IMPLEMENTING PRECAUTION IN BENEFIT-COST ANALYSIS: THE CASE OF DEEP SEABED MINING

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Abstract

The cumulative extraction of terrestrial mineral deposits has lead the mining industry to begin exploring seabed resources. The prospect of commercialized seabed mining poses major regulatory challenge for the International Seabed authority and countries with mineral resources in their coastal jurisdictions. The EU and the World Bank have initiated projects to build capacity to manage seabed mining activities. A particular concern is the nature of the economic evaluation that should be required for the assessment of mining leases. This study reviews the academic literature on economic decision-making under deep uncertainty, and makes recommendations for incorporating precautionary measures within the benefit-cost analysis of seabed mining operations.

1. Introduction

The possibility of commercializing deep seabed mining (DSM) has generated significant interest and controversy. Large concentrations of minerals are found on ocean floors, often in comingled deposits that can include some combination of manganese, silver, gold, cobalt, nickel, zinc, and rare earth elements. The cumulative terrestrial extraction of these minerals has reduced their concentrations and accessibility on dry lands, and some terrestrial supply regions are politically unstable. Against this backdrop, the mining industry has projected a global rise in the demand for minerals, as markets for advanced battery technologies and alternative energy sources develop (Heffernan, 2019).

Seabed minerals are located in international waters known as "the Area," which the International Seabed Authority (ISA) administers, and are also found in the jurisdictional waters of coastal countries (hereafter, "national jurisdictions").[1] In the past two decades, exploratory leasing has significantly increased in the seabeds of both of these regions. As of this writing, the ISA has granted 30 exploration leases to contractors from countries in Europe, Asia, Cuba, Russia, and the Pacific Islands,[2] while Pacific Island countries have issued over 300 exploration leases (World Bank 2017). The ISA has also drafted a mining code, with the finalized regulations scheduled to be issued in 2020 after review and revision.[3] Even if the mining code is issued on schedule, however, regulatory reviews, technology constraints, and financing issues are likely to delay the industry's start-up for a number of years (Heffernan, 2019).

In fact, the DSM industry faces a number of uncertainties. The technology is being adapted from terrestrial mining technologies, but the reliability of this equipment has not been demonstrated under operating conditions. The mining industry is optimistic about minerals futures,[4] but the price of minerals historically have fluctuated widely (Christian, 2009). New technology development sometimes offers a first-mover advantage (Childs and Triantis, 1999), but free-riding on the technology development or sunk costs of other firms can also give a second-mover advantage (Hausman and Myers, 2002; Pindyck, 2005). In the case of DSM, mineral deposits discovered through exploratory activities cannot be listed as "reserves" in firms' asset valuations until the extraction technology is demonstrated. This offers a powerful "second mover advantage," as the first firm to demonstrate the technology will enable the entire industry to claim discovered deposits as resource reserves (Land, 2018). Financing risks, and the financial stability of mining firms, are also of concern.

The environmental risks associated with DSM have generated significant attention from researchers, stakeholders, and regulatory authorities (Le et al., 2017; Levin et al., 2016; Dunn et

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[1] "National jurisdictions" are defined herein as the territorial waters of sovereign nations, their associated exclusive economic zones (EEZs), and continental shelf extensions of EEZs as defined in international law. The seabed mineral rights in these regions are under the jurisdictions of sovereign nations. The "Area" comprises the residual waters not under national jurisdiction.

[2] See International Seabed Authority: Deep Seabed Minerals Contractors.

[3] Draft regulations on the exploitation of mineral resources in the Area, International Seabed Authority; Comments on the draft regulations on the exploitation of mineral resources in the Area.

[4] See "China leads the race to exploit deep sea minerals: UN Body." Reuters Business News, October 23, 2019.

al., 2019). Exploratory leasing has generated information about seabed ecosystems, but the quality of baseline environmental information is poor, and knowledge of environmental impacts is uncertain (World Bank, 2017, 2018; Dunn et al., 2018; Washburn et al., 2019). Seabed mining in the waters of national jurisdictions raises concerns about the biodiversity impacts on continental shelves, and impacts of maritime activities on local economies and cultures.

As DSM steps in the direction of commercialization, weighing the benefits and risks of mining lease proposals will be an important task for the ISA, and national jurisdictions. DSM involves siting an industrial facility in a novel environment with unknown risks, and distributing profit shares in the form of royalties and/or equity stakes in the mining operation. An integrated stakeholder benefit-cost analysis is a necessary condition to assure that the returns from the project are sufficient to justify initiation. The uncertainties associated with acceptable project performance are "deep" or "fundamental", as these terms are used in the decision science literature on uncertainty evaluation e.g., Knight, (1921); Lempert et al., (2013a); Walker et al., (2013). As such, the use of benefit-cost analysis to evaluate DSM lease proposals faces similar challenges as the evaluation of projects to reduce or adapt to global climate risks.

The goal of this article is to offer methodology guidance for the economic evaluation of DSM lease proposals that reflect the unique attributes of seabed mining. We draw on insights from a JBCA symposium "Perspectives on Implementing Benefit-Cost Analysis in Climate Assessment in 2014," and reports from the European Union and the World Bank completed as part of a capacity building program with the Pacific Community to support DSM decision-making in Pacific Island countries.[5] We also review academic literature on ways of incorporating a precautionary element into economic evaluation, including literature on safe minimum standards; sequential decision making, involving real options and adaptive environmental management approaches; and "bottom up" or "robustness-based" decision methods.

To begin this assessment, the next section provides some background on deep seabed mining. Section 3 then describes the uncertainties that can arise in DSM project evaluation, and overviews uncertainty evaluation perspectives that can be incorporated into benefit-cost analysis. Section 4 develops three methods of incorporating precaution into the benefit-cost analysis of DSM projects. Section 5 reviews and evaluates an EU-sponsored Benefit-Cost Analysis of deep seabed mining (Cardno, 2016; Wakefield and Myers, 2018), and suggests an alternative way to structure the DSM evaluation. Section 6 discusses the key findings and offers a conclusion.

2. Deep Seabed Mining

Seabed minerals are found in several kinds of formations. Polymetallic Sulfides (also known as "seafloor massive sulfides (SMS)") occur on active and inactive hydrothermal vents located on mid-ocean ridges at tectonic plate boundaries in areas of active volcanism. Cobalt-rich crusts are found on the surfaces of sea mounts. Polymetallic nodules (also known as manganese nodules)

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[5] The articles from the JBCA symposium include Lempert (2014), Sussman et al., (2014a, 2014b); and Toman (2014). Reports and articles stemming from the EU and World Bank program with the Pacific Community include Cardno (2016), Wakefield and Myers (2018), and World Bank (2017, 2018).

are scattered on the surface of abyssal plains in deep ocean waters (World Bank 2017). Polymetallic nodules on seabeds in the Clarion–Clipperton Zone (CCZ) – a broad expanse in the Pacific Ocean between Hawaii and Baja California -- may contain more cobalt, magnesium, and nickel than the total known terrestrial deposits of these minerals (Hefferman, 2019).

The ISA has issued eighteen exploratory contracts for polymetallic nodules (16 in the CCZ, and two in the Indian Ocean); seven for seafloor massive sulfides (SMS) in the South West Indian Ridge, Central Indian Ridge and the Mid-Atlantic Ridge; and five for cobalt-rich crusts in the Western Pacific Ocean (See Footnote 2). In 2011, Papua New Guinea issued the first (and so far only) mining license to the Nautilus Mining company for the purpose of developing SMS deposits in an area 16 km off the coast of New Ireland. Known as the Solwara project, this lease contained 12 proposed sites, which were to be developed over a 20 year period. However, financing difficulties and local opposition aborted the Solwara project, [6] and the mining polymetallic nodules in the CCZ zone is now seen as the most likely start of the DSM industry (Heffernan, 2019). (See Footnote 4). There is still considerable interest in SMS mining, however (Dunn et al., 2018). The mining of cobalt crusts seems to be a more distant prospect.

DSM will involve several components. A production support vehicle (PSV) will be located on the ocean surface directly above the mine site, while mining equipment, adapted to the specific type of mineral deposit, will be used to excavate minerals from the seafloor. A riser/lift system will convey the extracted mixture of minerals, sediments, and water from the seabed to the PSV. At the PSV, a dewatering process will be used to remove minerals from the solution in which they are suspended. The dewatered minerals will then be loaded onto barges and shipped to onshore processing facilities, with the return water pumped back down the riser/lift system. The PSV will control the entire operation (World Bank 2017).

The different mineral formations are located at different depths, and the extraction periods and mining footprints will vary (World Bank, 2017). Seamounts with cobalt-rich crusts range in depth from 800 to 2,500 meters. Mining is expected to take place over a 20 year period. For the site located in the national waters of the Marshall Islands in the EU-sponsored benefit-cost analysis (Cardno 2016) – hereafter, "the EU BCA" -- this 20 year mining operation would leave a footprint of 470 km^2.

Seafloor massive sulfides (SMS) occur at the depth of 1,000 to 3,500 meters. Because the areal extent of hydrothermal vents is relatively localized, mining at any one site leaves a footprint of only 10 to 20 hectare, and the mining will only last from one to two years. But multiple sites are likely to be developed over a longer period of time as part of a single mining lease, as was the case for the Solwara project (AMC 2018).

Abyssal plains lie 4,000 to 6,500 meters beneath the ocean surface. In the prototypic mining operation evaluated in the EU BCA, the designated site would be mined annually for twenty years at the rate of 135 km^2 per year. The total footprint over the operational life of the mine

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[6] See "Collapse of PNG deep-sea mining venture sparks calls for moratorium"

would be about 2,705 km^2. This site lies in the national waters of the Cook Islands about 300 km from the nearest island.

Ecological characteristics differ within and across the three types of formations, and the associated ecosystem processes have different spatial and temporal scales (Dunn et al., 2018). Exploratory activities have turned up rich biodiversity in all of these areas, including abyssal plains which feature low biological productivity (Le et al., 2017). Sediment compaction and habit removal associated with DSM will destroy ecological communities in the mining footprint, and sediment plumes, which may contain toxics, can travel beyond the footprints (Washburn et al., 2019). Computer simulation of plume behavior is at the early stages (Heffernan, 2019). Light, noise, and sonic vibrations will be produced by DSM equipment, and sonic vibrations can occur from operating the riser lift system. Handling return water presents technical and cost issues; releases may occur near the seabed, or take place at mid-water (Heffernan, 2019). Tailings plumes from dewatering operations contain fine particles under 10 µm, and may drift beyond mining sites (Washburn et al., 2019). Of particular concern to marine scientist is the cumulative effects of these impacts on ecosystem functioning and connectivity as multiple seabed mining sites are developed over time (Dunn et al., 2018).

The existing information about DSM impacts is poor. Acquiring information on deep seabed environments is costly and technically challenging. Exploratory leases have been used to complement other studies on marine ecosystems. Expert surveys have also been used to help assess the environmental effects (Clark et al., 2016; Washburn et al., 2019). In a recent survey of expert opinion, the authors state that a ".. striking result is … the relative paucity of experts willing and able . . . to offer an opinion about the vulnerability of mineral-associated habitats to a variety of risk sources …" (Washburn et al., (2019, pp 36). The authors suggest that "survey outcomes . . . underscore the need for risk assessment to progress from expert opinion with low certainty to data-rich and ecosystem-relevant scientific research assessments to yield much higher certainty" (Washburn et al., (2019, pp 25).

3. Uncertainty, BCA, and DSM Decision Making

The term "uncertainty" is used in importantly different ways in the literature. This section reviews some distinctions about different types of uncertainty, and their relevance for decision making methodology. We then review the standard modeling framework for uncertainty evaluation in BCA, labeled "predict-then-act" in the decision-science literature (see Lempert et al., 2013a). Following this discussion, we provide some perspective on the precautionary principle, and consider some uncertainty evaluation methods that can be used to implement it. These methods are described in more detail in Section 4.

3.1. Dimensions of DSM Uncertainties

The uncertainties associated with DSM involve the performance of technologies, production costs, market conditions for products, and the environmental impacts of alternative mining activities. The uncertainties associated with these categories can occur at different levels. Classically, Knight (1921) distinguished uncertainty levels as "risk, "uncertainty," and "ignorance." "Risk" describes an informational context where a component in the state of nature has a known set of possible values and a probability for each (for example, a probability distribution for mineral prices). "Uncertainty" conveys a lower state of knowledge where probabilities are unknown. Finally, "ignorance" describes situations where even the possibilities are unknown (for example a lack of knowledge about what species DSM might affect).

More recently, there has been a focus in the literature on distinctions at the lower knowledge end of Knight's spectrum, using labels such as "deep uncertainty" or "fundamental uncertainty." In a taxonomy by Walker et al., (2013, "Level 4" uncertainty occurs when multiple possible outcomes are possible without the information to rank them for likelihood, possibly due to a lack of understanding about the functional relationships among variables. In this context, decision-makers may have different views about how to formulate the model, solve it, and attach values to outcomes. In level 5, the analyst knows almost nothing other than their awareness of the unknowns. Lempert et al. (2003) define "deep uncertainty" to be the situation that "the parties to a decision cannot agree upon (1) the appropriate models to describe interactions among system variables, (2) the probability distributions to represent uncertainty about key parameters in the models, and/or (3) how to value the desirability of alternative outcomes."

These nuances about the nature of fundamental uncertainty are likely to apply to different aspects of DSM. There is more data about market conditions, for example, than about technology performance or seabed ecosystem structure and function. These differences have implications for the degree to which different methods like simulation modeling and expert opinion can be used in project evaluation.

A further dimension for classifying uncertainty deals with whether the process to resolve the uncertainty is exogenous to the mining operation, or is endogenously produced as a result of the mining activity itself. Exogenous uncertainties include the future economic value of marine environments relative to the future value of mineral commodities, and the prices of inputs used in DSM mining. This kind of uncertainty is sometimes referred to as "market uncertainty' (Mahnovski, 2007). Endogenous uncertainties concern the performance, cost, and reliability of DSM technology, and the environmental impacts associated with DSM operations. The strategic behavior of firms in the DSM industry is another endogenous uncertainty.

Another dimension to uncertainty involves the way that reversibility or irreversibility impacts the likelihood of outcomes (Gollier and Treich, 2003; Krutilla, 1967; Dixit and Pindyck, 1994). Investments in DSM operations are likely to be "sunk" in the standard sense of being largely unrecoverable should the project fail. Additionally, some of the environmental impacts of DSM could prove to be irreversible. The impacts of mining on dynamically complex marine systems raises the possibility of tipping these systems into different equilibrium states (Morgan et al., 2017; Perrings et al., 1992). Once the system resides in these new equilibrium states, it can be extremely difficult, if not impossible, to reverse engineer the system back to the original condition (Crépin et al., 2012).[7]

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[7] Such regime shifts in other contexts include the eutrophication of lakes from excess phosphorous input, the change in coral ecosystems to algae-dominated reefs due to acidification, and the conversion of tropical forests into grasslands from non-sustainable logging (Crépin et al., 2012).

A related issue is the timing and degree to which DSM environmental impacts are observed. Flow environmental impacts like the turbidity associated with mining operations can be observed during the course of the operation, and possibly controlled or mitigated in real time. On the other hand, cumulative environmental damages may not become apparent until after thresholds are reached (Liski and Salanie, 2019; Crépin et al., 2012). Disequilibrium adjustment paths can occur over an extended period of time, as lag times associated with dynamic feedbacks delay the effects of perturbations (Roe and Baker, 2007). As the system approach a new equilibrium, minor shocks can shift dominant feedbacks, tipping the system quickly into a new equilibrium state. This phenomenon explains why regime shifts often appear to emerge quickly, catching observers unaware (Crépin et al., 2012).

These types of uncertainty are also present in the dynamic system driving climate change, and present challenges for conducting benefit-cost analysis (Sussman et al., 2014a; 2014b; Toman 2014). In the next section, the standard approach for uncertainty analysis in BCA is reviewed, followed by an alternative precautionary approach that can be used in an information environment featuring fundamental uncertainty.

3.2 Predict-Then-Act Methods

The decision structure in traditional benefit-cost analysis assumes that the issue is whether or not to take action in the present, based on different forecasts or projections of an expected future. Specifically, the question is whether NPV is expected to be greater than zero with enough confidence to recommend a project go-ahead. In this setting, analysts have a significant degree of consensus about the structure of the models producing the forecasts, but are likely to have doubts about some parameter values. In standard BCA the uncertain parameters commonly involve the baseline state of the world; the effectiveness of the project in perturbing the baseline; and the value of economic variables, such as the discount rate.

When joint probability distributions are available for all relevant parameters, expected value analysis is typically used along with Monte Carlo methods to generate expected outcomes. Using expected values in this context requires the further assumption that decision makers are risk neutral (that the social value of monetary values are linearly related to social value over their range of possibilities). When downside risks are viewed as more important than upside potentials, there will be a departure from the subjective valuation of an alternative (the certainty equivalent) and the expected value. The difference between the expected value and the certainty equivalent (the risk premium) represents the value willingly paid to avoid the risk.

Risks can be mitigated by pooling or reallocation, e.g., using insurance. Volatility in commodity prices can be hedged using futures or derivatives markets. However, the terms of these contracts are too short to hedge against risks over the 20 year project horizons that will be typical for seabed exploitation leases. In some cases it is possible to undertake longer-term contracts to reallocate some project risks on a bilateral basis with other market actors (Jenkins et al., 2019).

The predict-then-act decision structure is suited to the informational setting described as “risk” by Knight. It is has serious limitations when information is not good enough to make convincing predictions, and the consequence of being wrong are substantial and/or irreversible. There are also fewer opportunities to reallocate risks through contracting in this informational setting. In a low information environment, the uncertainty evaluation needs to incorporate precautionary elements that reflect the possibility of unanticipated downside outcomes. We turn to that issue in the following section.

3.3. The Precautionary Principle and its Implementation

In a general sense, the precautionary principle conveys the notion that an extra burden of proof should be met before taking actions with deeply uncertain and potentially irreversible consequences. In the limiting extreme the burden of proof might be high enough to proscribe an activity entirely. However, the precautionary principle is often construed with enough flexibly to allow some action to proceed with an extra margin of safety (Harding and Fischer, 1999).

Because the precautionary principle does not define quantitative methods or targets, it does not offer clear guidance for implementation. This is an important challenge facing the regulation and evaluation of DSM activities. The World Bank recommends the precautionary framework for DSM decision-making in Pacific Island Countries, and some countries have adopted the precautionary principle into their domestic mining laws (World Bank 2018). Regarding international waters, the legal framework of UNCLOS requires the protection of marine environments, including the imposition of environmental controls on DSM operations to avoid "harmful effects," and the protection and conservation of marine flora and fauna (UNCLOS Article 145). The ISA is empowered to suspend or adjust mining activities to achieve these aims, as well as to establish mining exclusion zones where ". . .evidence indicates the risk of serious harm to the environment" (UNCLOS Article 162(2); paragraphs w and x). The definitions of "harmful effects" and "serious harm" are not spelled out in UNCLOS, however, and the criteria for defining these terms is the subject of active research and discussion in the marine science literature (See Levin et al., 2016; Jaeckel, 2017).

The draft mining code issued by the ISA implements the legal obligations established by UNCLOS, including the development of environmental management plans in areas subject to DSM (Regulation 2(e)). Establishing a regulatory framework before DSM is allowed to commence is a notably prudential approach. However, the ISA's inspection and enforcement capabilities may be limited, given its multiple responsibilities and relatively limited budget.

In the following section, we review three general approaches for promoting precaution in DSM mining evaluations. The first is "safe minimum" standards, which provide a conservative performance criterion for development decisions. The second is "sequential decision-making approaches," which allow decisions to evolve over time in response to new information (see Hammitt et al., 1992). Sequential decision-making is an encompassing category, and two particularly relevant approaches for DSM decision-making are considered: "real options", and "adaptive management." The last category reviewed is "bottom up" decision-making methods from the decision-science literature, focusing principally on robust decision-making (RDM). Bottom-up approaches evaluate the performance of projects over a wide variety of futures, and systematically explore vulnerabilities to uncertain contingencies that are essentially impossible to forecast. Project designs are then adjusted to reduce these vulnerabilities in repeated simulations.

4. Incorporating Precautionary Elements in DSM evaluations

4.1 Safe Minimum Standards

As the name suggests, “safe minimum standards” establish threshold limits that afford an extra margin for error in judgments about uncertainties and variations in circumstance. They are commonly seen as permissible exposure levels in regulations addressing public health or occupational safety; as structural requirements in building codes; and as engineering design specifications for infrastructures ranging from bridges to nuclear power plants. Safe minimum standards in construction projects provide a buffer for potential hazards varying from snow loads to earthquakes. These kinds of standards are designed to avoid bad outcomes with a significant degree of confidence.

In the sustainability literature, the traditional motivation for safe minimum is to reduce the risk of irreversible ecological or environmental losses to current and future generations. The emergence of the systems dynamics literature in ecology and climate science in the past 25 years has added to this concern, identifying the possibility of irreversible regime shifts in dynamic environmental systems (Crépin et al., 2012; Morgan et al., 2017; Perrings et al., 1992; Roe and Baker, 2007).

The “mini-max principle” is one formal approach for implementing safe minimum standards. The circumstances for which each alternative is most vulnerable (worst case for each alternative) is used in this evaluation. By choosing the alternative with the best worst case, assurance is provided that nothing worse than this outcome occurs. This is a pessimistic approach in that it forgoes upside possibilities if they have large downsides in some states of the world. This approach can be broadly applied in decision-making, and has been used as a criterion for the protection of natural environments (Bishop, 1978, Woodward and Bishop, 1997).

Some combinations of uncertain parameters (states of nature) can be inherently bad no matter what alternative is chosen, dominating the mini-max evaluation. Savage (1954) proposed an approach for making decisions without knowing probabilities by using a retrospective view. For each combination of alternative and state of nature, a level of regret is constructed by evaluating how much worse the alternative is compared to the best alternative for that state of nature. In the next phase, the mini-max principle is used on these regret levels (mini-max regret). This criterion is less pessimistic than the mini-max approach, and thus, offers weaker guarantees about outcomes. Again, though, it is a flexible criterion that can applied broadly in decision-contexts with deep uncertainty. Palmini (1999) uses this criterion in identifying safe minimum for species preservation contexts and risk averse decision makers.

A limitation for implementing either the mini-max or mini-max regrets criteria is the need for models that can predict outcomes for all states of nature and alternative courses of action. This is nontrivial requirement. A less formal mechanism for implementing safe minimum standards with lower informational requirements is to administratively divide the decision space into zones where economic trade-offs are permitted and zones where prescriptive standards apply (Toman 1994). In the sustainability area, natural reserves would fall in the space where development activities are proscribed, reflecting a consensus about the relative value of different spaces in development and preservation. In fact, a number of countries, including Mexico, the United

States, Canada, and Portugal, have used this approach to establish marine preserves in their national jurisdictions (Van Doren, 2011). The ISA is now developing environmental management plans (EMPs) that would protect 30% to 50% of seabeds around mining areas (Dunn et al., 2018). EMPs must be based on the precautionary principle and the principle of ecosystem management (Regulation 2e, paras (i and ii) of the draft mining code). An EMP has been completed for manganese nodules in the CCZ, and a plan is being developed for SMS (Dunn et al., 2018).

4.2. Real Options and the Value of Information

The "real options" approach is relevant in a decision-making context when choices about the timing and/or the scale of decisions are flexible, and taking actions in the present imposes sunk costs. Consider the exogenous informational setting first. For investments, such as those in DSM facilities, that entail large upfront costs having limited salvage value, and which face uncertainty about future input or commodity prices, deferring the investment can avoid the down-side market risks, should they materialize, and the associated loss of investment funds. On the other hand, if market conditions become favorable, the investment project can be initiated (Farrow, 2004; Dixit and Pindyck, 1994). The value of being able to choose to defer the decision in this context is the conceptual equivalent of a financial call option. Such a "real option" does not trade on secondary markets, and may be more difficult to value than financial options.[8]

When information is exogenous, the real options approach can be used to frame a precautionary approach to environmental risks. Limiting the scale of initial development provides an opportunity for observing uncertainty and taking subsequent actions accordingly. The benefits of this delay are particularly significant when the environmental risks are cumulative and irreversible, and decision-makers have the type of preferences that would induce them to increase savings in the face of future uncertainties (Gollier et al., 2000; Gollier and Treich, 2003).[9]

A related value of information perspective arises from an assumption about exogenous trends in the future value of natural environments relative to the value of economically produced goods (Krutilla, 1967). The relative societal value of undeveloped natural environments, like marine resources, can be expected to rise in the future as they become scarcer, and as the willingness to pay for environmental services increases with income. These trends are buttressed by the comparatively low substitutability of natural environments in consumption relative to their use as inputs into production. For example, induced technology change can facilitate substitution away from costly mineral inputs. A related factor is that delaying the initiation of a project is not an irreversible decision, because production can be scaled up subsequently as conditions warrant. Under these circumstances, there is a positive value to waiting for more information (Arrow and Fischer (1974)).

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[8] However, production rights on leased mining tracts may be exchanged bilaterally among producers.

[9] Technically, this savings attitude requires a utility function with a particular relationship between third and second derivatives. In Gollier et al, 2000 and Gollier and Treich 2003, "prudence" must be greater than two times absolute risk aversion to give a precautionary delay.

Recent trends and projections for some key minerals prices are not inconsistent with this perspective. The prices for nickel, copper, and zinc do not show significant rises, past or projected, from the period 2014 to 2030 (See Figure 1). The same is true for the precious metal prices; gold and platinum in Figure 2, and silver in Figure 3, the price of which is projected to decline. Figure 4 shows a 10 year price history for cobalt. The price of cobalt at the time of this writing is marginally lower than 10 years ago. But the price rose dramatically from a decade low in January of 2016 to a decade high in March 2018 (See Figure 4). The dramatic price jump was stimulated by a perception in the market that the time had arrived for electric vehicles; and thus, that the derived demand for cobalt, which is used in lithium ion batteries, would significantly increase. Additionally, 50% of the terrestrial supply of cobalt is sourced from the Democratic Republic of Congo -- a politically unstable country. However, in March of 2018 Elon Musk announced that the batteries for his electric cars would not rely on cobalt. That news stimulated the precipitous decline in cobalt prices from their highpoint to the present period.[10]

{Figures about here}

As has been discussed, the value of information can justify delaying the commitment of resources to development projects. However, delaying new investments is not always economically desirable. Even in the context of exogenous uncertainty, the value of investing in the present period may be large enough to offset the opportunity cost of lost information from taking current-period actions (Dixit and Pindyck, 1994). For endogenous uncertainty, the opportunity cost generally runs in the opposite direction: information is revealed by taking action and observing the results (Adner and Levinthal, 2004). For example, the endogenous resolution of technical uncertainties could justify more rapid development of mineral resources (Dixit and Pindyck, 1994).[11]

In summary, the literature on real options does not offer a theoretical prior on the optimal timing or scale of investments. The value of parameters in the model and the type of uncertainty will influence the decision-making. However, the literature does imply the need for including the timing and scale of projects as alternatives in the evaluation framework, if there is the flexibility to do so. Foreclosing the possibility of adapting the decision-making to the information environment can reduce the net present value of the project.

4.3 Adaptive Management

Adaptive management involves taking actions and monitoring the effects in order to produce information that reduces endogenous uncertainty. The term has several interpretations in the literature. Adaptive management is sometimes conceived of as a structured experimental approach, which systematically test assumptions about the environment (Walters and Holling, 1990). In the seabed mining context, for example, a few tracts of seabed could be reserved, each representing a different ecological context for risk. Disturbing the habitat would provide insights

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[10] See "How the cobalt market fell victim to the allure of electric cars". Bloomberg News, March 1, 2019

[11] See Graham (2001) for additional factors that affect the value of information from taking versus deferring actions.

about the environmental impacts of new technologies in various deep sea habitats.[12] The so called DISCOL experiment, which has been running for over 30 years, is the closed example to this approach conducted on deep seabeds. An 8 meter wide "harrow plow" has been dragged over an area of abyssal plain in the CCZ to observe the effects of disturbing the seabed (Heffernan 2019).

Piloting small scale seabed mining trials would allow for small-scale actions to be taken with correspondingly small risks, as way to provide information about the costs, performance, and environmental impacts of DSM. Based on the information revealed from these activities, adjustments could be made in the resource development plan going forward – including the possibility of halting the operation. As of now, mining trials have not been conducted on deep seabeds. They have high upfront costs, and the possibility for scale up faces regulatory uncertainty. Additionally, without realized or fairly certain returns, firms or the governments may be unwilling to fund the set up and implementation of costly monitoring programs.

Adaptive management can also be construed to allow for activities to proceed at full capacity with careful monitoring and evaluation. The assumption in this case is that ex post adjustments would be made on an as-needed basis as information accumulates.[13] This approach is consistent with the evolving DSM management strategy for international waters. Exploratory activities are being leased to produce baseline information; mining activities will be excluded from protected areas defined in environmental management plans (situated outside the exploration areas); and ex-post mining activities will be allowed to proceed with regulation and monitoring (Dunn et al., 2018). This approach will allow for adjustments to leasing procedures and regulations based on the observed performance of DSM operations.

Adaptive management strategies with commercial-scale projects run the risk of unexpected impacts along the development trajectory. Early stage monitoring can only pick up short-run, observable flow effects, and as noted before, non-observable and irreversible stock effects are possible as the deep seabed mining industry advances. Some research has shown that useful information can be gleaned from pushing ahead with "development experiments" (Liski and Salanie, 2019). In this case, it seems prudent also to continue research and structural model building to help provide insights about longer-run risks.

4.4. Robustness-Based Approaches

Robustness-based decision-evaluation methods (sometimes called "bottom up" methods) are recommended in the decision science literature for evaluation contexts associated with fundamental uncertainty. Robustness-based methods include Decision Scaling, Information-Gap, Robust-Decision Making (RDM), Many Objective Robust Decision-Making, and Adaptive

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[12] Whether or not mining is ultimately initiated, there is a public interest in deep seabed exploration taking place in order to generate marine and mineral scientific data. The value of this exploration externality should be considered in the initial decision between protecting or opening up areas for exploration.

[13] The New Zealand's Economic Zone and Continental Shelf (Environmental Effects) Act of 2012 (EEZ Act) requires adaptive management provisions in lease applications for seabed mining on continental shelves. As defined in the EEZ Act, adaptive management can include small scale experiments and pilot projects as well as full capacity development with monitoring and evaluation (Section 64(2); Sections 64(3,4)).

Dynamic Pathways.[14] Such approaches have frequently been used to support planning efforts for climate adaptation, including water capacity planning and coastal zone management (Arin and Rozenberg, 2018; Lempert et al., 2013a, 2013b).

Robustness-based methods start with the premise that the modeling assumptions and probabilistic methods commonly used in "predict-then-act" evaluations cannot be applied with confidence. Instead, "exploratory modeling", focusing on conjecture and possibility, is used to produce an ensemble of plausible models. The conjectures surrounding these models may be about a number of attributes including the parameters in the model and the functional forms that link inputs and outcomes. When uncertainty is even greater, several plausible theories about the structure of models can be offered. Different modeling structures can be used to probe and test where outcome uncertainties are greatest, and where plans or projects are most vulnerable to poor performance. In this way, modeling experiments are used to produce information and reduce the uncertainties associated with project evaluation.

Different modeling assumptions will give different plausible scenarios about the future. To use robust decision-making as an example, a wide range of plausible scenarios is generated, taking into account a multitude of ways that the physical/environmental systems in question and the economic elements involved might function in the future. Scenario outcomes are then plotted against key characteristics of interest that differ across the scenarios. Stakeholders can then review performance in different realizations of the future, and learn about the key vulnerabilities of plans or projects. With the insight gleaned from this exercise, adjustments can be made to address the vulnerabilities identified, and tests run again. This stress testing can continue iteratively until there is convergence of opinion to the plan or project design that performs best, which reflects the way stakeholders evaluate tradeoffs and uncertainties.

Robustness-based decision-making methods have the following key features:

1) They rely on methods for efficiently deriving a range of possible values for uncertain input parameters. This range has to be broad enough include possible outliers, e.g., extreme events, that could increase the vulnerability of proposed plans or projects.

2) Based on this sampling, a large number of potential scenarios (combinations of input parameters) is generated. Probability distributions or correlations among scenarios are not considered.

3) Data mining tools are used to generate a handful of discussable scenarios with respect to vulnerability or any other performance criteria of interest. These scenarios can then be shared and discussed with stakeholders.

4) By identifying regions where decisions are vulnerable, the stakeholder discussion can generate counter proposals. These new proposals can then be stress tested for robustness in a new round of simulations. This process continues until there is agreement on the desirable course of action.

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[14] See Hadka (2015), Haasnoot et al., (2013), and Kwakkel et al., (2016) for a description of these approaches and the technical distinctions among them.

Robustness-based methods are flexible about the definition of performance measures used to identify regions of interest. They can accommodate dynamic models with sequential decisions, including real options (e.g., Mahnovski, S., 2007) and adaptive management approaches (e.g. Lempert et al 2013a, 2013b; Hallegatte et al, 2012). Although outcomes are generally compared using multi-criteria analysis, benefit-cost analysis can also be integrated into these frameworks (Lempert, 2014).

Robustness-based approaches have large data and computational requirements, and the need for expertise and financial resources to implement them (Bhave et al., 2016). While data has been available for dry land adaptive climate change planning, there is currently little information about the environmental risks of seabed mining. However, the technology, economic, and market risks associated with DSM might be tractable to scenario analysis within a robustness-based framework.

5. Benefit-Cost Analysis of Deep Seabed Mining

In this section we shift gears to review and evaluate a benefit-cost analysis of deep seabed mining sponsored by the EU for the Pacific Community. This study might be considered the benchmark BCA performed on DSM to date. It is entitled "An Assessment of the Costs and Benefits of Mining Deep-Sea Minerals in the Pacific Island Region: Deep-Sea Mining Cost-Benefit Analysis." The study was performed by the Cardno consulting firm, and is summarized in Wakefield and Myers, 2018. After this assessment, we turn to the uncertainty evaluation literatures reviewed in Section 3 and 4 to suggest a modified BCA approach for DSM evaluation.

5.1. The EU-Sponsored BCA[15]

The EU BCA is conducted from the stakeholder perspective of the Pacific Island Countries, who would be sponsoring DSM in their national waters. The study uses the "predict-then-act" decision structure, framing the choice as whether to undertake seabed mining in the present, based on predictions of future conditions. In making this judgement, the BCA relies on information from hypothetical mining prototypes assembled from technology concepts provided by mining companies (e.g., Nautilus) and consultant reports (e.g., SRK Consulting, 2010). Prototypes are described for mining seafloor-metal sulfides (SMS); manganese nodules, and cobalt-rich crusts.

The EU BCA assumes that countries will contract with a private mining company to conduct the seabed mining, and use a combination of taxes, fees, and royalties to recover a share of the gross profits from the mining activity. If the country takes an equity stake in the mining operation, it will also receive a profit share from its ownership position.

The first step of the EU BCA is to assess the commercial viability of the mining prototypes from the private mining company perspective. The net present value of the gross private profits from the mining operation are computed, less some external costs that the mining firm is assumed to

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[15] Information in this section is drawn from Wakefield and Myers (2018) and Cardno (2016).

be required to internalize in the lease agreement. The revenue side is estimated from assumed output rates, the expected composition of the output (in terms of mixes and concentrations of recovered minerals excavated at each location) and the expected prices of the minerals. The cost side is derived from estimates of the costs of exploration activities (which are assumed to occur for several years before the mine site becomes operational), fixed investment, and operations. The external costs that the mining firm is expect to internalize include the purchase of offsets for the CO_2 releases associated with fuel consumption; the costs of technology to reduce sedimentation and the risk of nutrient-rich water returns in the water column close to the surface; and insurance for any financial liability that might arise from potential fuel spills or accidents. It is also assumed that the lease agreement will require the mining firm to internalize the administrative costs that the host government incurs to develop and issue seabed mining regulations, as well as to monitor and enforce these regulations.

Using this revenue-cost structure, the net present value of profits are computed for each seabed site. If the profits are found to be positive, the analysis proceeds to a next step, which assesses environmental impacts and cultural effects within a larger "social benefit-cost analysis" (Wakefield and Meyers, 2018). An attempt is made to monetize the environmental costs, while the social costs are treated qualitatively. It is assumed that the burden of these costs will fall exclusively on the host country. Thus, from the host country perspective, the benefit-cost analysis becomes a comparison of the profit share received from the mining activity to the cost of local environmental and social impacts. The social impacts are differentiated by the local stakeholder groups potentially affected by seabed mining, including traditional peoples with seabed ownership claims, subsistence fishers potentially impacted by environmental effects, workers potentially affected by employment shifts, and the general population potentially influenced by changes in societal norms.

The EU BCA uses Monte Carlo simulation to characterize parameter uncertainty in the composition of mineral output, the prices of minerals, fixed and operating costs, and the price of CO_2 offsets (See Table 1). The economic cost of removing and/or disturbing benthic communities is computed in what the Cardno BCA regards as a bounding analysis that, in the view of the analysts, gives an overestimate of possible losses. This judgement is based on computing the value of ecosystem services lost from benthic habitats based on studies on the costs of disturbing terrestrial habitats that have higher gross productivities than benthic ecosystems. A bounding analysis is also used to characterize the possible damages from low probability, high impact ecosystem disturbances. In this case, the costs of the Deepwater Horizon accident is taken as the high boundary reference point.

{Table 1 about here}

Using this methodology, the analysis finds that the gross profit earned from mining SMS deposits and manganese nodules is likely to be positive, while the gross profits earned from mining cobalt-rich crusts is likely to be negative. The probability that profits from SMS mining are positive is 83%. The range is -$75 to $260 million, with an expected value of $80 million.

The study finds that there is no chance that profits from mining manganese nodules will be negative. The range is 150 million to over $1billion, with a median value of $500 million.[16]

These gross profit estimates are significantly larger than the boundary cost estimates for unavoidable ecological impacts to benthic environments caused by mining activities, which are $0.5 million for SMS and $18.3 million for manganese nodules. The study concludes that cultural impacts on Papua New Guinea from SMS mining will be *de minimis.* Cultural impacts on the Cook Islands from manganese mining will be significant, but the study concludes that it is unclear whether these effects will be regarded as positive or negative. The study also considers the expected cost of unplanned fuel spills as $40,000 and $260,000 for SMS and manganese nodule mining, respectively. The possibility of catastrophic environmental damages is bounded using the figure for the worst case oil spill ever recorded – the Deepwater Horizon accident -- which cost $8.8 billion. In the event of damages of this magnitude, the costs of DSM would be larger than the benefits.

The study provisionally concludes that SMS mining and manganese nodule recovery are economically promising from a host country perspective. To quote from Wakefield and Meyers (2018, pp 1): "It is expected that the results of these initial analyses can be tentatively extrapolated to other Pacific countries with similar resources until more data becomes available to warrant additional country-specific analyses." The study provides caveats that cumulative impacts might differ from those based on site-specific studies, revenue receipts could be misused by the governments that collect them – providing little social benefit -- and that the future evolution of technology, scientific information, and markets could affect conclusions.

5.2. Evaluation and Recommendation

The methodology approach in the EU BCA is commonly used in economic evaluation. Yet as suggested in Sections 3 and 4, the literatures on deep uncertainty evaluation and the precautionary principle suggest that this approach is not well suited to a decision-context with fundamental uncertainties.

Uncertainties about the operational reliability and performance of DSM technology, given the status of the industry, suggest that production volumes, the composition of output, and the operational reliability of environmental controls (such as those to reduce sedimentation and return water releases) are uncertain -- at least initially. The costs of the DSM mining, given the technological uncertainties, are not known with confidence. Financial returns and the financial condition of mining firms are affected by market risks. Other than gold – a special case – mineral prices decline in response to financial crisis and recessions (Christian, 2009). The possibility of financial or economic instability over a 20 year mining lease period cannot be ruled out with confidence.

Financial risks for lessors are especially significant in the case of joint ventures. UNCLOS establishes a mechanism for joint-ventures in international waters ("the Enterprise"; Article 170).

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[16] These numbers are from a discussion in Wakefield and Meyers (2018) using Figure 1 on pp 2 and Table 1 on pp 8. They are based on a 5% discount rate. These numbers are somewhat different than the numbers in the Cardno (2016) study, which are reported for a 7% discount rate.

The government of Papua New Guinea had a partnership with the Nautilus mining company to mine SMS. The financial failure of this venture ended up costing Papua New Guinea $157 million. (see Footnote 6). In the case of joint ventures, the financial condition of prospective lessees should be integrated into a stakeholder benefit-cost analysis, following standard methods for financial feasibility assessments used for infrastructure projects (ADB 2015). Whether the value of the pending mining lease comprises a significant share of the mining company's portfolio – as was the case with Nautilus -- or a small share of a large and diversified portfolio is an obviously relevant consideration.

Regardless of the structure of a mining firms' portfolios, mining firms and/or their supporting governments will not necessarily have the same risk tolerances as the ISA or countries leasing DSM operations in their national jurisdictions. Private markets may not fully internalize the benefits of precaution (Gollier and Treich, 2003). Difference in risk tolerances between mining companies and lessors can be reflected in a stakeholder BCA that represents the position of both. Risk-adjusted discount rates could also differ, owing to the tax status of mining firms and possible differences in capital costs for mining companies and the entities leasing DSM operations. These difference can also be reflected in stakeholder BCA (See Krutilla and Graham, 2012).

For countries leasing seabed mining activities relatively close to their shorelines, local stakeholder attitudes can affect the viability of projects. Indeed, local opposition to the failed Solwara 1 project was significant.[17] Political reactions of local stakeholders can be included as a deep uncertainty in some evaluation frameworks, e.g., RDM. Adding this variable will make confidence intervals for project outcomes wider. An alternative would be earlier and/or more impactful stakeholder engagement. As physical exploration can help to reduce uncertainties about aspects of the physical environment, "social exploration" in the nature of early stakeholder engagement can help decision-makers better understand and reduce stakeholder concerns.

Given the uncertainties associated with DSM, it would be reasonable for the ISA and littoral countries with seabed resources to require benefit-cost analysis of DSM project proposals as a condition for lease applications. These BCAs should reflect precautionary approaches to deep uncertainty evaluation, and could be performed and evaluated by independent experts. The lease applicant could pay for these studies. This process is used in the National Investment System in Chile, which comprehensively screens investment projects in the country (Gómez-Lobo, 2012). Such a system goes beyond the evaluation requirements of emerging DSM regulations, and research would be needed to help formulate an evaluation platform for routine benefit-cost analyses of deep seabed lease proposals.

6. Discussion and Conclusion

This article has reviewed decision-making methods in the context of potentially irreversible and deeply uncertain impacts of an at-the-horizon industry, deep seabed mining. This seems to be a tailor-made case for application of the precautionary principle. However, general statements of the precautionary principle do not provide a quantitative framework for setting targets and

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[17] Nautilus minerals still lost at sea with no life raft in sight. MiningWatch. Canada. November 25, 2019

evaluating alternatives. This structure is essential for a transparent, well-grounded, and consistent approach to evaluation, whether for individual mining projects or for broader policy guidelines.

Three approaches in the literature for a more rigorous framing of precautionary stances include the concept of safe minimum standards; real options analysis for valuing the benefit of new information, and robustness-based approaches for decision-making under deep uncertainty. Hybrid combinations of these approaches are possible. A real-options approach puts less explicit weight on precautionary motivations than the other two; as typically implemented, it is an extension of general benefit-cost analysis that accounts for the consequences of changes in the feasible set of choices with new information. The safe minimum standard explicitly reflects a precautionary motive given its roots in minimax and mini-max regrets strategies, and in the environmental area, the tradition of administratively reserving natural areas as preserves in which development is proscribed. Robustness-based approaches can embody mini-max regrets as a performance measure but do not need to; in multiple-criteria applications, the user can specify the desired tradeoff between giving up net-benefits in "average" outcomes versus mitigating large losses in "adverse" outcomes.

Neither RDM nor a safe minimum standard approach provide a sharp answer to a go-no question. Rather, they would present lessors and lessees with a range of possible outcomes for the share of mining profits received and levels of risks needing to be borne, thus allowing judgements to be shaped about acceptable performance. As noted, these approaches also can help identify which unknowns could have the biggest impacts on outcomes.

Although there are large uncertainties about future demands for minerals, and deep uncertainties about DSM technologies and costs, our reading of the literature (including the EU-sponsored BCA) is that there is enough information available for some form of RDM, possibly incorporating real options analysis. Initially, the analysis would have to be highly stylized. Nevertheless, by explicitly considering different scales and timing of proposed seabed mining operations as alternatives, valuable information could be provided about the minimum scale of investment needed to return a profit, and the sensitivity of economic returns to different key assumptions about technology cost and productivity.

In principle, the analysis of costs, returns, and environmental impacts should be treated jointly in benefit-cost analysis. However, knowledge about the environmental effects of DSM at this time is more fragmentary than is the understanding of technology and market risks. In concept, RDM might be used in these circumstances to conduct an integrated analysis of economic and environmental impacts, relying on expert opinion and stakeholder judgements to roughly characterize potential environmental outcomes, and to explore "what if" scenarios that try to ascertain how large economic gains might have to be in order for different levels of environmental hazard to be accepted. Whether the information provided by this approach is worth the cost is an open question.

Overall, a searching examination of the economic and environmental uncertainties associated with seabed mining projects is an important requirement for precaution in the development of the DSM industry. Environmental uncertainties are the subject of a regulatory program for international waters, but there is room for additional attention on the economic side. This article has suggested evaluation approaches that can address deep uncertainties within a benefit-cost framework of DSM projects, providing an element of precaution in the assessment of decisions about seabed mining.

FIGURES

Figure 1
World Bank Commodities Price Forecast - Nickel, Copper, & Zinc
(Constant US dollars; Unit: $/mt)

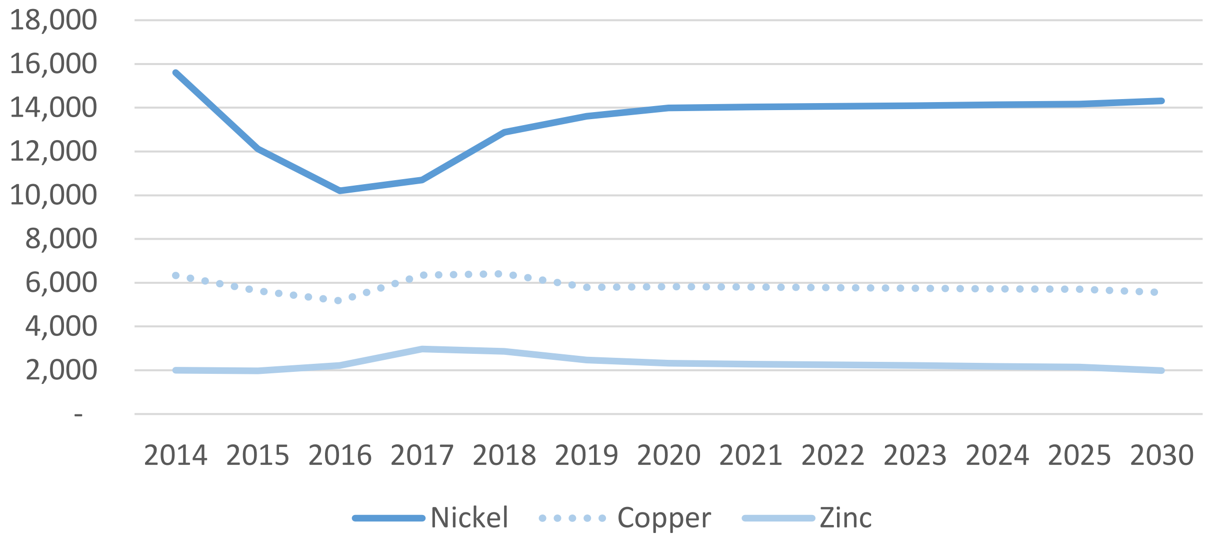
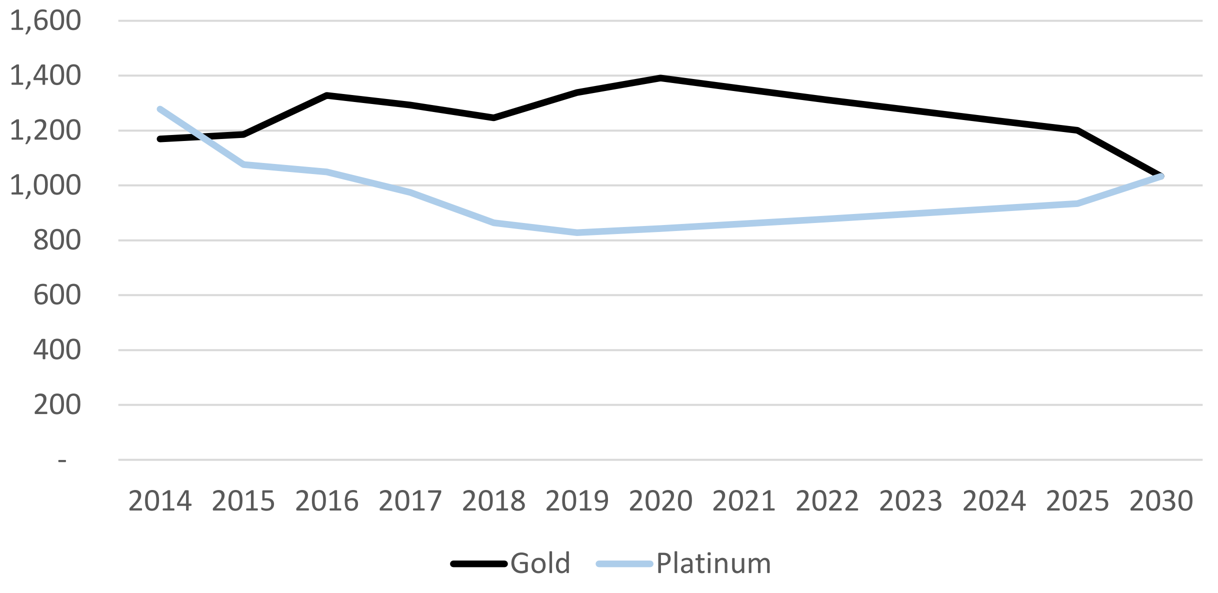


Figure 2
World Bank Commodities Price Forecast - Gold & Platinum
(Constant US dollars; Unit: $/toz)



FIGURES

Figure 3
World Bank Commodities Price Forecast - Silver
(Constant US dollars; Unit: $/toz)

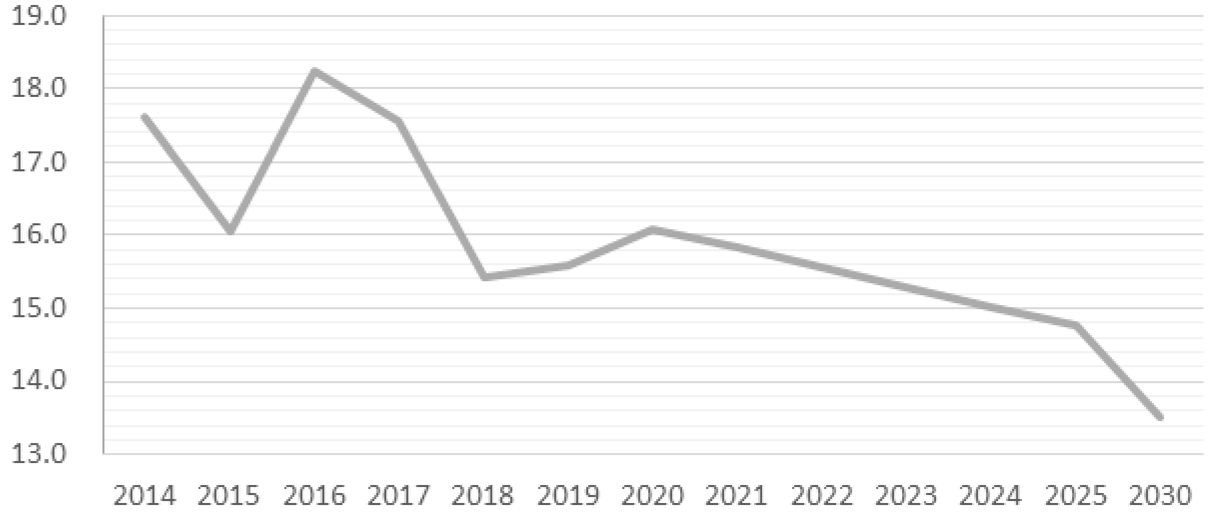
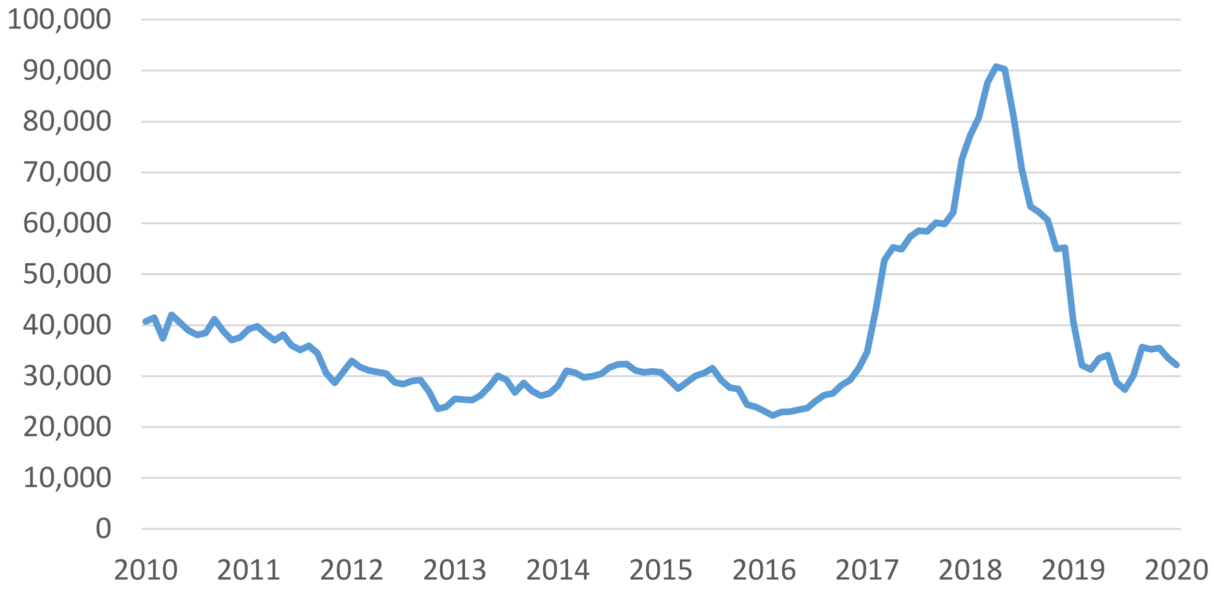


Figure 4
Ten Year Historical Price Series - Cobalt
(Constant US dollars; Unit: $/mt)



Source: Trading Economics

Table 1. Variables included in the Monte Carlo Simulation for the EU BCA

Parameter	Ranges for Randomized Parameters			Source
	Low Bound	Midpoint	High Bound	
Production composition (Percent mineral)	No Information	No Information	No Information	Study: SKC 2010
Mineral Prices	-50%	Current Price	+50%	No Source Cited
Fixed Capital Costs	-20%	Current Estimated Cost	+%20	No Source Cited
Operational Costs	-20%	Current Estimated Cost	+20%	No Source Cited
Price of carbon offsets from mining	$3.7	$5.80	$7.4	Study: Report on the State of the Carbon Market

Source: Cardno (2016).

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