment costs to build up capital for production (Fig. 7). This goes on to show that the marine mining sector could leverage its advantage of abundant resources if it finds a reasonable approach to extraction. A doubling of m_2 also turns the marine sector into the dominant producer (Fig. 8).

Discussion

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, outside the given time horizon of interest. The behavior exhibited in this solution is aligned with theory and common sense. The problem is unrealistic, and the solution is unsurprising. However, it serves a purpose by validating the model's functionality and establishing a baseline for comparison.

Reserve-independent capital efficiency suggests that mineral sites are equally accessible and that the mineral concentration and distribution in mines are uniform, onshore, and offshore, respectively. However, accessibility and ore grades are in decline, increasing the unit

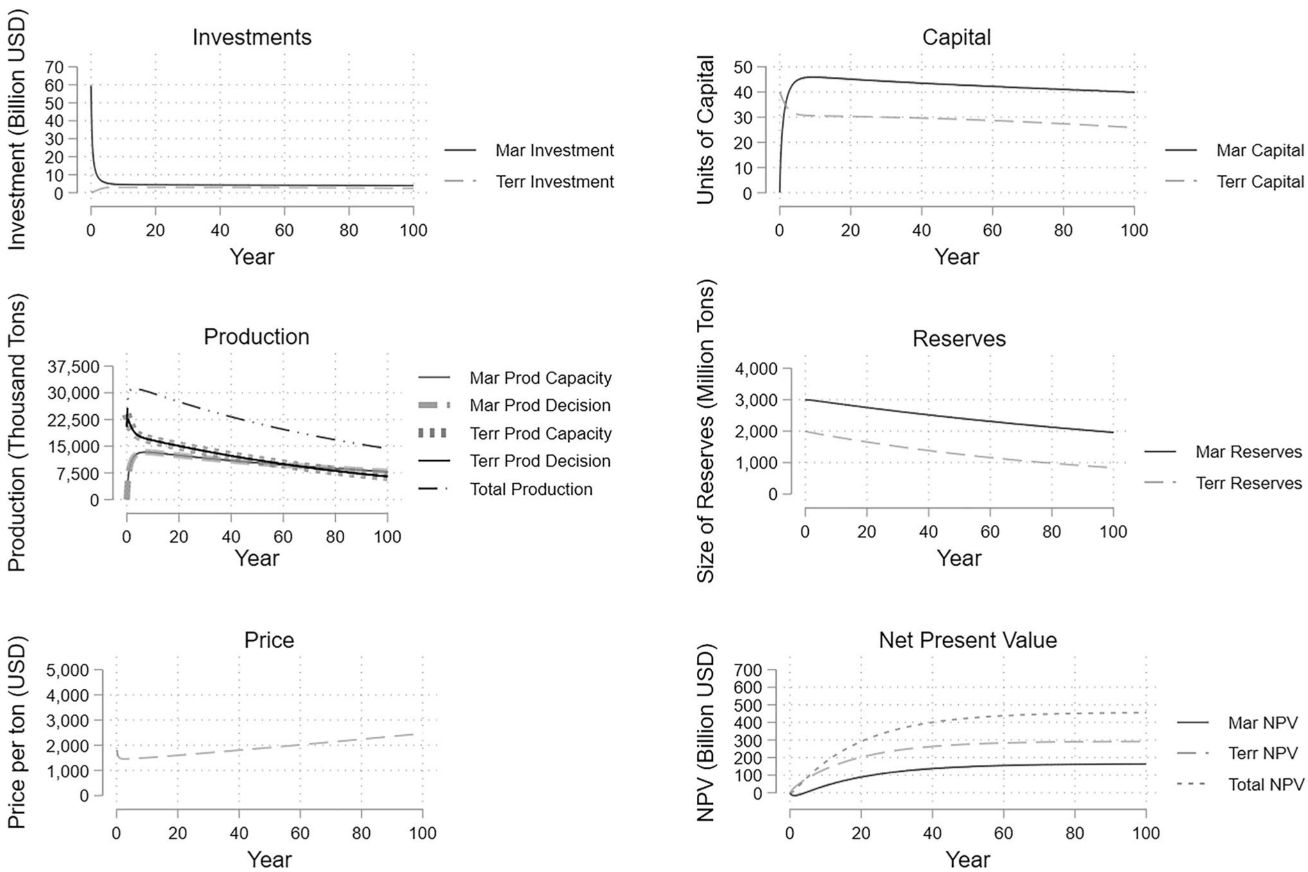

Fig. 4 Solution to problem 4: reserve-dependent capital efficiency, cross-sector competition, and asymmetric mineral security considerations

costs of extraction (International Energy Agency (IEA) 2021; Ragnarsdóttir 2008; Schulz et al. 2017; Sverdrup et al. 2019). Such development can also be expected in a possible marine industry after possible initiation and prolonged marine mining—rational miners will prefer to start with the most accessible sites with the highest ore grade before moving on to less accessible sites with lower ore grade (given full knowledge of all resources).

The second scenario, which considers a monopoly situation with reserve-dependent capital efficiency, demonstrates the effects of declining accessibility and ore grade. The conceptual results show that a transition to marine mining will occur well before the terrestrial reserves near depletion, at a much earlier point in time, within the given time horizon. Moreover, the results indicate a transition to an industry with co-existing terrestrial and marine mining. Under monopoly conditions, there is no competition driving the transition, yet the principal maximizes profits by entering marine mining early to offset the effects of declining ore grade or accessibility in terrestrial resources. As such, these results clearly indicate that reserve-dependence can drive a possible transition. This suggests that the observed real-world phenomena of declining ore grade and accessibility can play a significant role in the future development of the mining industry, for example, to include extraction of less accessible but higher-grade ore, which marine mineral deposits may represent.

The duopoly configuration of the model abstracts two phenomena—the emergence of a marine mining sector that is separate from the existing onshore mining sector in terms of ownership, and a changing geopolitical environment for minerals supply. The geographical distribution of minerals, including both onshore and offshore minerals, can indicate separate onshore and offshore owners, implying possible cross-sector competition between the existing onshore industry and an emerging marine industry. There have already been several initiatives to advance the emergence of a commercial marine mining industry. For decades, different

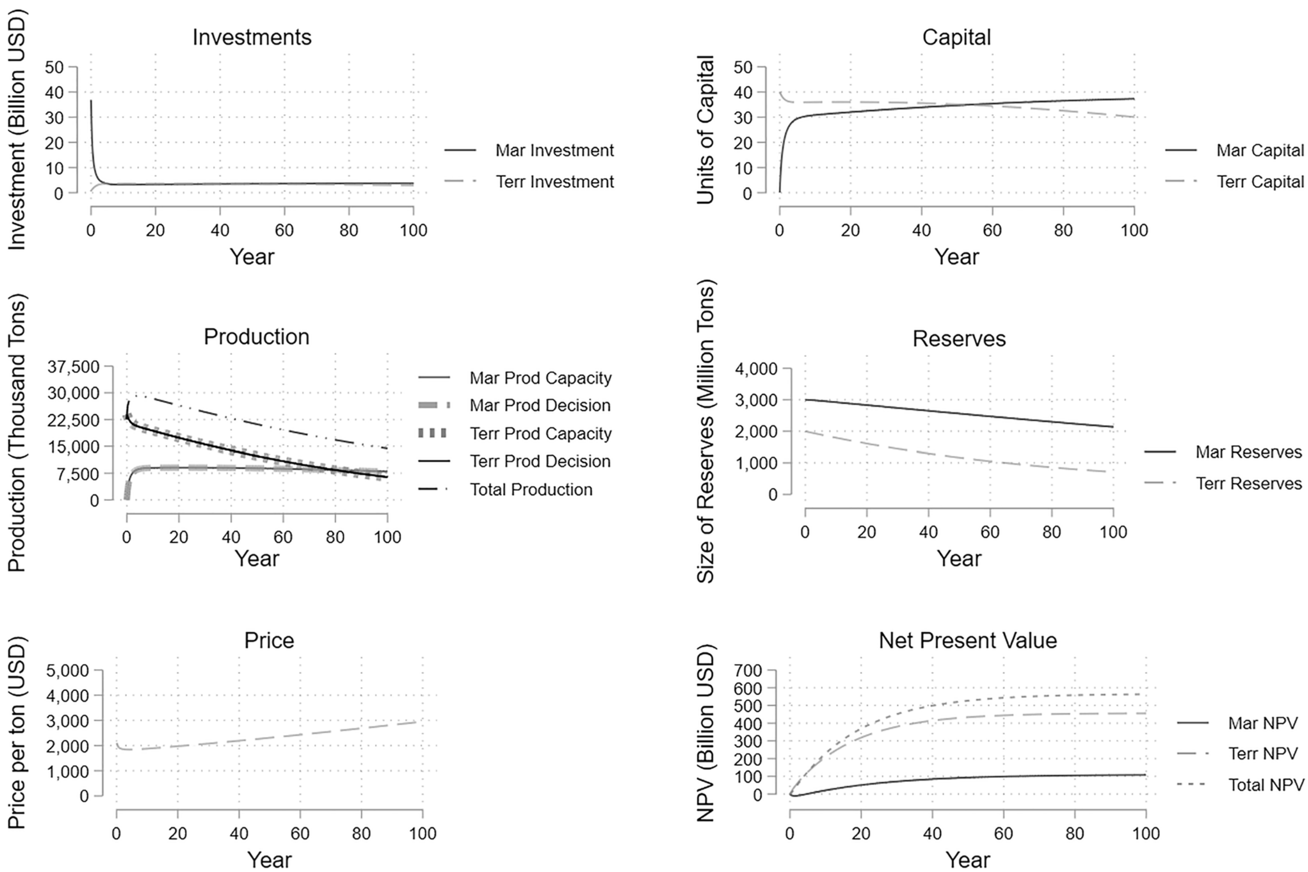

Fig. 5 Solution to problem 3 with 20% increase in P_{max}: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

national, international, and private organizations have worked towards establishing commercial marine mining (Boomsma and Warnaars 2015; Childs 2020; Sparenberg 2019; Volkmann and Lehnen 2018). Even though no commercial success has been achieved as of May 2022, the initiatives to develop technology, legislation, and commercial entities to extract minerals from the seabed continue to persist outside interest spheres that are currently dominating mineral supply.

In the duopoly situation with reserve-dependent capital efficiency, but without mineral security considerations, the results indicate an immediate and powerful transition to an industry with co-existing terrestrial and marine mining. Now, this scenario is interesting because it truly shows the effect of competition on transition in a resource-based, resource-scarce, and profitable industry. Considering the development in the onshore mining industry, with falling ore grades and increasing extraction costs, it is useful to demonstrate that reserve-dependence and cross-sector competition can trigger transition towards marine mining.

The geopolitical divides made evident by the full-scale Russian invasion of Ukraine in 2022 actualize the duopolistic model configuration with asymmetric mineral security considerations. In the wake of the war in Ukraine, the European Union responded almost immediately by declaring the urgency of a diversified supply of critical raw materials (European Council 2022). As such, the two competing cartels may be considered a simplified representation of, e.g., a western interest sphere on the one side and a Russo-aligned interest sphere on the other. Moreover, it is not farfetched to suggest that interests in mineral security can result in support schemes for further development of the European mining industry, including marine mining—i.e., Europe assigning additional value to independent European extraction of minerals beyond the financial gain from extraction.

The results from the duopoly scenario with reserve-dependent capital efficiency and marine mineral security considerations indicate an immediate transition to an industry with co-existing terrestrial and marine mining, just like in the duopoly scenario with reserve-dependent

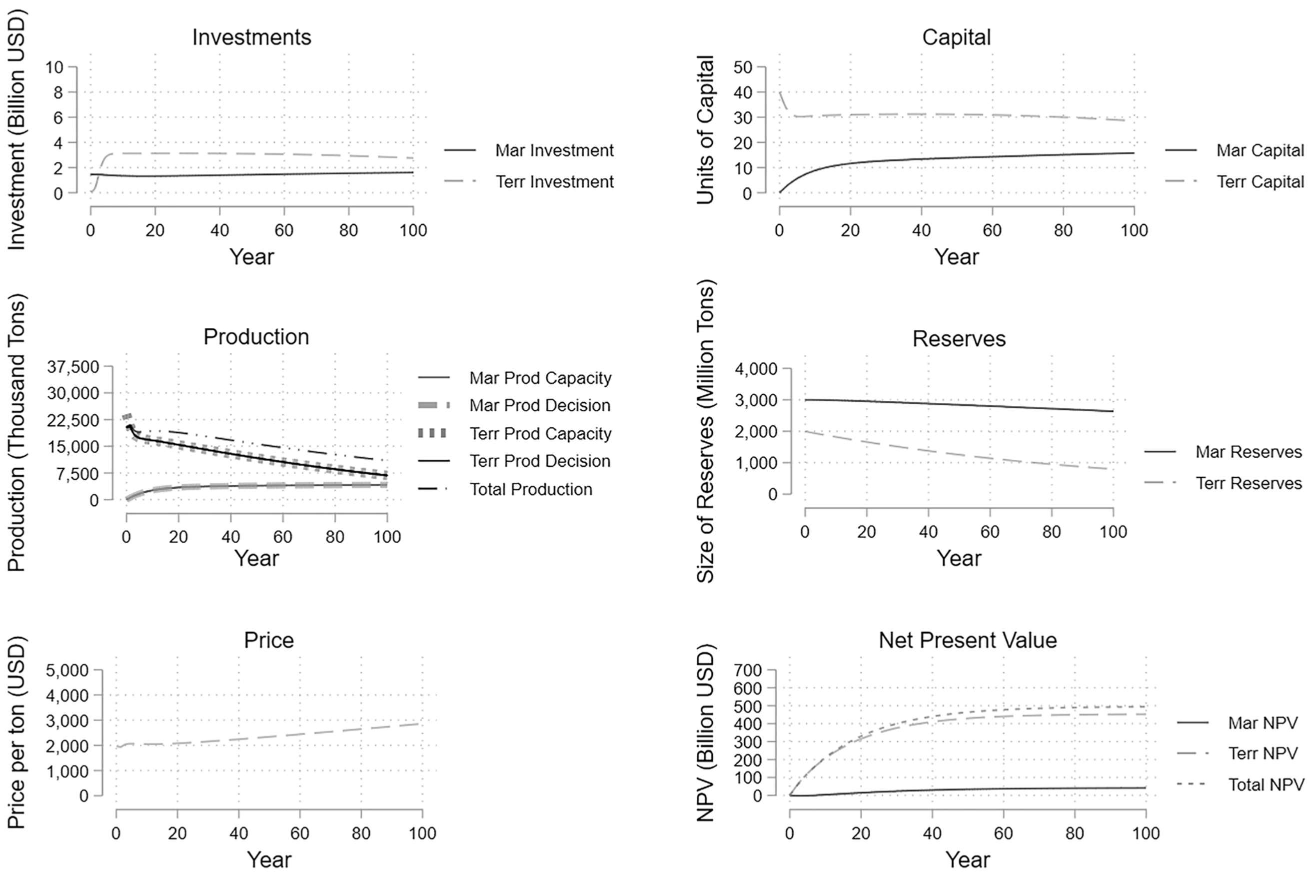

Fig. 6 Solution to problem 3 with doubling of γ_2: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

capital efficiency and no mineral security considerations. However, in the duopoly scenario with reserve-dependent capital efficiency and mineral security considerations, the marine mining sector increases initial investments and extraction, leading to an overall much higher production. As such, these results also show that mineral security considerations can help drive transition to marine mining.

Security considerations have received considerable attention in lieu of the 2022 invasion of Ukraine. In the Versailles declaration of March 2022, the European Council expressed intent to secure access to critical materials (European Council 2022). This makes the insight from the solution to problem 4 highly relevant and can be encouraging to those organizations already investing in the development of a marine mining industry. That said, the reader should also note that European mineral security considerations can also impact the terrestrial mining sector in the European sphere of allies—it would not only impact marine mining. As such, European mineral security considerations need not have an as strong asymmetric effect upon a transition to marine mining as sketched out by our results.

Although our results indicate that an industry with both onshore and offshore mining may be near, and that a transition may happen quickly, we must remind the reader that our model and analysis is conceptual, and that there are certain limitations. First, the model does not consider exploration, costs tied to innovation, technological development, delays, nor externalities. Second, the numerical specifications of our problems represent fabricated values—as such, they are only meant for illustrative purposes and cannot be considered realistic, although they do have some empirical grounding. A more realistic model would consider at least some of the forementioned factors. And a model that incorporate these factors may sketch out a different transitional behavior than the ones outlined in the solutions to the problems presented here. As such, our results should not, and cannot, be considered forecasts.

Regarding the missing factors, we can only speculate how they would affect a transition. For example,

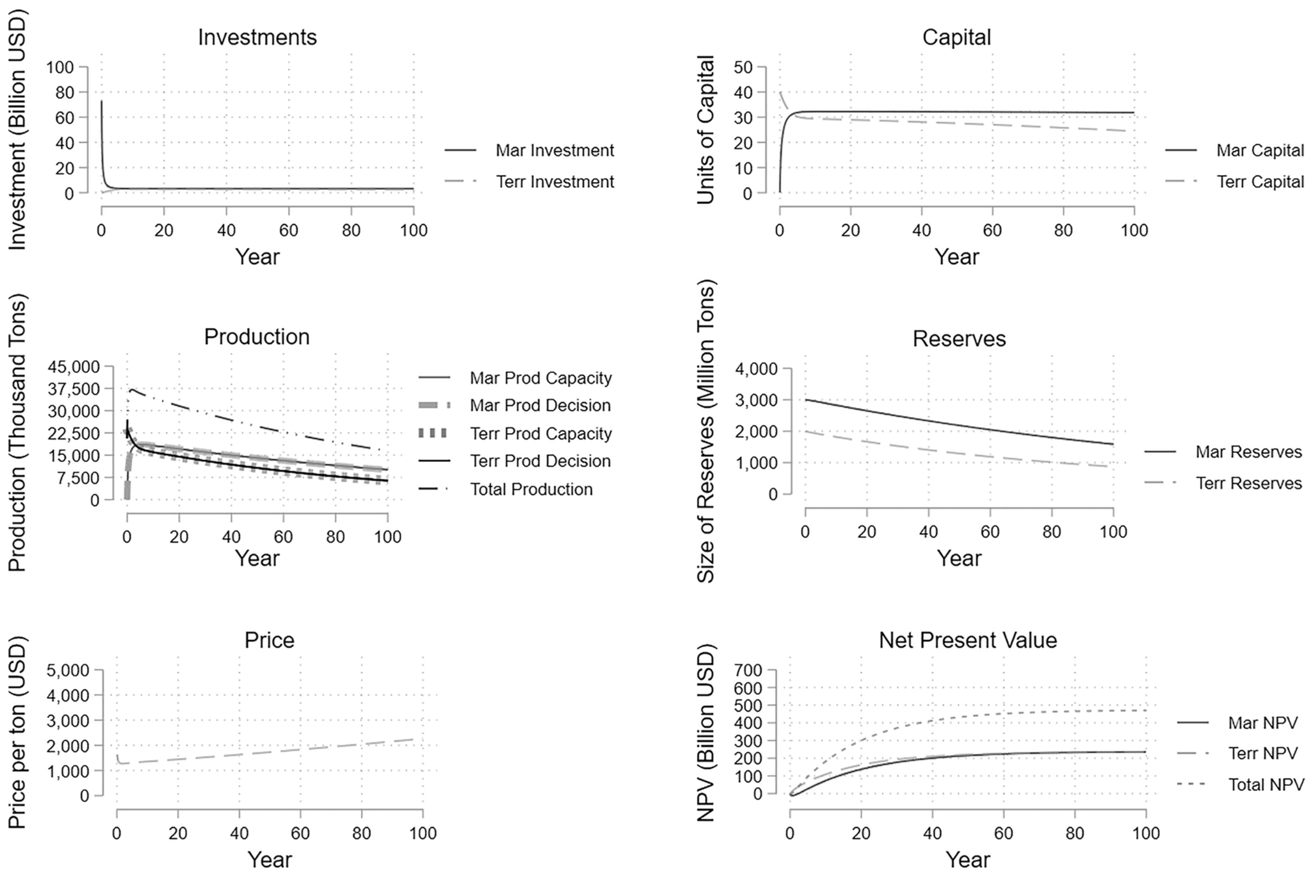

Fig. 7 Solution to problem 3 with doubling of A_2: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

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. Moreover, in the real world, significant new mineral discoveries can be made onshore, and onshore technology could improve significantly relative to marine technology. New onshore discoveries and development in onshore mining technology could impede the emergence of marine mining. Furthermore, it is possible that inclusion of delays and costs tied to innovation would hamper a transition, 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 accelerates (until reaching some desired level, and thereafter decline). This seems reasonable because investment-delivery delays infer that expenditure occur today, while the benefits are reaped much later, and as such, discounted harder. Furthermore, it seems reasonable to argue that the costs of acquiring one unit of production capital are high when the technology is not yet invented, because time and money must be invested in research and development.

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 (Niner et al. 2018; Sharma 2017, pp. 445–507; Van Dover et al. 2017; Wakefield and Myers 2018). Such considerations could also be built into models for future research on mineral industry transition. In such a case, one must also consider 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.

Conclusion

This study pinpoints three highly relevant factors that can play important roles in a possible transition to marine mining, namely reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations. Furthermore, it investigates how these factors can

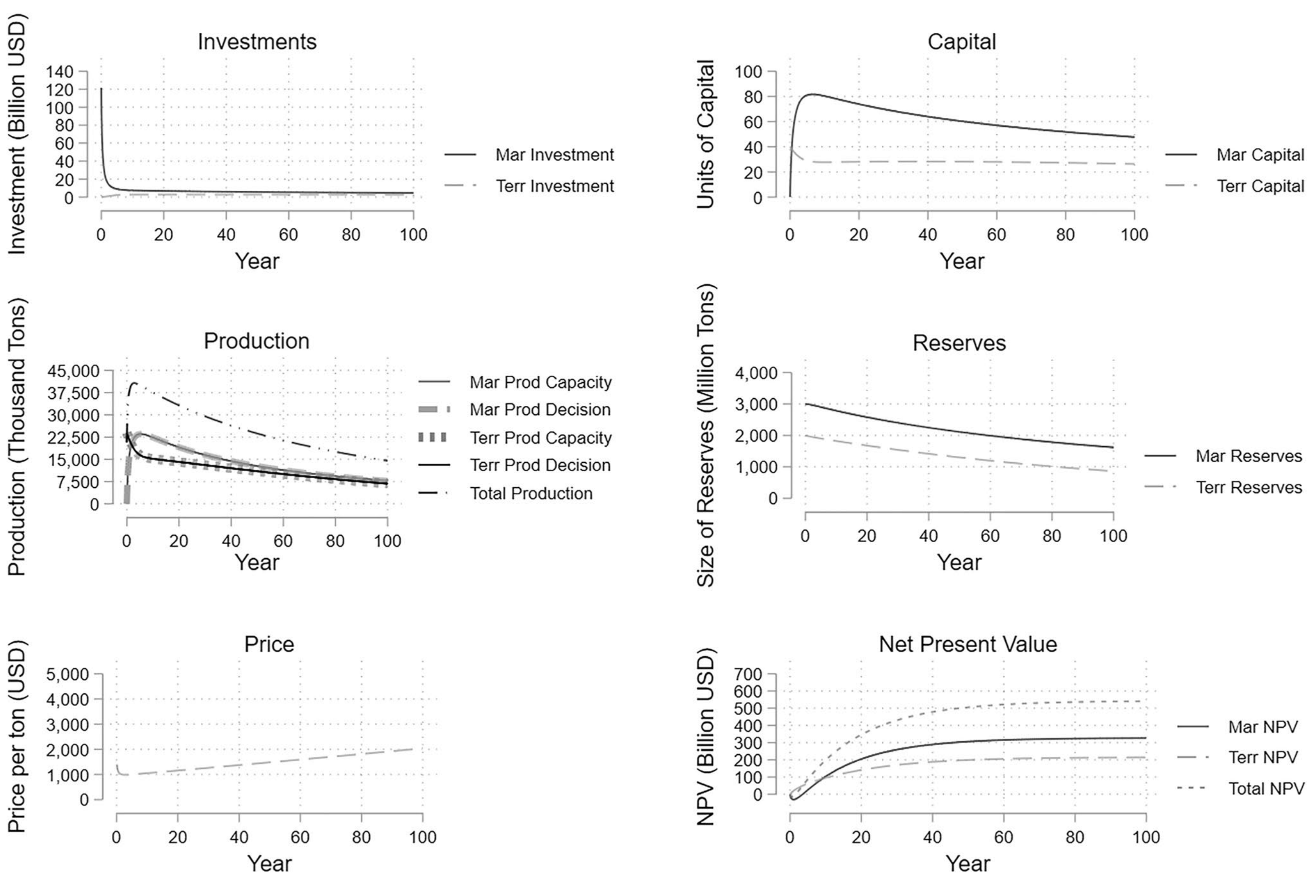

Fig. 8 Solution to problem 4 with doubling of m_2: reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations

affect a transition. The optimization results and sensitivity analysis indicate that all three factors can catalyze transition to marine mineral extraction.

Today's terrestrial mining sector is turning towards lesser deposits with lower accessibility and ore grade to meet demand. As a result, onshore miners experience increasing unit extraction costs. By studying development trajectories when miner(s) face reserve-independent and reserve-dependent capital efficiency, we were able to isolate and illustrate the effect of reserve-dependency on a transition to marine mining. The relevant results suggest that the phenomenon of reserve-dependency can initialize or strengthen the emergence of a marine mining industry.

Although there is no commercial extraction of marine minerals in 2022, several technological, legislative, and commercial initiatives are ongoing. Considering decreasing ore grades and accessibility on land, the model results suggest that competition can trigger or strengthen the emergence of commercial marine mineral extraction. However, that said, we also highlight that new mineral discoveries onshore, and development in onshore mining technology, may hamper a transition to marine mining.

In the wake of the 2022 war in Ukraine, the European Union has expressed an explicit intent to secure the supply of critical materials, which may imply future European support schemes to the mineral industry in Europe, including a possible marine mining industry. When studying a situation in which the marine agent who make decisions on behalf of marine resource owner(s), government(s), and producer(s), value mineral security, while the onshore agent does not, the model results show that mineral security can accelerate the emergence of a marine minerals industry. However, in the real world, mineral security considerations may also have a positive impact on existing onshore industry. This is of course also of relevance to when a possible transition may occur.

Appendix

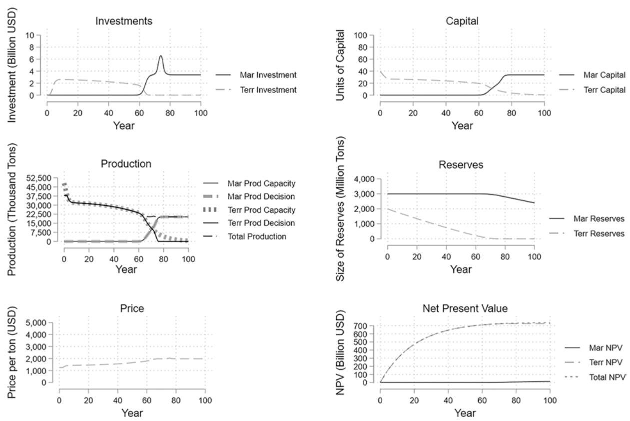

Fig. 9 Solution to problem 1 with doubling of A_1 and A_2: reserve-dependent capital efficiency, no competition, and no mineral security considerations

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Author contribution The authors have contributed to the project on equal terms.

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Declarations

The authors declare no competing interests. The author, Lars-Kristian Trellevik, who has 15 years of onshore and offshore industry experience with surveying/exploration, salvage, and autonomous operations, works as an external technical (survey and mapping) consultant for a company that aims to take part in the potential future marine mineral industry in Norway. However, the author's work here has no ties or direct relevance to his work as a consultant for that company.

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