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Faculty of School of Economics and Business

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Sustainable use of minerals in the context of a digital and energy transition

Bærekraftig bruk av mineraler i sammenheng med en digital- og energiomstilling

Diana Roa

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For Maia, Leo, and Isabel

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"How effective is lithium recycling as a remedy for resource scarcity?"
Coauthored with Knut Einar Rosendahl.
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Paper 4.
"How effective are environmental taxes in the mining industry?".
Working Paper

Abstract

This thesis examines the sustainable use of minerals in the context of a low-carbon and digital transition. Based on original research, this thesis contributes to designing policy interventions, namely market-based instruments to use nature and mineral resources sensibly. The thesis consists of two parts. The first part analyses a global mineral market and shows how to overcome supply shortages through recycling (Paper 1) and how to internalize the social costs of used mineral waste (Paper 2). In the second part, only extractors are in the spotlight to check how their decision to extract more resources will depend on the hidden environmental costs of doing it (Paper 3) and assess the fiscal and financial implications of implementing taxes in the mining sector (Paper 4). Although the conclusions in this thesis were derived from the lithium sector, the economic models originated in this research can be replicated in a broader range of mineral industries.

The first paper investigates to what extent recycling can remedy minerals scarcity. By using a dynamic partial equilibrium model of the global lithium market, the research shows that markets are inefficient when we lose the opportunity of recycling valuable mineral waste, and prices do not reveal the mineral's actual (durable) value. The findings suggest that a proper set of subsidies may achieve an efficient outcome. The second paper further examines the effect of subsidizing the recycling mineral sector, considering the adverse effects of waste. The paper discovers that high subsidies cannot be an optimal policy because it increases waste demand and causes rebound effects. A key finding is that irrespective of damage levels, a landfill tax is the most efficient policy, as it targets the hidden costs of waste disposal and promotes the best results in recycling levels, damage reduction, and welfare gains. The third paper departs from the duel between mining development versus ecological preservation. The investigation shows that policymakers can design a mineral extraction tax to minimize wetland damages while maximizing the benefits of a mineral boom. The fourth and last paper questions the effectiveness of environmental taxes in the mining industry. The results of this study confirm that authorities must consider existing and new distortions of the tax system to safeguard environmental tax effectiveness.

Oppsummering

Denne avhandlingen studerer bærekraftig bruk av mineraler i sammenheng med et grønt og digitalt skifte. Basert på ny forskning bidrar avhandlingen til kunnskap om utforming av politiske inngrep, nærmere bestemt markedsbaserte virkemidler for fornuftig bruk av natur og mineralressurser. Avhandlingen består av to deler. Den første delen analyserer et globalt mineralmarked og viser hvordan man kan overvinne forsyningsmangel gjennom resirkulering (artikkel 1) og internalisering av de eksterne kostnadene ved brukt mineralavfall (artikkel 2). I den andre delen er det mineral utvinnere som er i søkelyset, for å undersøke hvordan deres beslutning om å utvinne mer ressurser vil avhenge av miljøkostnadene ved å gjøre det (artikkel 3) og vurdere de skattemessige og økonomiske konsekvensene av å implementere skatter i gruvesektoren (artikkel 4). Selv om konklusjonene i avhandlingen er basert på litiumsektoren, kan de økonomiske modellene som brukes i denne forskningen anvendes i et bredere spekter av mineralindustrier.

Den første artikkelen undersøker i hvilken grad resirkulering kan avhjelpe mineralmangel. Ved å bruke en dynamisk partiell likevektsmodell for det globale litiummarkedet viser forskningen at markedene er ineffektive når vi ikke utnytter muligheten til å resirkulere verdifullt mineralavfall, og prisene reflekterer ikke mineralets faktiske (holdbare) verdi. Resultatene tyder på at et riktig sett med subsidier kan oppnå et effektivt utfall. Den andre artikkelen undersøker ytterligere effekten av å subsidiere gjenvinning av mineraler, men tar også hensyn til de negative miljøeffektene av avfall. Denne artikkelen finner at subsidier ikke er en optimal politikk fordi det øker etterspørselen etter avfall og forårsaker rebound-effekter. Et sentralt funn er at uavhengig av skadenivåer er en deponiavgift den mest effektive politikken, siden den retter seg mot de eksterne kostnadene ved avfall og fører til optimale gjenvinningsnivåer, skadereduksjon og velferdsgevinster. Den tredje artikkelen tar utgangspunkt i avveiningen mellom gruveutvikling og økologisk bevaring. Studien viser at beslutningstakere kan utforme en mineralutvinningsskatt for å minimere skader på våtmark samtidig som de maksimerer fordelene med mineralutvinning. Den fjerde og siste artikkelen stiller spørsmål ved effektiviteten av miljøavgifter i gruveindustrien. Resultatene av denne studien tilsier at myndighetene må vurdere eksisterende og nye vridninger av skattesystemet for å ivareta effektiviteten av miljøskatter.

Resumen

Esta tesis examina el uso sostenible de los minerales en el contexto de una transición digital y de bajo carbono. Basada en un estudio original, esta tesis contribuye al diseño de políticas públicas, en particular instrumentos de mercado como subsidios e impuestos para manejar la naturaleza y los recursos minerales de forma sensata. La tesis consta de dos partes. La primera parte analiza un mercado mundial de minerales y muestra cómo superar la escasez de suministro mediante el reciclaje (artículo 1) y cómo internalizar los costos sociales de los desechos minerales usados (artículo 2). En la segunda parte, solo los extractores están bajo análisis para verificar cómo su decisión de extraer más recursos dependerá de los costos ambientales ocultos de la minería (artículo 3) y evaluar las consecuencias fiscales y financieras de implementar impuestos ambientales en el sector minero (artículo 4). Aunque las conclusiones de esta tesis se derivaron del sector del litio, los modelos económicos originados en esta investigación se pueden replicar a una gama más amplia de industrias minerales.

El primer artículo investiga hasta qué punto el reciclaje puede remediar la escasez de minerales. Mediante el uso de un modelo dinámico de equilibrio parcial que simula el mercado mundial del litio, la investigación muestra que los mercados son ineficientes cuando perdemos la oportunidad de reciclar desechos minerales valiosos y los precios no revelan el valor real (duradero) del mineral. Los hallazgos sugieren que un conjunto adecuado de subsidios puede lograr un resultado eficiente. El segundo artículo examina además el efecto de subsidiar el sector de reciclaje de minerales, considerando los efectos adversos de los desechos. El estudio descubre que los altos subsidios no pueden ser una política óptima porque aumenta la demanda de residuos y provoca efectos de rebote. Un hallazgo clave es que, independientemente de los niveles de daño, un impuesto a los vertederos es la política más eficiente, ya que se enfoca en los costos ocultos de la eliminación de desechos y promueve los mejores resultados en los niveles de reciclaje, la reducción de daños y las ganancias de bienestar. El tercer artículo parte del duelo entre desarrollo minero versus preservación ecológica. La investigación muestra que los formuladores de políticas pueden diseñar un impuesto a la extracción de minerales para minimizar los daños a los humedales y maximizar los beneficios de un auge mineral. El cuarto y último artículo cuestiona la efectividad de los impuestos ambientales en la industria minera. Los resultados de este estudio confirman que las autoridades deben considerar las distorsiones existentes y nuevas del sistema tributario para salvaguardar la efectividad de los impuestos ambientales.

Synopsis

1. Motivation

The low-carbon transition makes evident our deep reliance on mineral resources. A big concern for industrialized countries, especially Europe and North America, has been securing critical minerals to keep up with technological advances to electrify their economies. This has led to a boost in demand and prices for several minerals. For resource-rich nations, especially in Latin America and Africa, rents from mineral resources offer a chance to leapfrog development. However, mining extraction is portrayed as an environmentally and socially destructive industry. Furthermore, most of the world's post-use mineral waste, specifically e-waste, is not safely managed. Therefore, the low-carbon transition also shows that current mineral production and consumption patterns are unsustainable.

The challenges that the sustainable use of minerals poses for policymakers motivate the subject of this thesis. I aim to contribute to the policy design discussion considering potential market failures. In this thesis, the sustainable use of minerals refers to the extraction, processing, and utilization of minerals to minimize adverse environmental impacts while maximizing economic benefits for present and future generations. It implies that the use of minerals must be conducted in a way that is within the Earth's capacity to, for example, maintain biodiversity and absorb and process waste and pollution. This constraint requires a shift towards a circular economy that prioritizes the reduction of waste and pollution and the efficient use and recycling of resources. It also involves promoting policies that reduce the associated environmental impact of using minerals at different instances of their life cycle.

Central to the entire discipline of economics are the concepts of scarcity, efficiency, and sustainability. In the second part of this synopsis, I reflect on these concepts and signal how I applied them in each paper. Later, I discuss other fundamental questions about market failures, policy failures, and sustainability trade-offs. The methods supporting this research are drawn on dynamic optimization models applied to natural resource economics. Thus, I briefly explain why such traditional methods can be used to gain more understanding of contemporary problems around natural resources, recognizing their advantages and limitations.

The thesis consists of four research papers in addition to this synopsis. The first paper discusses mineral waste values and how recycling may alleviate resource scarcity. The second paper takes a closer look at the circularity criteria and assesses the efficient conditions for waste markets. While these two papers are based on a similar analytical model, the policy outcomes refer to different spheres and market failures. The third paper accounts for the impact of mineral extraction and how it competes with overlapping ecosystem landscapes. The fourth and last paper analyses the fiscal implications of implementing environmental taxes in the mining sector and examines which factors may affect tax effectiveness.

This thesis focuses on the environmental dimension of sustainability. That includes minimizing carbon emissions in mining operations, reducing land use, preserving biodiversity and ecosystems, and managing used-mineral waste. The social dimension of sustainable mining (e.g., improving the well-being of local communities and workers, preventing social conflict, and enhancing the governance of natural resource wealth) is equally important for gaining support for a consequent, responsible, and just transition. However, that community and labor dimension is out of the scope of this thesis.

2. Key concepts

a. Scarce or critical materials?

Between 1991 and 2022, identified lithium resources multiplied from 12 to about 100 million tons. During this period, global lithium production has ramped from 6.3 to 130 thousand tons, and lithium prices have soared from USD 4 to 37 thousand per ton.[1] Yet from 1991 onwards, lithium reserves and production has been concentrated in four countries. In other words, for almost three decades, lithium has no longer been a scarce resource, but it has been in control by a few. With the shift to a clean energy system, lithium demand is set to rise dramatically. Jointly with other materials like cobalt, copper, nickel, and graphite, lithium is an essential component of battery-powered electric technologies and has been declared critical for the clean energy transition.

Here a note of caution is important. Scarce materials and critical materials are related but distinct concepts. Scarce materials refer to rare materials or limited reserves, making them difficult or expensive to obtain. Therefore, geological, technological, and certain economic factors define their availability (Mayer & Gleich, 2015). These materials may include precious metals or rare earth elements. Advances in technology can make it possible to extract minerals that were previously considered too scarce or too difficult to extract. For example, advances in offshore drilling have made it possible to extract minerals from deeper underground, also on the seabed (Hannington et al., 2017). Therefore, the economic viability of mining and extracting minerals can change over time; as the price of a mineral increases, it becomes more economically attractive to invest in exploration, which can increase the available mineral supply.

Critical materials, on the other hand, are materials essential for certain applications, with few or no substitutes and risks associated with their availability and market

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[1] USGS Commodity Survey from (1991) and (2023).

power (Erdmann & Graedel, 2011; Graedel et al., 2012). For instance, beryllium is essential for aerospace and defense systems. It became a critical material because geopolitical and extraordinary factors have threatened its availability. Likewise, the COVID-19 pandemic and Russia's invasion of Ukraine have disrupted global supply chains in energy and technology (Schwellnus et al., 2023), extending the list of critical minerals.[2]

Not all scarce materials are critical, and not all critical materials are scarce. For example, gold is a scarce material, but it is not considered a critical one because it has few industrial applications beyond its use in jewelry and currency. In contrast, the market configuration of lithium makes it a critical material, not necessarily scarce, because increasing lithium prices allow exploring a variety of sources and ore grades expanding reserves. In the worst case, scarce materials may also be critical. Gallium, for example, is a critical input for integrated circuits -IC- and optical devices. Uses of ICs include defense applications, high-performance computers, and telecommunications equipment. Scarce gallium resources make the United States a net import reliant on primary sources like China and Ukraine.[3] Therefore, mineral availability is also a question of security and hyper-competition in the tech imperium (Kalantzakos, 2023).

In the context of a low-carbon energy transition, a key question is how policymakers' and companies' responses to resource discovery (scarcity) and importance (criticality) will determine whether minerals enable the clean energy transition or become a bottleneck. Besides the dominant role of a few countries as global suppliers of critical materials, the vulnerability of supply chains might be exacerbated by export restrictions such as excessive export taxes in China and imposed sanctions on Russia in 2022. The OECD (2022) suggests that a key step in reducing the vulnerability of value chains is avoiding trade restrictions. The IPCC (2022, p. 32) suggests that material and supply diversification strategies, technological improvements, and circular material flows can increase material efficiency and reduce material supply risks. The IEA (2022) recommends that besides an adequate investment in diversifying sources of new supply and enhancing supply chain resilience and market transparency, scaling up recycling has a pivotal role in preparing for the rapid growth of waste volumes.

The first paper of this thesis analyses how recycling can be a solution to alleviate resource scarcity for a critical material like lithium. The words "scarcity" and "criticality" are almost interchangeable in the paper. The study demonstrates that the more scarce or critical the resource is, the more crucial recycling is to secure future mineral supply. With persistent scarcity (or criticality) and without the ability to recycle, mineral prices will likely be much higher to balance supply and

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[2] In 2011, the European Commission published a list of 14 critical materials crucial to Europe's economy. In 2020, the list grew to 30 materials. In 2023, the USGS listed 50 critical commodities essential for US security and economic development.

[3] The 2022 US Critical minerals list, Table 4, Page 21, in USGS (2023)

demand. In this research, recycling is an efficient way to expand and diversify mineral sources while maximizing collective benefits because more material volumes are affordable. Climate action is urgent; therefore, government intervention is warranted to achieve material efficiency in due time to accelerate electromobility. That can be done by creating incentives, via subsidies to consumers, for example. Nevertheless, such subsidies cannot be too high or exist for too long, and the first paper of this thesis explains why.

b. Market failures and policy failures

In this thesis, the government is a powerful planning institution, and public policy can fix any market failure. Throughout this thesis, we can see how subsidies can fix an inefficient recycling market (Paper 1); landfill taxes internalize the social costs of harmful waste (Paper 2); Pigouvian taxes in extraction will account for mining ecological externalities (Paper 3); and carbon taxes will tag harmful emissions (Paper 4). Despite all well-intentioned purposes for addressing market failures, policies can sometimes do more harm than good if they are not well-designed and implemented.

To some extent, certain unintended consequences can be foreseen. For example, in the first paper, we see that subsidies are intended to stimulate recycling and reduce material scarcity concerns. However, when subsidy payments are very high, much higher than the net welfare gains, that will unnecessarily increase the burden of public spending on recycling. Furthermore, research has shown that when subsidies target the recycler's inputs instead of outputs, the policy may lead to illegal burning or dumping (Fullerton & Kinnaman, 1995; Ino & Matsueda, 2019). On the other hand, some recycling technologies do not necessarily provide benefits but can rather cause additional environmental impacts (Lafforgue & Lorang, 2022; Mohr et al., 2020). Such unintended effects suggest that if recycling is a desirable outcome, the government should target subsidies directly to the recycled output, keep subsidy payments at a moderate level and time, implement additional environmental regulations, and monitor waste management practices.

In the second paper, the results can lead the discussion about another unintended and perverse consequence of policy intervention; in this case, landfill taxes may also induce illegal dumping (Briguglio, 2021), dis-incentivize material recovery, and discourage investment in separation technologies (Fletcher et al., 2018). Furthermore, unilateral policies for waste management will remain with minor effects if weak waste management regulations, particularly in developing countries, facilitate illegal transboundary movements (Cheshmeh et al., 2023).

In the second paper, we can also see how policies, particularly subsidies to recyclers aiming for material efficiency and waste management, can cause rebound effects. The rebound effect in natural resource exhaustion refers to the phenomenon where increased efficiency in using a resource can lead to an increase in its overall consumption rather than a decrease. For example, the efficiency of mineral use increases with recycling, but the rate of resource raw mineral consumption may not decrease proportionally. Essentially, the rebound effect can undermine the expected benefits of greater resource efficiency, potentially resulting in no net savings in resource use, more waste, and greater environmental damages. This effect highlights the importance of other strategies, such as conservation and substitution, especially if the final goal is not merely to reduce mineral consumption and waste but to make a clean energy transition less dependent on critical materials in the long term.

The discussion so far has been that well-intended policies can have unintended consequences. This suggests that the policy analysis developed here is deterministic and in line with what philosophers call "consequentialist thinking" and economists call "classic utilitarianism". Consequentialist or utilitarian public policy focuses on maximizing the overall well-being of society by evaluating the outcomes of different policy options and selecting the one that will produce the greatest net benefit (Sinnott-Armstrong, 2022). While this approach has some advantages, there are some practical constraints that limit its effectiveness. For example, there may be uncertain factors that make it difficult to assess future consequences of present actions in human-environment systems, making it challenging to accurately measure the well-being of society. Likewise, neutralizing externalities via market policies, such as carbon taxes, may allow compensation for foreseen damages of present actions but not for past or accumulated irreversible damages because such policies cannot revise past actions (Hoberg & Baumgärtner, 2017). In other words, policies that act under uncertainty and irreversibility face a trade-off between (ex-post) efficiency and intergenerational equity (Íbid, p. 24). This trade-off implies that in front of problems affecting several generations, such as climate change, policies fail to capture the maximal potential utility for all generations or to distribute utility equally across generations.

c. Sustainability trade-offs

The latest IPCC report (2023) emphasizes that "the extent to which current and future generations will experience a warmer and different world depends on our choices now and in the near term". We do have a factual awareness of the catastrophic consequences of climate change. However, even if we act now with altruism for a long-run sustainable future, our actions and policies will face conflicting goals and unintended consequences.

For example, low-carbon technologies can effectively mitigate climate change but carry contradictions because they intensify mining patterns that pose severe threats to biodiversity (IPBES-IPCC, 2021; Sonter et al., 2020). Moreover, mining can inadvertently degrade several ecological limits. Such limits can be set as the planetary boundaries defined by Rockström et al. (2009), within which humanity can operate safely and sustainably. Among nine boundaries, mining can pressure at least five boundaries, including biodiversity loss, land use change, freshwater depletion, chemical pollution, and air pollution, which can ultimately exacerbate climate change. Policymakers, therefore, face a dilemma because well-intended policies to reduce climate change will aggravate other tensions (Engström et al., 2020).

At this point, we ponder that despite government efforts to increase material efficiency to push electromobility, some mineral reserves will remain untapped, notably because of environmental issues and local pressures. The third article of this thesis extends the sustainability dimension and considers the transgression of two other boundaries: land use and biodiversity. There, the focus shifts toward the beginning of the production chain and analyzes the impact of mineral extraction in its very cradle. In this case, we analyze the problem of resource depletion from the resource owner's perspective. Here only extractors are in the spotlight to check how their decision to extract more resources will vary depending on whether environmental costs are considered. If policymakers tax those hidden costs, production paths will slow down.

The third paper focuses on a country case: Chile, one of the four major producers of lithium. Because the lithium supply has few players involved, one can expect that if a Pigouvian tax is successfully implemented, the subsequent reduced Chilean supply will influence the global lithium market. It means that lowered supply will push mineral prices up and that temporary resource scarcity may give incentives to recycling. Still, higher mineral prices will incentivize exploration, viability, and harmful extraction of mineral resources elsewhere, meaning sustainability trade-offs also have a spatial dimension. All these post-tax effects are plausible but were out of the scope of the paper analysis. What remains evident is that while governments try to address one market failure in one place, their policy actions may also have unintended effects elsewhere.

The fourth article of this thesis suggests that when it comes to natural resource exhaustion, in some contexts, society inevitably faces an intergenerational sustainability trade-off. Developing countries, for example, often face significant economic and development pressures, such as poverty, unemployment, and inequality. For them, the exploitation of mineral resources can be seen as a way to generate revenue, create jobs, and promote economic growth. However, this may come at the expense of long-term sustainability objectives.

Despite the accumulated environmental burden of mining, mineral-rich countries like Chile continue to rely heavily on mining revenues to support their economies. Under such conditions, Pigouvian taxes may be seen as a threat to this revenue stream, as they increase the costs of mining and reduce profits for mining companies. Consequently, implementing regressive taxes such as Pigouvian taxes may find resistance as governments may sacrifice public revenues for environmental preservation. In addition, developing countries may also lack regulatory frameworks and enforcement mechanisms needed to effectively implement and enforce environmental taxes. This can create additional resistance to environmental taxes, as they will be seen as ineffective or unfair if they are not applied consistently or if there are loopholes, such as transfer mispricing, that allow mining companies to avoid paying the taxes.

As shown in paper four, if Pigouvian taxes are difficult to implement or are suspected to be ineffective, the only way to prevent ecological damages is to reduce mining projects and leave mineral resources in the ground at the expense of less public and private revenue. So, instead of a high Pigouvian tax, the government can reduce the project size from the beginning. Then, a reduced accumulated production will protect the environment, reducing at the same time project cash flows, mining project profitability, and government revenues. At this point, policymakers are facing a trade-off: hopefully, less environmental damage but less mining revenues.

Politicians may be incentivized to prioritize the interest of current voters over future generations and prioritize policies that benefit their citizens in the short term, even if they have negative impacts on future generations (Portney & Weyant, 2013). Nevertheless, the trade-off between short-term efficiency and intertemporal equity might not be caused solely by political incentives. In the fourth article, discount rates reflect relative time preferences and how public and private interests may differ when prioritizing immediate over deferred cash flows. Despite that, mining is proven to be a highly rentable activity, and it would be less financially affected if a global carbon tax were introduced compared to other sectors (Cox et al., 2022). Still, policymakers may lack accurate information about average capital costs and the long-term impacts of different policy options. Therefore, asymmetric information and lack of transparency may reinforce all trade-offs as policymakers do not have access to sufficient data to predict the opportunity costs of mining projects and the subsequent effects of environmental policies.

3. Methods

a. Hotelling and the scarcity question

Hotelling's rule is an essential concept in natural resource economics because it provides a framework for understanding the optimal depletion of non-renewable resources over time. In Hotelling's analytical model, natural resources such as minerals are finite and, therefore, scarce. Thus, the longevity of the finite resource will depend on the producer's decisions on extraction rates. According to Hotelling (1931, p. 141), in a perfectly competitive market, the price of a resource stock will increase along with the real interest rate. Some scholars refer to this price as the "asset price" (Gaudet, 2007), "shadow price" (Lin et al., 2009), or scarcity rent, meaning that the optimal depletion of a non-renewable resource involves extracting it at a rate that balances the current and future benefits of extraction considering fix stocks and latent scarcity. If the resource is extracted too quickly, that asset price will be low in the short term but will increase rapidly as the resource becomes scarcer (Hotelling, 1931, p. 139).

While the Hotelling theory is widely accepted, there are some assumptions underlying the theory that the literature has challenged. The simple Hotelling rule assumes that the amount of minerals in Earth's crust is fixed and known. However, as was discussed in section 2.1 above, in some cases, we can question the idea that minerals are scarce because discovery rates are above zero. When new discoveries of mineral deposits can increase the total amount of the resource available, then supply curves will shift upward, affecting the price trajectory (Gaudet, 2007). Researchers try to constantly reconcile the Hotelling rule with empirical evidence on world mineral prices and find that mineral market prices (not necessarily asset prices) have been trendless despite temporary resource shortages (Cynthia Lin & Wagner, 2007; Lin et al., 2009).

Another assumption that can challenge the Hotelling rule is related to the durability of resources and metals. The Hotelling rule assumes that once minerals are extracted and used, they are lost forever. However, minerals are durable resources meaning that once extracted, durable minerals can maintain a continuous flow of services (Gaudet, 2007), so they can be reused and recycled. Another implication of a durable resource is that its demand will depend on the *stock in circulation* rather than flows of production, and prices will depend on expected *changes* in future prices as well as current price levels (Levhari & Pindyck, 1981). Assuming that recycling technologies are affordable and that consumers are aware of the importance of circular economies, it will be possible to recover and reuse minerals from discarded products. Consequently, durability can enlarge mineral supply (Schulze, 1974), release affordability concerns (Rosendahl & Rubiano, 2019; Weinstein & Zeckhauser, 1974), and even contribute to the long-term growth of the economy (Pittel et al., 2010) and reduce environmental pressures from waste and emissions (Lafforgue & Lorang, 2022). In all those cases, asset prices may or may not follow the Hotelling rule, and the initial resource stock matters to determine price levels.

The Hotelling rule assumes that there are no substitutes for non-renewable resources. However, the literature has shown that substitution can take place when the mineral price rises to a certain level which makes alternative sources economically more attractive (Hoogmartens et al., 2018). If the direct substitute is a recyclable material, then market power and strategic behavior can explain why mineral prices and scarcity rents may be U-shaped (Ba & Soubeyran, 2023). On the other hand, advances in materials science and engineering are making it possible to develop alternative materials that can replace or reduce the need for the resource. Under the urgency of scaling up electronic devices, scientists are trying to develop a new generation of batteries where critical materials like lithium are no longer necessary (Philippot et al., 2023). This can reduce mineral demand and make its price trajectory less predictable.

The role of consumers' behavior can also challenge the Hotelling rule's assumptions. Demand does not have significant attention in the Hotelling analysis, barely when it is identified as a linear function (1931, p. 158). However, when choosing empirical forms for demand curves and including the possibility of substitution, the problem of exhaustible mineral assets and price prediction becomes entangled. In the context of a clean energy transition, changes in consumer preferences and government policies to promote renewable energy have led to shifts in mineral resources demand affecting their price trajectory. The remaining question is whether mineral prices are currently facing an early face of a super-cycle and for how long this could be the major driver of economic development, particularly for mineral-rich developing countries.

b. Dynamic optimization and nature as an economic asset

Under the assumption that resource efficiency is no longer required to be static but dynamic, Hotelling introduced for the first time the concept of dynamic optimization to the analysis of resource economics. That dynamic efficiency requires that each asset or resource earns the same rate of return and that this rate of return is the same at all points in time, being equal to the social rate of discount (Perman et al., 2003, p. 496). In other words, if we consider natural resources as an asset, then they will be efficiently managed if their discounted prices are equal today and in the (distant) future.

The rationality of dynamic efficiency has also been applied to other natural resources like ecosystems. Because ecosystem resources are also becoming scarcer, that makes it is necessary to critically understand how to value ecosystems and how to manage them over time. As shown in the third paper of this thesis, dynamic optimization techniques can be useful to find the management strategy that maximizes the net present value of resources wealth, both in the form of minerals and ecosystems, which incorporates both the economic benefits and the ecological damage costs of different management options over time. These techniques involve solving for the optimal trajectory of resource exhaustion that maximize the net present value subject to ecological and economic constraints. The results of the dynamic optimization analysis can provide policymakers and stakeholders with insights into the long-term economic and ecological consequences of different management decisions, including reducing exhaustion intensity or charging Pigouvian taxes for ecological damages. This can inform decisions about how to manage and value ecosystems, taking into account both economic and ecological considerations.

The first assumption of this dynamic analysis is classifying ecosystems as economic assets (Barbier, 2011; Daily et al., 2000). The categorization of ecosystems as capital assets is controversial, especially outside economics, because it raises a number of ethical and ecological concerns. Some critics argue that categorizing ecosystems as capital assets commodifies nature and reduces it to a set of economic features (Wilson, 2013), arguing that nature is something more than a form of capital to be traded. Others argue that the commodification of ecosystems may exacerbate existing social and economic inequalities, as those who own or control ecosystems may be able to extract rents or benefits from them, while those who depend on them for their livelihoods may be marginalized or excluded (Muradian & Gómez-Baggethun, 2021).

The valuation of ecosystems as capital assets often involves the use of discount rates to account for the time value of money. In general, setting accurate discount rates is a fundamental question in economics because it affects the way we value future benefits and costs relative to present ones. In environmental policy assessment, discount rates are crucial as it allows us to value the benefits of, for example, mitigating climate change or protecting biodiversity. A relatively high discount rate may undervalue the benefits of these policies, particularly those that accrue in the distant future and lead to inadequate or delayed action (Nesje et al., 2022).

Despite these concerns, some argue that categorizing ecosystems as capital assets can help to raise awareness of their economic value and prevent over-exploitation and sustainable use. However, any approach that seeks to categorize ecosystems as capital assets must be sensitive to non-monetary aspects and must be based on a comprehensive understanding of the role of ecosystems in supporting human well-being and maintaining the health of the planet (Folkersen, 2018).

c. The question of value and valuation

The question of value is controversial in economics because it involves fundamental ethical, theoretical, and policy issues that have far-reaching implications for economic activity and society. A final note of caution about the difference between the concepts of price and value. Along with this thesis, prices may not always reflect how minerals are produced (externalities) and may ignore the possibility of being reused and recycled (missing markets). That, in turn, justifies market intervention and the use of prices mechanisms such as subsidies and taxes in a way that final prices can inform society about the resource durability and (circular) value and the true cost of production, including the environmental and social impacts associated with their extraction and use. In the end, price mechanisms will encourage or discourage certain behaviors, such as using renewable energy or recycling.

In this thesis, I use the term shadow value to describe the recycling value of minerals (Paper 1), the value of waste (Paper 2), and the impact of mining on ecosystem values (Paper 3 and Paper 4). Because none of these goods are traded in markets, their hidden values are not captured by traditional market prices. Therefore, shadow values can be thought of as the additional benefits or costs that are not reflected in the price of a good or service but are still important to consider when making economic decisions because it has implications on human welfare, which, in turn, is the result of an overall assessment of costs and benefits.

Valuing nature, on the other hand, is controversial because it involves a complex and multifaceted set of issues that are not easily captured by traditional economic models. A great part of this thesis (paper 3 and 4) deal with the challenge of valuing nature. There is often disagreement on how to measure nature's values and, first, whether environmental management should depend on such valuations. Different methods of valuation may yield vastly different estimates of value, leading to debates over which method is most appropriate (Johnston et al., 2021). Suggesting new or better ecosystem valuation techniques was out of the scope of the thesis. Still, and despite being difficult to quantify nature, I believe that an approximate estimate can help to reconcile environmental economics with ecological sciences because it might help to explain why people make certain choices about ecosystem use and how their respective (shadow) values may guide natural resources management and avoid over-exploitation of scarce and irreplaceable goods.

4. Summary of the papers

Paper 1. How effective is lithium recycling as a remedy for resource scarcity?

Research questions

Considering mineral supply risks and the absence of substitutes for critical minerals, the key questions this paper examines are how recycling can remedy resource scarcity and whether market intervention is desired.

Methodology

The framework's skeleton is a standard dynamic partial equilibrium model in two scenarios: a free market and a social planner solution with its respective market-based policies. The analysis departs from the assumption that there is an opportunity of recycling valuable discarded resources. Therefore, an efficient market for both raw and used mineral resources may arise by itself if and only if consumers value the durability of mineral products. When market prices do not internalize the durable (and reusable) function of minerals, policy intervention is desirable to restore optimality. To simulate that situation, we develop a dynamic model of the global lithium market. This framework derives from the Hoteling resource model and introduces a material balance constraint together with non-linear extraction and recycling costs functions. The simulated market contains extraction, consumption, recycling, and waste accumulation. For the numerical simulation, we set a Mixed Linear Complementarity Model -MCP- programmed in GAMS software.

Findings and Policy Implications

A key finding is that without a market for lithium waste, the efficient outcome can alternatively be achieved through a proper set of subsidies to either buyers or sellers of both virgin and recycled lithium. The size of these subsidies depends, however, on several uncertain assumptions, such as technological progress in recycling, quality grade of recovered lithium, and demand elasticity. Overall, the potential costs of public funds to cover subsidies and the inherent uncertainty in mineral markets demonstrate the importance of establishing an efficient market for depreciated minerals in due time and how critical consumer awareness is of the lasting value of minerals after use.

Originality/Novelty

At the time of this publication, the cost dynamics of this model is an important contribution of this paper. That assumption allows us to infer that recycling becomes gradually more important due to a combination of higher lithium prices (related to the depletion of virgin lithium) and cost reductions for recycling. In addition, to my knowledge, no other study has simulated alternative scenarios where the government subsidizes mineral recycling, showing the subsequent welfare gains considering demand elasticity, mineral quality, technological changes, and variable costs.

Reproducibility and replicability

To verify the consistency and validity of this research results, the computational code is available online (link here). Thus, the reader can reproduce the results using the same input data or apply them to other mineral market cases and data.

Limitations

The subsidy policy suggestion is deduced from a global optimization problem which makes it difficult to implement given a wide range of uncertain assumptions and the potential burden on public budgets. Being limited to the problem of scarcity and the focus on the efficient use of durable -and recyclable- resources, this study ignores some important sustainability issues. The research did not consider the externalities of mineral use and recycling, which can adversely affect welfare. Therefore, an efficient material market is a necessary but not sufficient condition for a socially optimal solution when environmental externalities exist.

Paper 2. Policies for material circularity: the case of lithium

Research questions

This paper points out the importance of electronic waste as a problem to be addressed because improper waste management carries social risks and dissipates high-value materials. The study aims to analyze the impact of market-based policies to promote circular material reuse. The key questions are how prices can inform society about their resource use impact and how subsidies and taxes can optimize material use.

Methodology

In this study, the analytical model extends the framework presented in Paper 1 by including a negative externality from waste disposal. It incorporates a material balance condition and waste damage costs. The paper elaborates on four policy scenarios and explains the effects of optimal and suboptimal solutions. Considering a range of highly uncertain parameters, this study offers a sensitivity analysis to investigate to what extent ambiguous information affects the results and conclusions.

Findings and Policy Implications

The results of this study confirm that when it comes to waste reduction, “sticks” are more effective than “carrots”. It means a penalty tax on landfill waste disposal is more effective than subsidies to encourage recycling to reduce waste damages at optimal levels. Another reason to implement recycling subsidies cautiously is that they can promote rebound effects. The rebound effect occurs when recycling subsidies reduce the cost of using minerals, increasing mineral demand and waste and negating the environmental benefits of recycling. Governments might consider combining consumer taxes and recycling subsidies if they want to avoid rebound effects. Such measures will also have a limited impact on government budgets.

Originality / Novelty

This article deals with a timely and relevant topic about how to deal with growing electronic waste stocks. This study complements previous mainly theoretical studies on resource waste management with a quantitative analysis based on an original numerical simulation. The results are discussed in the context of relevant policy debates, making the article interesting to a wide audience of academics and policymakers.

Reproducibility and replicability

The computational code is available online (link here). Thus, the reader can verify the consistency and validity of this research results, reproduce them using the same input data or apply the model to other cases and data.

Limitations

Being limited to the problem of harmful mineral waste, this study ignores other externalities derived from extraction, recycling, and land use. Market-based policies may imply additional implementation costs. For example, implementing subsidies to recyclers may involve additional costs to monitor recycling firms' activities; thus, recycling subsidies may not provide enough incentives when dumping is an option. In certain circumstances taxing waste disposal leads to unintended consequences. For example, charging waste holders directly for disposal costs can lead to illegal burning or dumping or transboundary waste movements. Therefore, optimal policy design should also assess how uncertainty and incorrect information lead to efficiency losses.

Paper 3. Accounting for unintended ecological effects of our electric future: Optimizing lithium mining and biodiversity preservation in the Chilean High-Andean wetlands.

Research questions

This paper examines how we should account for mineral extraction's ecological impact and how that accountability may facilitate a sustainable transition to cleaner energy. The key question is, what is the socially optimal mineral extraction path when we account for ecosystem values?

Methodology

This study departs from the assumption that policymaker deals with the dilemma of rapid resource exploitation versus conservation. Then, the problem will be to maximize the "social value of the resource", which includes mineral market values and ecosystems values. Here we consider extraction in a single country and hence take the global lithium price as given. We first estimate the value of overlapping ecosystems landscapes. To do so, we use a meta-regression analysis developed by Chaikumbung et al. (2016) and follow the guidelines to use benefit transfer techniques (Johnston et al., 2021). Then, we plug those values into a competing land use model (Barbier, 2011) to evaluate the mining and conservation paths numerically and examine how the mineral market and ecosystem values compete. Our model provides an ecosystem conservation policy output based on the Pigouvian taxes to be applied for wetland losses due to mining.

Findings and Policy Implications

The evidence from this study supports the idea that any policy to control ecosystem loss, such as a tax imposed on mineral extraction, should also vary with the wetland size. Our findings provide insights into how policymakers can enforce control parameters to avoid complete wetland damages and still benefit from a mineral boom and increasing prices. Although this research focuses on lithium extraction and high Andean wetlands in Chile, the findings may well represent the broader challenge of sustainable mining and ecosystem conservation worldwide.

Originality/Novelty

This paper contributes to the scarce literature on accounting for the economic value of ecological impacts of mining critical resources for the energy transition. Despite the critical importance of the High Andean wetlands, the value of these ecosystem services is largely unknown. This paper applies a novel combination of a competing land use model and benefit transfer techniques to a case that may well represent the sustainable challenge of mining worldwide.

Reproducibility and replicability

To verify the consistency and validity of this research results, the computational code is available online (link here). Thus, the reader can reproduce the results using the same input data and apply them to other mineral market cases and data.

Limitations

One source of weakness in this study was the ecosystem damage parameter which could have affected the measurements of Pigouvian taxes. That parameter comes from an existing work that shows a continued vegetation coverage decline over time from 1997 to 2017 which is attributed to mining activity. As the parameter was estimated from historical satellite images, this does not allow us to understand to what extent the decline in vegetation in these high-Andean locations may be attributed to climate change instead. This study can be improved by calibrating this damage parameter and developing additional discussions and robustness checks, especially in the combined effect of increasing global temperatures on these sensitive ecosystems in addition to potential mining. Another source of weakness is the ecosystem values obtained from the benefit transfer function. Instead of getting a single value for wetlands, it can be possible to obtain a range of potential values that are conditional on the assumptions inherent to the wetlands and context features.

Paper 4. How effective are environmental taxes in the mining industry?

Research questions

The study was designed to discover which factors can limit the economic and environmental effects of Pigouvian taxes at a project level. The research has raised several questions about how governments in mineral-rich developing countries can introduce environmental taxes without exacerbating the possible disadvantages of their fiscal regimes. A key question is how fiscal policies can enhance environmental policies.

Methodology

The analysis of this study is based on the financial cashflow model called "Fiscal Analysis of Resource Industries" – FARI developed by the International Monetary Fund. The benefit of this approach is that it allows the design and evaluation of a fiscal regime by assessing a mining project's economic and financial characteristics. Another advantage is that it allows estimating the government and investor participation in a resource project, thus providing indicators and results in language understandable to business and financial analysts and government agents.

Findings and Policy Implications

The results of this study confirm that only if the tax rate is set at an appropriate level, environmental taxes will give enough incentives to pursue strategies to minimize environmental damages. Furthermore, flaws in environmental tax design can reduce its effectiveness in reducing environmental harm. For example, when applied as an *ad valorem* charge on production, such as a royalty, Pigouvian taxes can be affected by transfer pricing manipulation. Thus, the opacity of market prices can compromise the effectiveness of environmental taxes. The results of this study reveal that authorities cannot design environmental taxes in the mining sector in isolation from other taxes. It must consider existing and new distortions of the tax system.

Originality/Novelty

To my knowledge, this is the first study examining the fiscal impact of environmental taxes in the mining industry at a project level. Different international advisory institutions, including the IMF, NRGI, and UN, have developed financial models to provide technical assistance and evaluate fiscal regimes in extractive industries, but so far, little attention has been paid to environmental taxes.

Reproducibility and replicability

To verify the consistency and validity of this research results, the financial model is available online (link here). Thus, the reader can reproduce the results using the same input data and apply them to other mineral market cases and data.

Limitations

This study also makes evident the importance of setting private and social discount rates more precisely. When private hurdle and discount rates are set too high, they will likely lead to false rejection of projects that will help social development. Another area to improve in this study is the assumptions on alternative energy sources and mitigation policy costs. The results are susceptible to those assumptions affecting the estimates of future public revenues. Besides, a financial cash flow analysis does not allow us to infer whether environmental taxes bring double dividends to the economy. Further research must consider the welfare and distribution effects of environmental tax reforms in the mining sector and how environmental taxes can be an instrument to enhance a more decentralized natural resource governance that better apprehends the needs and citizens' preferences for their natural resource wealth.

5. Concluding remarks and research agenda

This thesis contributes to the discussion on policy design for the sustainable use of minerals. This research work has challenged some of the basic assumptions in the analysis of the dynamic efficiency of natural resources, such as scarcity, durability, and minerals values after use. The first paper assumes that when it comes to material scarcity, recycling is an efficient way to expand and diversify material sources while maximizing collective benefits with more affordable resources. Thus, government intervention is justified to achieve that efficient solution, given the pressure to speed up electromobility based on critical and scarce mineral resources. The scope of this study was limited in terms of material efficiency. Despite this, the study certainly adds to our understanding of the durable and circular properties of minerals and how prices will respond to that durability condition. A natural progression of this work is to analyze how raw mineral stocks may change when introducing a discovery rate based on historical data as well as technological conditions. The effect of market power and strategic behavior defied by a recycling market (Ba & Soubeyran, 2023; Hoogmartens et al., 2018) can be complemented with the analysis of applying subsidies to recycled output instead of waste input. Introducing the role of the mineral processing sector and battery producers in the case of lithium is also an interesting extension of the model.

This research has questioned the extent to which material efficiency is consistent with the environmental concerns due to expanding volumes of electronic waste. The second paper of this thesis argues that prices can inform society about their resource use impact, but only when considering the durable value of minerals and their impact after use. So, the market failure focuses on the environmental issues of (electronic) waste, still considering the condition of material circularity. This study has found that, generally, a landfill tax is an optimal way to reduce mineral product waste. The findings will be of interest to researchers and policymakers concerned with the design of policies promoting the circular reuse of minerals and to those agents or institutions actively concerned about how to account for the health cost of toxic waste. Efficient circular material may require a more comprehensive and integrated approach to reusing and re-manufacturing products. For example, electric vehicle batteries can be reused in off-grid-based stationary infrastructure. The modeling framework can also be extended to incorporate a landfill capacity constraint which will add not only a land stock constraint but also the potential cost of waste management in the landfills, meaning how to make residual waste less harmful.

This thesis argues that low-carbon technologies may not be sustainable when they intensify mineral extraction, pushing land use and biodiversity to their limits. In the third paper of this thesis, dynamic optimization techniques aid in determining the best management strategy for resource wealth, both minerals and ecosystems, incorporating both the economic benefits and the ecological damage costs of different management options over time. The results of a dynamic optimization analysis provide insights into the long-term environmental and economic consequences of various management decisions, such as reducing exhaustion intensity or charging Pigouvian taxes for ecosystem damage for different landscape sizes. This can inform decisions about the pace at which mineral production should take place, considering both economic and ecological considerations. The estimates of the wetland's coverage change due to mining make these finding less generalizable as mining impacts on ecosystems are context dependent. To fully understand the environmental impact of mining, experts from various disciplines must work together to analyze the complex interactions between the mining process and the surrounding environment.

This thesis establishes an important note of caution about the difference between the concepts of price and value. In all papers, shadow prices expose hidden values and costs not captured by traditional market prices. The fourth paper, however, shows that despite any accurate estimation of the true mineral production and ecological costs with its corresponding Pigouvian tax, asymmetric information, and market price opacity can compromise the environmental benefits of such taxes. Therefore, it is suggested that Pigouvian taxes in the mining sector target the inputs of mining operations to influence production methods. The welfare and distribution effects of environmental tax reforms in the mining sector need to be examined further, as well as how environmental taxes can enhance decentralized natural resource governance that is better suited to citizens' needs and preferences in relation to their natural resources. Further research can assess alternative financial instruments to manage the environmental impact of mineral projects, as environmental taxes must be justified primarily by the cost-effective achievement of environmental goals.

The problems I have raised in this thesis are more prominent and much harder to solve. But if any of the suggested tools are put into practice, a learning process will begin, which will eventually lead to a distinction of control parameters and action scope. Although the conclusions in this thesis were derived from the lithium market, the economic models originated in this research can be applied in a broader range of mineral industries. These models can evolve to include probability and stochastic analyses. All computational and financial models used in this thesis are publicly available, so the results can be verified and validated using the same input data, computational steps, and conditions of analysis. The accessibility to these models is also an invitation for other students, researchers, and policymakers to replicate these models and apply them across other studies aimed at answering similar or complementary scientific questions.

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Paper 1

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How Effective is Lithium Recycling as a Remedy for Resource Scarcity?

Knut Einar Rosendahl[1] · Diana Roa Rubiano[1]

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Abstract
We investigate to what extent recycling can remedy resource scarcity, and whether market intervention is desired. For doing so, we develop a dynamic model of the global lithium market. An efficient market for resource waste allows consumers to internalize the waste value when they buy the resource. Without a market for lithium waste, we show that the efficient outcome can alternatively be realized through a proper set of subsidies to either buyers or sellers of both virgin and recycled lithium. We find that optimal subsidies may become quite substantial in the second half of this century. The size of these subsidies depends, however, on several uncertain assumptions such as technological progress in recycling, quality-grade of recovered lithium, and demand elasticity.

Keywords Natural resource economics · Exhaustible resources · Minerals · Recycling

1 Introduction

Lithium resources are crucial for the electrical revolution, especially when it comes to electrifying the transport sector through lithium-ion batteries (LiBs). Lithium is a non-renewable resource, and its availability allows low-carbon technologies development and electricity storage from intermittent sources like sun and wind, such as smart grid storage. Most lithium resources are in a few countries, with more than half of identified resources found in the three South American countries Argentina, Bolivia and Chile. Furthermore, all identified resources globally are located onshore (brines, pegmatite and clays). Extraction costs appear to be competitive enough to secure supply in the medium-term. However, we question the affordability of primary lithium resources in the long run, and whether there exist alternatives to continuing this energy transition.

Lithium recycling can extend the life span of the lithium stocks, yet, some researchers have questioned the potential for such a solution (Kushnir and Sanden 2012; Pehlken et al. 2017). Nowadays, lithium recycling is neither functional nor economically feasible

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✉ Diana Roa Rubiano
diru@nmbu.no

Knut Einar Rosendahl
knut.einar.rosendahl@nmbu.no

[1] School of Economics and Business, Norwegian University of Life Sciences, Chr. Magnus Falsens vei 18, 1430 Ås, Norway

(Andersson et al. 2017). Therefore, a market for second hand lithium does not exist. However, lithium prices are likely to climb as lithium demand continues to rise. Thus, the incentives to recycle depreciated lithium will be enhanced as lithium prices rise. Also, the rush of lithium will promote new investments and discoveries. Even remote and costly resources from the ocean could become economically attractive, and then increase available stocks (Sverdrup 2016).

In this paper, we ask whether an efficient market for depreciated lithium will emerge in the future. We investigate to what extent a recycling market can remedy resource scarcity, and whether market intervention is desired. To do so, we develop a dynamic model of the global market for lithium. We first derive analytical conditions, comparing the socially optimal outcome with the market outcome. Next, we calibrate the model to the global lithium market and perform simulations to derive insights about the importance of recycling of lithium and related policies.

Recycling is a way to conserve natural resources. Economists studying this issue reformulated the traditional Hoteling model of resource exhaustion and indicated the recycling effects in two perspectives. First, recycling enlarges supply with waste recovery (Schulze 1974), releases affordability concerns (Weinstein and Zeckhauser 1974), and even contributes to the long-term growth of the economy (Pittel et al. 2010). Second, recycling can mitigate environmental damages (Hoel 1978). It can lower landfill costs of waste, reduce water and energy use, and preserve ecosystems mostly affected by strip mining. Here, we set aside environmental waste impacts and focus on the opportunity of "mining" valuable discarded resources.

We argue that there exists a positive externality if there is no efficient market for lithium waste, e.g., that consumers do not consider that they can sell depreciated lithium. Lithium's durability through the recycling process provides it with additional consumer utility. Lithium can withstand regular recycling without losing useful properties. As a result, durability promotes added longevity to value. Thus, the mineral will hold value as long as people find it a useful substance in consumer products, and this influences price behavior (Levhari and Pindyck 1981). In batteries and electronic consumer products, lithium will lose apparent value as the product depreciates, but the recycling process restores value to the discarded material, or re-*circulation of matter*.

Our model assesses what happens when recyclable minerals could return indefinitely to the market, and the effects of simultaneous actions by consumers and producers. Collecting and recycling depreciated resources affects mineral consumers and producers. Mineral suppliers can affect both what remains to be extracted and what could be recycled in the next period, creating potential competition between mining firms and recyclers (Ba and Mahenc 2018). Mining firms may find that their most important competition comes not from other firms' products, but from their own earlier production (Stewart 1980). In our case, recycling greatly affects consumer surplus and producers' profitability.

The literature on recycling of non-renewable resources assumed constant or zero extraction and recycling costs (Weinstein and Zeckhauser 1974; Andre and Cerda 2006; Pittel et al. 2010). We assume unit extraction cost increases with accumulated production but decreases along time due to progress in technology. We also acknowledge that recycling costs are positive, assuming that marginal costs are strictly increasing in the recycled quantity, creating a gap between the shadow price of depreciated lithium and the resale value of recycled lithium. In line with Schulze (1974), we point out that scrap resources will become so precious that the society cannot afford the opportunity cost of accumulating waste.

An efficient market for resource waste allows consumers to internalize the waste value when they buy the resource. Pittel et al. (2010) propose subsidies to resource extractors and recyclers to restore optimality in an inefficient market. We evaluate, in the context of lithium resources, how subsidies may enhance society's welfare while market shifts from an unregulated and inefficient market to a social planner solution. Although our work is close to Pittel et al. (2010), the models differ in several respects. Where they assume zero extraction and recycling costs, we consider non-linear cost functions for both extraction and recycling. We also apply the model to the lithium market and simulate a range of scenarios to get a better insight about this market, in particular the importance of recycling and the potential need for market intervention. We are not aware of previous studies that have applied dynamic models of non-renewable and recyclable resources which such cost dynamics.

In Sect. 2 we introduce the model and emphasize the differences between the (free) market outcome and the efficient (social planner) solution. We show that a proper set of subsidies to buyers or sellers of both virgin and recycled lithium can realize an efficient solution. Section 3 describes the numerical model, building on the analytical part, and presents our simulations for the global lithium market. We find that optimal worldwide subsidies may become quite substantial in the second half of this century. The size of these subsidies depends, however, on uncertain assumptions, such as technological progress in both extraction and recycling, quality-grade of recovered lithium, and demand elasticity. To conclude, in Sect. 4, we provide policy insights and outline some issues worthy of further research.

2 Analytical Model for the Global Lithium Market

This section presents our theoretical model for the global lithium market. Although we formulate it in the lithium context, it generalizes to other non-renewable and recyclable resources. We first derive the free market solution (Sect. 2.1), then describe efficient or social organized solution (Sect. 2.2) and compare with the free market one. In this analytical model section, we consider one representative consumer, one representative producer, and one representative recycler.[1]

2.1 Free Market Solution

We first consider the market outcome. Free entry and competitive behavior in both the mining industry and the recycling sector is assumed, except that access to lithium resources are needed to supply primary lithium.[2] In a market solution, consumers may, or may not contemplate that used lithium has a value for society. Let P^L denote the market price of lithium, i.e., either virgin lithium or recycled but quality-grade adjusted lithium. Further, let

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[1] In the numerical simulations, we consider several consuming sectors and several producing countries. Moreover, we let utility and cost functions change exogenously over time, reflecting income growth and technological change. The qualitative insights drawn in this section would not change if we incorporated these features in the analytical model.

[2] The effects of market power and strategic behavior in this context have been studied by, e.g., Grant (1999), Sourisseau et al. (2017), Martin (1982) and Ba and Mahenc (2018). For instance, the latter study shows that a monopolistic extractor will slow down extraction vis-à-vis the socially optimal solution when facing a prospective recycler.

P^W denote the price of depreciated waste of lithium, which the recycling industry will buy in the market, and P_C^W the price consumers will get if they are able to sell their used lithium. We will consider the cases $P_C^W = P^W$ and $P_C^W = 0$ (see discussion at the end of this section).

2.1.1 Extraction of Lithium

To produce primary lithium x_t, a firm faces the following optimization problem:

$$\max_{x_t \geq 0} \pi^E = \int_0^\infty \left[P^L x_t - c^E\left(A_t\right)x_t\right]e^{-rt}dt \tag{1}$$

Although lithium is a non-renewable resource, we do not consider a given stock of lithium resources. Instead we assume that unit extraction cost $c^E\left(A_t\right)$ increases with accumulated extraction $A_t(\partial_{A_t} c^E > 0)$, where accumulated extraction increases according to $\dot{A} = \frac{dA}{dt} = x_t$. This is in line with the theoretical formulations of Farzin (1992) and similar to dynamic models of fossil fuel extraction, e.g., Berg et al. (2002) and Grimsrud et al. (2016). Total extraction costs are then given by $CE = c^E\left(A_t\right)x_t$. This cost function disregard short-term capacity constraints, as we are interested in the long-run effects.[3]

We adjust the cost function to a more realistic form. In contrast to Pittel et al. (2010), we use a cost function of mineral extraction that considers the effect of accumulated production and technological change:

$$c^E\left(A_t\right) = c_0 e^{\eta A_t - \tau} \tag{2}$$

Equation (2) assumes that unit extraction costs (starting at c_0) increase with accumulated supply (A_t) and decrease with (exogenous) technological progress (τ). The parameter η represents the rising costs rate as accumulated production increases and is calibrated to the initial stock levels of lithium resources for each producer.

As accumulated production imposes a constraint on the maximum affordable extraction costs and remaining profits, this shadow cost or scarcity rent is represented by $\lambda^E \leq 0$. The transversality condition on terminal stocks $\dot{A}$ requires that the discounted shadow value λ^E tends to zero as time goes to infinity:

$$A_{t=0} = 0 \quad \text{and} \quad \lim_{t \to \infty} e^{-rt}\lambda A_t = 0 \tag{3}$$

The current-value Hamiltonian is: $H^C = P^L x_t - c_0 e^{\eta A_t - \tau} x_t + \lambda^E x_t$. Thus, the necessary conditions for an interior solution ($x_t > 0$) are:

$$x_t : \quad P^L = c^E\left(A_t\right) - \lambda^E \tag{4}$$

$$A_t : \quad \dot{\lambda}^E = r\lambda^E + \eta c_0 e^{\eta A_t - \tau} x_t \tag{5}$$

Then, an optimal production level will be chosen when lithium prices equal extraction costs minus the shadow cost of the resource property rights. The optimal path of the expected rent from future accessible resources (λ^E) will grow at a pace defined by the interest rate and the increasing marginal costs as extraction accumulates ($\partial_{A_t} c^E = \eta\, c_0 e^{\eta A_t - \tau}$).

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[3] In the numerical simulations we also account for transport costs as well as the costs of adjusting output from the base year level to the optimal level. (See “Appendix 1” for more details).

Extraction costs vary with ore-grades. Thus, it is economically optimal to deplete the cheapest resource first (Solow and Wan 1976; Boyce 2012). As low-cost resources become exhausted, extraction must turn towards deeper and costlier deposits. While extraction costs increase, scarcity rents may or may not decrease with time (Hanson 1980).

2.1.2 Consumption of Lithium

Lithium consumption can come from either virgin lithium (x_t), or recycled lithium (w_t). Recycled lithium may have inferior quality, and $q \leq 1$ denotes the quality-grade of recycled lithium relative to virgin lithium. We assume that the two types of lithium are homogeneous, when adjusting for possibly inferior quality-grade of recycled lithium. Thus, disregarding storage of lithium, we must have $y_t \leq x_t + qw_t$.

Let $U\left(y_t\right)$ denote the consumer's money-metric utility of using lithium, and $MU\left(y_t\right)$ the marginal utility of consuming lithium. So $U\left(y_t\right) = \int_0^{y_t} MU\left(y_t\right)dt$ represents the willingness to pay for combined industry output, virgin and recycled. This also represents the gross consumer surplus of consuming lithium. For the empirical test of this assumptions, we adjust the utility function to a more realistic form. We assume the following standard utility function:

$$U_t\left(y_t\right) = \boldsymbol{\Phi} + \beta_t\left(y_t\right)^{\frac{1+\alpha}{\alpha}} \tag{6}$$

where $\boldsymbol{\Phi}$ some constant, α represents the (long-term) price elasticity of demand, and $\beta_t = \frac{\alpha}{1+\alpha}\left(\frac{1}{y_0\sigma_t}\right)^{\frac{1}{\alpha}}$. The term y_0 denotes the initial demand level, while σ_t is an exogenous growth function reflecting the underlying growth in demand. For more details on the marginal utility and demand functions see "Appendix 2".

The stock of lithium in use L_t develops according to $\dot{L} = \frac{dL}{dt} = y_t - \gamma L_t$,[4] where γ denotes the annual depreciation rate of lithium stocks in use (thus, $1/\gamma$ is a measure of the lifetime of the lithium before it has to be recycled or discarded). Consumers also decide how to handle depreciated material. There is a competitive market for buying depreciated lithium and consumers may, or may not, have incentives to sell that input to recyclers.

The depreciated lithium (γL_t) is available for recycling. Thus, we have $w_t \leq l_t \leq \gamma L_t$, where l_t represents the input of depreciated lithium that enters the recycling process. In line with Schulze (1974), we assume that just a fraction of used material is recyclable, but the fraction is endogenous and depends on profitability. If recycling does not happen the following year or period, we assume that the depreciated lithium stock is unavailable for recycling in the future, due to excessive collection and storage costs.

The representative consumer faces the following optimization problem, maximizing their net consumer surplus CS:

$$\max_{y_t, l_t \geq 0} CS = \int_0^\infty \left[U\left(y_t\right) - P^L\left(y_t\right) + P_C^W l_t\right] e^{-rt} dt \tag{7}$$

Subject to:

$$\varphi^c : \quad \dot{L} = y_t - \delta L \tag{8}$$

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[4] Note that the lithium stock L_t is measured in value terms, not physical terms, as recycled lithium enters into L_t through $y_t = x_t + qw_t$.

$$\theta^c :\quad l_t \le \delta\, L \tag{9}$$

$\varphi^c \ge 0$ denotes the additional shadow value of the lithium stock in use ($\dot{L}$) giving the ability of recycling the resource and use it again. And $\theta^c \ge 0$ denote the shadow price of the constraint $l_t \le \delta\, L$. The transversality condition on terminal stocks $\dot{L}$, requires that the discounted shadow value φ^c tends to zero as time goes to infinity:

$$L_{t=0} = 0 \quad \text{and} \quad \lim_{t\to\infty} e^{-rt}\varphi^c L_t = 0 \tag{10}$$

Thus, we have the following current-value Hamiltonian for the consumer:

$$H^C = U\left(y_t\right) - P^L\left(y_t\right) + P^W_C l_t + \varphi^C\left(y_t - \gamma L\right) - \theta^C\left(l_t - \gamma L\right) \tag{11}$$

Thus, the necessary conditions for an interior solution ($y_t, l_t > 0$) gives:

$$y_t:\ MU\left(y_t\right) = \left(\frac{y_t}{y_0\sigma_t}\right)^{\frac{1}{\alpha}} = P^L - \varphi^C \tag{12}$$

$$l_t:\ P^W_C = \theta^C \tag{13}$$

$$\dot{L}:\ \dot{\varphi}^C = (r+\gamma)\varphi^C - \gamma\theta^C = (r+\gamma)\varphi^C - \gamma P^W_C \tag{14}$$

Equation (12) states that consumers will demand lithium up until the point where their marginal utility $MU\left(y_t\right)$ equals the difference between the price of lithium (P^L) and the shadow value of lithium stocks in use (φ^c). If consumers are myopic and do not recognize the impact of their present consumption decisions on future consumption, then the shadow price $\varphi^C = 0$, and we have the usual first order conditions that price is equal to marginal utility. In contrast, with a “rational” habit formation, consumers are forward and backward looking, so $\varphi^C > 0$. Both the myopic and rational specifications should be empirically tested because it is not obvious why one should adopt either perfect foresight; or why consumers should be unable to assess the precisely the future implications of their current decisions on future consumption (Pashardes 1986).

Depreciated lithium may be sold in the future at a price P^W_C. Equation (13) implies that if $P^W_C > 0$, then the shadow price $\theta^c > 0$, and accordingly we must have $l_t = \delta L$. That is, all depreciated lithium is sold to the recycling industry, as the depreciated lithium has no other value.

Equation (14) reflects dynamic features of lithium durability and accounts for the ability of recycling lithium and reuse it again. The dynamics of $\dot{\varphi}^c$ depends on the discount and depreciation rates ($r + \delta$) having perfect foresight ($\varphi^C > 0$), and on the P^W_C the price consumers may get if they are able to sell their used lithium l_t.

2.1.3 Recycling of Lithium

The competitive recycling industry buys depreciated l_t at the price P^W. This input price could be determined by the market, and e.g. equal to P^W_C, or it could be regulated by the government and possibly set equal to zero. We assume that recyclers do not have property rights over the stocks of depreciated waste of lithium, and that storing used lithium is too costly to be profitable. So, recyclers do not face an intertemporal trade-off between current and future available stocks, and their maximization problem has no a stock variable constraint. However, recyclers cannot buy more input than γL, so we need to account for this constraint (with shadow price θ^R).

They recycle (parts of) the lithium at cost $C^R\left(w_t, l_t\right)$, and sell the recovered lithium w_t at price $P^L q$. Marginal costs are strictly increasing in the recycled quantity $\partial_{w_t} C^R > 0$ and $\partial_{w_t w_t} C^R > 0$), and decreasing in the input of depreciated lithium that enters the recycling process ($\partial_{l_t} C^R \leq 0$ and $\partial_{l_t l_t} C^R \leq 0$); with strict inequality when $w_t > 0$. Moreover, we assume that $\lim_{w_t \to l_t} \partial_{w_t} C^R = \infty$, reflecting that complete recycling is not possible because, in practice, there exit limits imposed by product design recycling technologies and thermodynamics of separation (Reck and Graedel 2012). Thus, the constraint $w_t \leq l_t$ will never be binding.

Thereby, their instantaneous profit maximization problem is:

$$\max_{w_t, l_t \geq 0} \pi^W = P^L q w_t - P^W l_t - C^R\left(w_t, l_t\right) \tag{15}$$

This gives the following first order conditions for interior solutions ($w_t, l_t > 0$):

$$w_t: \quad P^L q = \partial_{w_t} C^R \tag{16}$$

$$l_t: \quad P^W = \theta^R - \partial_{l_t} C^R \tag{17}$$

Equation (16) states that the recycling industry will recycle lithium up until the point where marginal recycling costs ($\partial_{w_t} C^R$) equal the quality-adjusted price of lithium ($P^L q$), i.e., a standard competitive condition.

Equation (17) reflects that the industry will buy depreciated lithium as long as the price of lithium waste (P^W) does not exceed the marginal cost reduction ($\partial_{l_t} C^R$) of having access to more lithium waste, plus the shadow value θ^R of having access to more input than γL.

If the constraint $l_t \leq \gamma L$ is not binding, then $\theta^R = 0$ and the price P^W equals the marginal cost reduction; i.e. if there is an efficient market for used lithium the price of depreciated lithium is bid up until $\theta^R = 0$.

However, it seems more reasonable to assume that the constraint is binding, since the alternative cost of depreciated lithium is zero (i.e., it cannot be utilized for other purposes than recycling). Hence, $l_t = \gamma L$, and we may have $\theta^R > 0$ reflecting that the recyclers would like to buy more than what is available (at the price P^W). This could e.g. be the case if the recycling industry is getting access to the used lithium without paying the full price (e.g., through some government intervention).

In our numerical simulations, we assume the following recycling cost function to a non-linear and more realistic form:

$$C^R\left(w_t, l_t\right) = \left[cr_0 - ln\left(1 - \left(\frac{w_t}{l_t}\right)^{\rho}\right)\right] e^{-\kappa t} w_t \tag{18}$$

The cost function reflects that recycling unit costs vary depending on how large the share of used lithium is recycled $\left(\frac{w_t}{l_t}\right)$. The cost of the cheapest unit is cr_0. The parameter ρ determines how fast marginal costs increase as the share of used lithium available for recycling is actually recycled. When $w_t \to l_t$, we see that the (marginal) costs go towards infinity. Here we include technological progress that reduces the unit costs exogenously over time through the parameter κ. For more details on the total and marginal recycling cost functions see "Appendix 3".

Table 1 Comparing efficient solution and market outcome

Social organized solution		Free Market (decentralized) solution	
$\lambda = c^E(A_t) - \frac{1}{q}\partial_{w_t} C^R$	(21)	$\lambda^E = c^E(A_t) - P^L$	(4)
$\varphi = c^E(A_t) - \lambda - MU(y_t)$	(22)	$\varphi^C = P^L - MU(y_t)$	(12)
$MU(y_t) = \frac{1}{q}\partial_{w_t} C^R - \varphi$	(23)	$P^L = \frac{1}{q}\partial_{w_t} C^R$	(16)
$\dot{\lambda} = r\lambda + \partial_{A_t} C^E$	(24)	$\dot{\lambda}^E = r\lambda^E + \partial_{A_t} C^E$	(5)
$\dot{\varphi} = (r+\gamma)\varphi + \gamma\partial_{l_t} C^R$	(25)	$\dot{\varphi}^C = (r+\gamma)\varphi^C - \gamma P_C^W$	(14)
$\theta = -\partial_{l_t} C^R$	(26)	$\theta^C = P_C^W$	(13)
		$\theta^R - \partial_{l_t} C^R = P^W$	(17)

2.2 Efficient (Social Organized) Solution

The efficient solution is derived by maximizing the net present value of the sum of consumer and producer surplus in the global lithium market, which we will refer to as (global) welfare. As we are not concerned about distributional aspects between consumers and producers, or between regions, the welfare in each period is simply given by the gross consumer surplus minus extraction and recycling costs.

The efficient solution is given by maximizing the following welfare expression given a social discount rate r, which is assumed to be constant.

$$\max_{x_t, w_t, y_t, l_t \geq 0} W = \int_0^\infty \left[U(y_t) - c^E(A_t)x_t - C^R(w_t, l_t)\right]e^{-rt}dt \tag{19}$$

Given the constraints on $\dot{A}$, $\dot{L}$ and $l_t \leq \gamma L$ and an additional condition on market balance $x_t + qw_t \geq y_t$ with its respective $\mu \geq 0$.

The current-value Hamiltonian is:

$$H^C = U(y_t) - c^E(A_t)x_t - C^R(w_t, l_t) + \lambda x_t + \varphi(y_t - \gamma L) - \theta(l_t - \gamma L) - \mu(y_t - x_t - qw_t) \tag{20}$$

Table 1 shows the first order conditions for the state and control variables with interior solutions $(x_t, w_t, y_t, l_t \geq 0)$, from which we get that:

$$\lambda = c^E(A_t) - \frac{1}{q}\partial_{w_t} C^R \tag{21}$$

The difference between unit extraction and marginal recycling costs thus reflects the scarcity rent (λ). If recycling costs are too high, so that $\frac{1}{q}\partial_{w_t} C^R(0, l_t)$ exceeds $MU + \varphi$, then the optimal recycling level is zero (Eq. 23).

Table 1 compares the conditions under the social planner solution and the decentralized market solution. We notice that the conditions are mostly similar, i.e., the market solution may realize the socially optimal solution. However, this requires that there is an efficient market for recycled lithium, so that $P_C^W = P^W$ and $\theta^R = 0$. It also requires that consumers are forward-looking when they buy lithium, with rational price expectations about the future price of lithium waste.

On the other hand, if there is no efficient market for lithium waste, e.g., that consumers do not consider that they can sell depreciated lithium, then the consumer's shadow price of the stock of lithium is equal to zero ($\varphi^C = 0$ if $P_C^W = 0$ in all future periods). Consequently, consumers are not willing to pay more than their marginal utility. This tends to depress the price of lithium compared to the efficient solution, reducing the incentives to both extract and recycle lithium. This is a positive externality, as consumers do not contemplate that used lithium has a value for the society.

The externality may be corrected by e.g. introducing a subsidy equal to φ^C for purchase of virgin lithium, and a subsidy equal to $\varphi^C q$ for purchase of recycled lithium. This reestablishes the equality between the social optimal solution and the market solution in terms of marginal utility (Eq. 23), in combination with market prices (Eqs. 4 and 16). With such a social planner intervention, the positive externality is internalized, providing an efficient solution.

3 Numerical Simulation

We extend the analytical model application and investigate the lithium recycling potential in the global market for lithium. We now allow for several lithium producers (i.e., producing regions) and several lithium consumers (i.e., consuming sectors). We also do some minor adjustments compared to the analytical model to reflect the current market situation for lithium.

Recycling can happen in most sectors, but we assume that it is not possible for lithium consumed in the sector of industrial applications (e.g., pharmaceutical use, ceramics, and air conditioning). As explained in Sect. 2, we assume that recycled lithium supplants perfectly primary lithium, when adjusting for lower quality-grade.

As already indicated, some model parameters are uncertain, both on the demand side (α_i and σ_{it}), in extraction (η_j and τ_E), and in recycling (ρ and τ_R). Thus, the benchmark scenario should not be taken as a forecast of the future lithium market, and we perform a range of sensitivity analysis. This model exercise aims to get a better understanding of the lithium market, to highlight the recycling value and to observe how different the efficient solution is from the market outcome.

For this numerical simulation, we apply a Mixed Linear Complementarity Model—MCP. Here, we have an equilibrium model with a mixture of nonlinear equations and adjacent inequalities or complementarity constraints. The model is simulated in GAMS using MCP.[5] We run the model for 150 years (1-year periods), beginning in the calibration year 2016, focusing on the time towards 2100.[6]

Section 3.1 presents the scenarios we consider, and Sect. 3.2 presents the simulation results. We are particularly interested in comparing the market outcome with the efficient solution, but also the importance of recycling in the future market for lithium.

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[5] For more information on GAMS program and MCP solver see Brooke et al. (1996). GAMS release 2.25; a user's guide, GAMS Development Corporation, Washington, DC (EUA), ibid. and GAMS documentation.

[6] Thus, we run the model 65 years beyond the time horizon we consider. All shadow prices are set equal to zero in the last period of the simulation. Whereas the analytical model has an infinite time horizon, this is not possible for the numerical model. By running the model sufficiently many years beyond our time horizon, the results are practically identical to the results of an infinite time horizon model (this is confirmed by running the model for even longer periods).

Table 2 Lithium consuming sectors

	Transport	Grid storage	Consumer electronics	Industrial applications	Total
Demand[a] (Thousand tons)	23.8	4.3	67.2	121.4	216.7[c]
Assumed annual depreciation rate[b]	10%	7%	90%	–	Not applicable (N/A)

[a]Base year 2016

[b]For lithium used in industrial applications we assume no recycling

[c]Total lithium demand based on (Roskill 2019). Sector demand proportions are based on U.S. Geological Survey (2017)

Table 3 Lithium extracting regions

	Argentina	Australia	Bolivia	Chile	China	USA	Rest world	Total
Identified resources[a] (Million Tons)	9.8	5	9	8.4	7	6.8	7.5	53.35
Production[b] (Thousand Tons)	30.1	74.3	0.02	76	25.4	2.7	8.2	216.7

[a]Base year 2017. Data sources: Roskill (2019), (U.S. Geological Survey 2017)

[b]Base year 2016. Data source: Roskill (2019)

3.1 Data Calibration

The global lithium market is divided into four lithium consuming sectors *i,* and seven lithium extracting regions *j* (Table 2). In 2016, lithium demand in electric transport accounts for 11% of total lithium consumption but is expected to become the dominating sector after a few decades. Grid storage has a marginal share today (2%) but could grow substantially in the future in parallel with increasing market shares of intermittent renewable energy such as solar and wind power. Consumer electronics demand accounts for 31%, and industrial applications consume around 56% of total lithium consumption. Those applications include lubricating greases, ceramics and glass, air conditioning units, aluminum and pharmaceutics production.

On the supply side, three of the seven regions are located in South America (Argentina, Bolivia and Chile), together accounting for more than half of both current production and identified resources, see Table 3.[7] In the simulations, we calculate, for each country, when accumulated extraction surpasses the currently identified resources under benchmark conditions.

We assume a common (real) discount rate of 5 percent, both for the producers and consumers of lithium and for the social planner. Remaining parameters are shown in "Appendices 1, 2, and 3".

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[7] The numbers for "reserves" are much smaller, and less relevant for a long-run analysis. For instance, USGS' "reserves" in Bolivia are close to zero, while identified resources are in the same range as Chile. (See Fig. 8 in "Appendix 4" for more details).

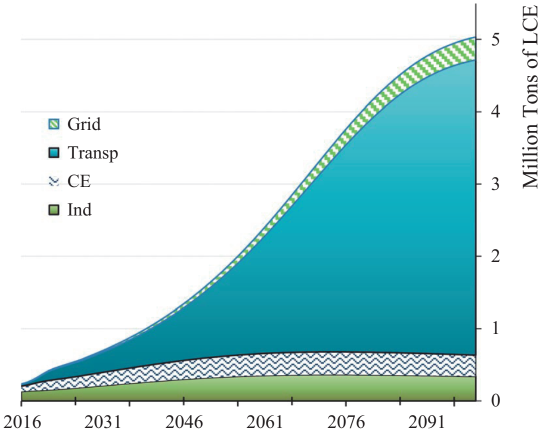

Fig. 1 Demand of Lithium Carbonate Equivalent (LCE) by sectors. The amount of lithium content in batteries is important for the dynamics of lithium demand. The range of lithium content in the transport sector (Transp) varies from 9 kg per kWh for a plug-in hybrid vehicle (PHEV) to 15 kg for battery electric vehicles (BEV) and 200 kg for an E-bus battery. Batteries for small electronics (CE) i.e., cell phone and laptops contain 12gr and 58gr of LCE respectively. Data based on (*Mackenzie* 2017)

3.2 Simulation Results

We start by presenting the market outcome, given our benchmark parameters, where we assume no efficient market for used lithium. As demonstrated in Sect. 2, the market outcome will then give too little incentive to extract and recycle lithium. We investigate how the market outcome compares with the efficient market. Finally, we consider how our results change if we change some of the important but uncertain parameters in the model.

3.2.1 Market Solution (MS)

We first project the demand of lithium carbonate equivalent—LCE—towards 2100, again emphasizing the large uncertainty in such long-term projections. We observe a momentous growth in all consumer sectors until 2030 (Fig. 1). Afterwards, it stabilizes gradually for industrial applications (Ind) and consumer electronics (CE), which are the dominating sectors today.

Whereas the transport sector accounts for 11% of current global lithium demand, it is expected to expand substantially in the following decades and become the dominating lithium demand sector in the second half of the century. While electric vehicle sales have already started to take off in several countries, LiBs improvements, in both the transport sector (e.g., E-bus) and the energy sector (e.g., Grid Storage), spur new markets with batteries of huge capacities. In fact, technological developments have pushed batteries' cost down and can lower the price of electric vehicles (EVs), and make them affordable to a broader segment of consumers. According to (Ciez and Whitacre 2016), higher lithium prices will not affect the cost of battery systems to a large extent. The grid storage expansion is uncertain—in our benchmark scenario its demand in 2100 compares to industrial applications (Ind) and consumer electronics (CE).

We next estimate how many batteries (light commercial vehicles) are likely to be produced with the amount of lithium consumed by the transport sector and assume that sales

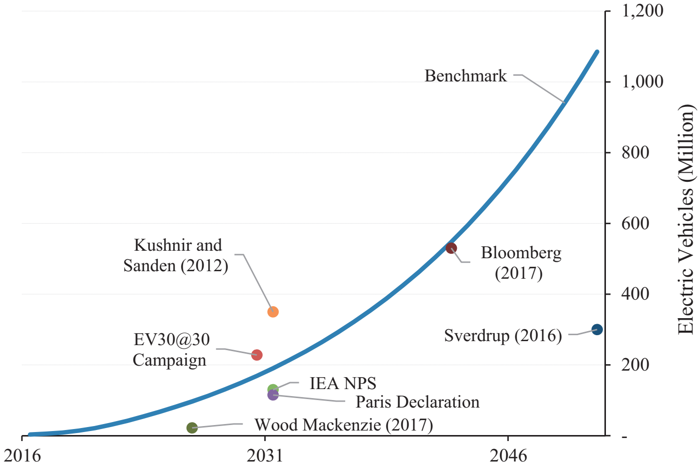

Fig. 2 Stock of electric cars (realizable vs. policy targets). The IEA NPS incorporates improvements to the current technological state. The Paris Declaration refers to the Electro-Mobility and Climate Change and Call to Action. These projections and and EV30@30 Campaign are based on IEA (2018a, 2018b). We assume that EVs sales will follow historical fashion, about 60% of electric vehicles (EVs) are battery electric vehicles (BEVs) and 40% plug-in hybrid vehicles (PHEVs)

evolve at the pace shown in Fig. 1. We compare our projections with the literature and find that it will be challenging to achieve the ambitions of electric vehicle adoption suggested by some scholars and by the "EV30@30" campaign. Still some scenarios suggested by policy makers in the Paris Agreement might be feasible (Fig. 2).[8] The assumptions of vehicle population and lithium content per battery for these estimations are unknown. Other studies consider how many EV batteries are realizable with the lithium resources available and linear demand trends (Bloomberg 2017; Sverdrup 2016; Mackenzie 2017).

Figure 3 shows how virgin and recycled lithium satiate demand in the (free) market solution MS (the figure also shows the efficient solution, which we return to below). Initially, recycling is too expensive, therefore extraction equals demand. From 2027, some recycling becomes profitable, and from around 2060 recycled waste accounts for more than half of the lithium market. This change reflects a combination of higher demand and higher extraction costs, which together cause soaring lithium prices (Fig. 4), making recycling gradually more profitable. The increase in recycled lithium is partly due to more lithium waste being available for recycling, and partly because the higher lithium price makes it profitable to recycle a larger share of the lithium waste. In 2035 about half of the lithium waste is recycled—around 2050 the share has grown to above 80% in this scenario.

Recycling lithium waste will become crucial for the future lithium market (Fig. 3). In fact, recycled lithium will meet around half of accumulated lithium demand from today until 2100 in our market scenario MS. This suggests that without the ability to recycle

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[8] Kushnir and Sanden (2012). Assume similar lithium content per EV battery as we do, and project that even with a low level of vehicle population growth (0.2 cars/capita), EV adoption reaches about 350 million EVs by 2030. Alternatively, the Clean Energy Ministerial forum launched a campaign "EV30@30" to accelerate EV, and reach 30% market share for electric vehicles in the total of all passenger cars, light commercial vehicles, buses and trucks by 2030 IEA (2018a). Global EV Outlook 2018, Towards cross-modal electrification, OECD, IEA (2018b). Global EV Outlook 2017, Two million and counting. Paris, OECD/IEA- International Energy Agency.

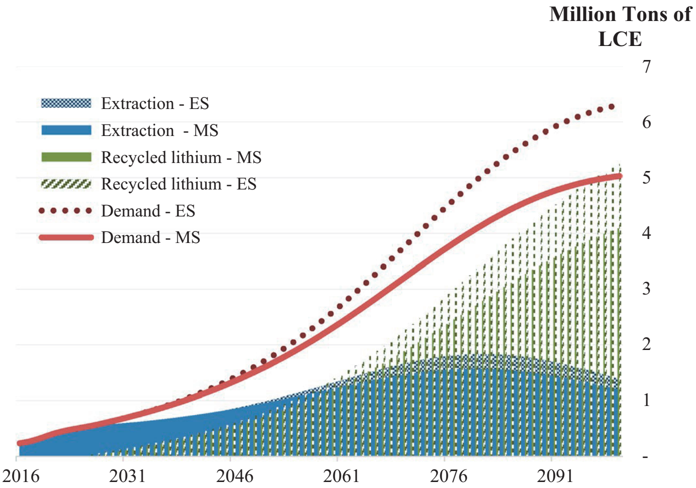

Fig. 3 Annual global demand, supply and recycling of Lithium Carbonate Equivalent (LCE) in the efficient (ES) and market (MS) solutions

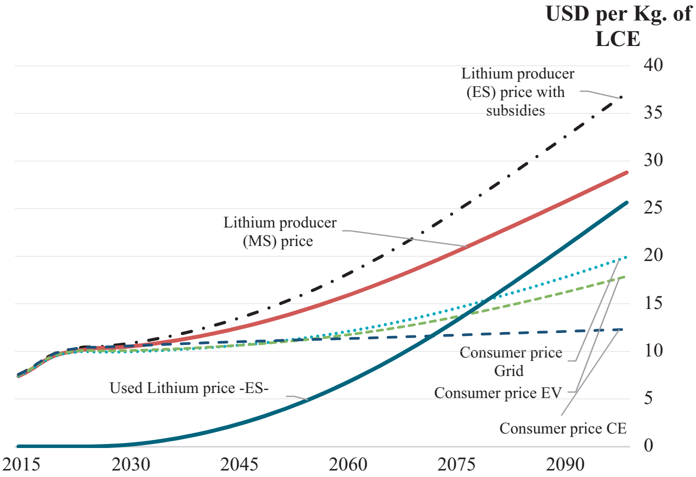

Fig. 4 Market and consumer prices of lithium in the Efficient (ES) and Market (MS) Solutions. This figure shows the willingness to pay for lithium $MU\left(y_t\right)$ in the efficient solution (Eq. (22) and (23)), together with the lithium price in the free market solution (Eqs. 4, 16) discussed in Sect. 2

lithium, prices of lithium would likely have to be much higher to balance supply and demand, especially in the future but also today. Thus, given the highly uncertain nature of future recycling costs, it is important to explore how different assumptions may affect the lithium market.

3.2.2 Comparing Efficient and Market Solutions

As explained in the theoretical part, when consumers cannot sell lithium waste (i.e., $P_C^W = 0$), their marginal willingness to pay for lithium is lower than if they can sell it after use. We now consider the efficient solution, which is realized if there is an efficient market for depreciated lithium. In that case, consumers anticipate having a positive shadow price (φ^C) of used lithium stock. LiB consumers then get paid for their worn-out batteries, proving that the waste stock is a valuable resource. This will boost lithium prices and increase the incentives to extract and recycle more lithium.

Alternatively, if an efficient market for used lithium is difficult to realize, proper global subsidies to all sales of lithium can also realize the efficient solution. This is the variant we will consider here.[9] A subsidy puts a wedge between the producer and the consumer prices, with the latter prices being below the former.

We notice that lithium market prices increase in the efficient solution (compared to the market solution), especially in the second half of the century (Fig. 4). Thus, sizeable subsidies are needed to realize the efficient solution. The subsidy is sector-specific due to different depreciation rates of lithium across sectors. Consequently, consumer prices differ too.[10] Buyers of lithium for consumer electronics will perceive a relatively low lithium price due to a high depreciation rate, implying highest subsidy levels for this sector.[11] In 2100, lithium producer (market) prices are around two times higher than consumer prices, illustrating the need for high subsidy rates unless an efficient market for used lithium arises by itself.

Along time, higher subsidy rates reflect higher lithium prices, also allied to higher shadow prices of used lithium. Therefore, the value of used lithium increases, and recycling is more rewarding.

In the efficient scenario, the subsidies generate greater extraction and recovered waste, absorbing a bigger demand level (Fig. 3). Accumulated demand between 2016 and 2100 will be 37 million tons larger than in the (unregulated) market solution, which is more than a half of currently identified lithium resources (53 million tons). 20% of the additional demand during this century comes from more extraction, while 80% comes from more recycling, which starts 1 year earlier in the efficient solution.

Both consumers and producers benefit from having an efficient market. Lithium producers earn greater resource rent compared to an unregulated market, bringing greater profit levels to all producer countries (Fig. 5). Total profits for all producers increase by 19 billion USD (net present value until 2100).

Lithium consumers also benefit due to the subsidy, that is, by 51 billion USD, whereas the recycling industry increases their profits by 35.3 billion USD, if they don’t have to pay for the used lithium. Nevertheless, the subsidy expenses must be counted as a cost (which someone must pay for eventually), and they amount to 100 billion USD. In total, net present value of global welfare until 2100 (Eq. 19) increases by 4.5 billion USD, that is, less than half of the increased profits for lithium producers. The increased welfare is consistent with the conclusions by Pittel et al. (2010), i.e., a “higher circulation of matter” enhances welfare.

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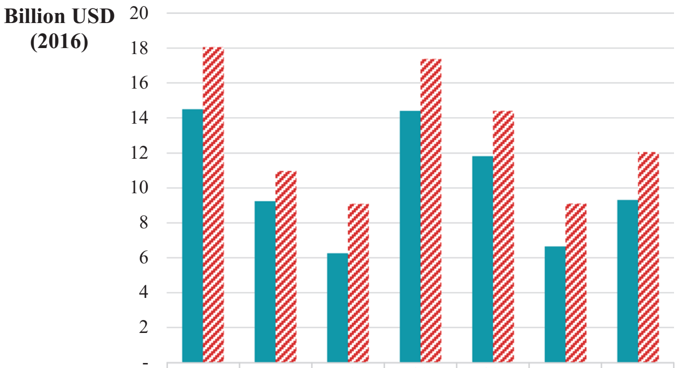
[9] Whereas the quantities obviously are the same in the two alternative efficient solutions, the consumer prices are different.

[10] If price discrimination is difficult, the efficient solution could alternatively be realized through a common subsidy to delivery of used lithium.

[11] This is not the case initially, however, when the lithium price increases rapidly.



	Arg	Aus	Boliv	Chile	China	USA	Rest
■ Unregulated MS (No Subsidies)	14.5	9.2	6.3	14.4	11.8	6.6	9.3
▨ Efficient market (With subsidies)	18.1	11.0	9.1	17.4	14.4	9.1	12.1

Fig. 5 Profits (Net present value) until 2100 for lithium producers in the efficient and market solution

Table 4 Parameters and hypothetical scenarios for sensitivity analysis

Parameters	Benchmark	1	2	3	4	5
α_I Elasticity of demand	−0.5	−0.25	−0.75			
θ_j^R Technological change in recycling	0.005			0.02		
cr_0 Initial unit recycling cost	10				15	
q Initial quality factor	0.9					0.5

3.2.3 Sensitivity Analysis

As stressed in the numerical model description above, there are several important but uncertain parameters in the model. This is obvious when we attempt to model a market towards 2100. We perform sensitivity analysis with respect to four parameters (Table 4).

The size of lithium price elasticity is very uncertain, especially in the long run when the price sensitivity depends e.g. on the availability of substitutes in batteries. Technological progress in recycling is crucial for the future costs of supplying lithium. There is also uncertainty about the initial recycling costs, as there is hardly any recycling going on today. Finally, the quality-grade of recovered lithium is essential for the value of recycling, both to the recycling industry itself and more generally to the future lithium market.

Figure 6 shows the lithium market price development in the efficient solution across scenarios, showing that the price deviates substantially across scenarios in the second half of this century when lithium becomes a scarcer resource. The price is highest with a lower quality-grade of recycled lithium. Technological progress in recycling has less impact on the lithium price. The reason is as follows: On the one hand, lower recycling costs increase the supply of lithium in the market, depressing the price. On the other hand, lower recycling costs increase the value of used lithium, which in turn increase the optimal subsidies. These subsidies reflect the shadow price of used lithium. Consequently, demand increases

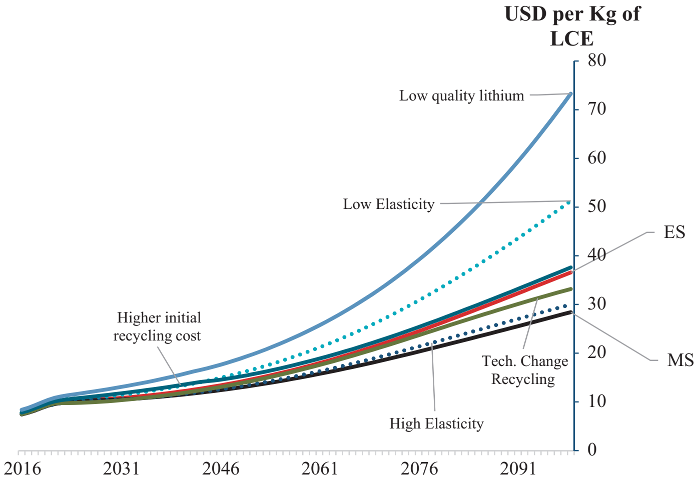


Fig. 6 Market price of lithium in different efficient solution scenario

and pushes the price upwards. The net effect is a small market price reduction. The effects of higher initial recycling costs are quite similar but go in opposite directions.

With a lower quality-grade of recycled lithium, primary lithium prices are twice as high at the end of the century compared to the benchmark scenario. Lower quality means less (quality-adjusted) recycled lithium supply per unit of used lithium. This further reduces lithium stocks in use ($\dot{L} = x + qw - \gamma L$), and implies less access to secondhand lithium available for recycling. Therefore, the deviation from the benchmark expands over time and reveals how the quality-grade of recycled lithium affects the future access to this resource.

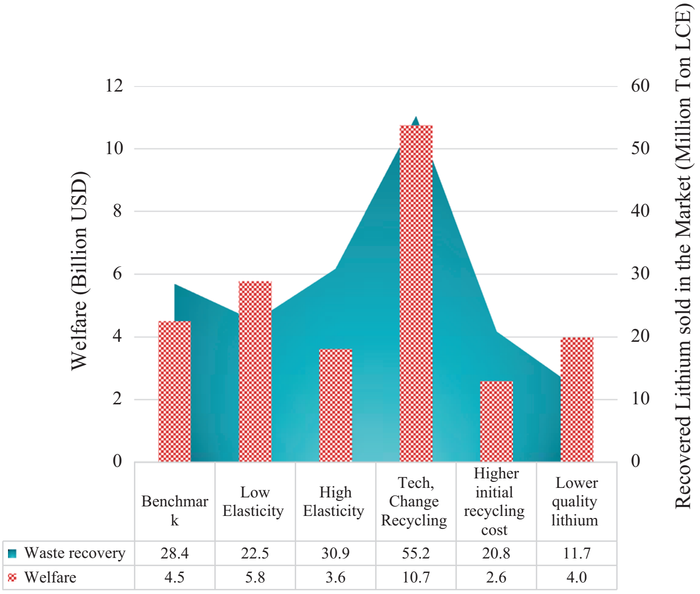
Lower demand elasticity also pushes the price of primary lithium up substantially, as higher prices are needed to balance the market when demand is quite insensitive to price changes. The opposite effect is the case with higher elasticity.

Future use of lithium varies substantially across scenarios. Faster technological change in recycling increases lithium demand growth and speeds up the deployment of EVs in the market. Figure 9 in "Appendix 4" shows the optimal subsidy rates in the transport sector across scenarios.

The efficient solution brings welfare benefits compared to the unregulated market solution in all simulated scenarios, but the welfare gains differ greatly (Fig. 7). Better recycling technologies offer the largest welfare gains, with 10.7 billion USD in increased net present value (until 2100). This scenario also brings about the biggest increase in accumulated waste recovery when shifting from the inefficient to the efficient solution. In fact, the increase in accumulated waste recovery until 2100 after introducing optimal subsidies (55.2 million tons) is comparable with the currently identified resources of lithium worldwide.

With lower quality of recycled lithium, an efficient market for used lithium becomes less important, and the welfare gains drop to 4 billion USD. The same is true with higher initial recycling costs, in which case the welfare gains are 2.6 billion USD. The increase in waste recovery is also much less than in the benchmark simulations, especially in the lower quality scenario.

We see that if lithium price elasticity is high, e.g., due to more substitutes available, the welfare gains from an efficient market, i.e., implementing subsidies, is reduced, whereas



	Benchmark	Low Elasticity	High Elasticity	Tech, Change Recycling	Higher initial recycling cost	Lower quality lithium
■ Waste recovery	28.4	22.5	30.9	55.2	20.8	11.7
▨ Welfare	4.5	5.8	3.6	10.7	2.6	4.0

Fig. 7 Welfare gains and recovered waste differences until 2100 between efficient and (unregulated) market solutions across scenarios

the opposite is the case if the elasticity is low. The changes in waste recovery are important though.

The sensitivity analysis shows that future costs and quality of recycled lithium will be crucial for the future lithium market. With current technology, recycling costs are relatively high compared to raw lithium extraction costs. Recycled lithium comes as a by-product of recovering other and more pricy materials like cobalt (Richa et al. 2014). In discarded batteries of electronics, lithium has low magnitude or quality-grade (Ziemann et al. 2012), collection and separation is costly, and recovered lithium has a lower quality-grade level (European-Commission 2016).

The engineer and material science literature continuously debate technical requirements that can reduce recycling costs. Battery design can make recycling easier, reduce material losses and increase mineral recovery (Ciacci et al. 2015). Strict industrial standards can ensure that recovered material meets the same high quality-grade as virgin minerals (Gaines et al. 2018). Moreover, recycling industry profits build upon economies of scale and the infrastructure capable to absorb the vast diversity of battery design (Wang et al. 2014).

Local market conditions can make recycling feasible (Rohr et al. 2017).[12] Yet, there is no consensus about to what extent local developments can reduce stress on foreign lithium dependency and shape a global competitive market of recycled lithium. This question affects mostly Europe and industrialized countries in the northern hemisphere that are making great advances on grid storage and electric cars production and consumption.

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[12] Hydro vil gjenvinne elbil-batterier i et samarbeid med Batteriretur og metallkonsernet Glencor. https://batteriretur.no/hydro-vil-gjenvinne-elbil-batterier-i-et-samarbeid-med-batteriretur-og-metallkonsernet-glencor/.

A potent collection system may affect recycling rates. A LiB can typically achieve 8 years of life (Wood et al. 2012). Current collection rates of spent LiBs is less than 10% in USA (Wang et al. 2014) and less than 1% in Europe (Swain 2017). Lack of regulation aggravates LiB waste management (Gaines et al. 2018), and neither the market nor the governments provide incentives to collect used LiBs.

In this paper, we discuss a regulated market efficient solution, where subsidies are strictly positive throughout the time horizon. We have examined the impacts of ending the subsidy scheme prematurely (see Fig. 10 in the “Appendix 4”). By 2050, more than 80% of depreciated lithium is recycled. Thus, it could be tempting to finish the subsidies when the recycling really takes off. However, if subsidies end in 2050, a very small share of the welfare gains remain. In fact, even if subsidies end in 2070, merely 30% of the welfare gains (NPV) remain, while less than 60% of the subsidy payments (NPV) are saved. This demonstrates the importance of establishing an efficient market for depreciated lithium in due time, including making consumers aware of the fact that they can sell the depreciated lithium after use.

4 Conclusions

In this paper, we investigate how effectively lithium recycling relieves resource scarcity, and whether a market intervention is desired. We have demonstrated two things: (1) the prospects for the lithium market depend heavily upon recycled lithium supply, and (2) unless an efficient market for depreciated lithium develops, a market intervention is desired to obtain optimal market outcomes. The paper demonstrates how lithium scarcity will be much more evident without the possibility to recycle lithium, and with prices increasing much faster. In our benchmark scenario, around half of accumulated lithium demand from today until 2100 will be met by recycled lithium.

In a free market solution, the incentives to recycle depreciated lithium will be enhanced as lithium prices rise, but lithium consumers do not necessarily consider the shadow value of lithium waste for future recycling. In the analytical part of our paper, we showed that subsidies to either buyers or sellers of both virgin and recycled lithium may realize the optimal solution. If incentives are created, our simulations have shown that this is likely to bring greater social benefits. The size of the optimal subsidies depends however, on several uncertain assumptions regarding the future lithium market development, such as initial costs and technological progress in recycling, the quality-grade of recovered lithium, and demand elasticity. Although our model is formulated in the lithium context, the qualitative findings should generalize to other non-renewable and recyclable resources.

Our policy implications are deduced from a global optimization problem. Optimal subsidies correspond to the shadow prices of the depreciated waste stock generated in a globally regulated market solution. These subsidies may of course be difficult to implement for several reasons. First, as mentioned above, the optimal subsidy level depends on a wide range of uncertain assumptions. This could be dealt with by updating the subsidy level over time as new insight is gathered, especially regarding recycling but also other features of the lithium market. Second, the optimal subsidy payments are very high, especially in the second half of this century, and much higher than the net welfare gains. Our analysis does not account for potential cost of public funds to cover the subsidy expenses. Third, since we do not have a global government, the subsidies must be implemented by national governments, which of course makes it even more challenging to implement optimal subsidies. We have not examined whether single countries, or a group of countries, should implement such subsidies unilaterally. However, these issues are worthy of further research.

Technological progress in lithium recycling, as well as the quality of recycled lithium, will be crucial for the future lithium market. One could, therefore, also advocate subsidizing R&D to promote a technological push in recycling that could lower long-term recycling costs. Besides, an efficient collection system requires a mechanism to give consumers the incentive to make lithium waste available for recycling. It may be necessary for governments to intervene and create a collection system if such a solution does not exist. Given the challenges involved in imposing optimal subsidies, establishing an efficient market for depreciated lithium could be the best way forward. This includes making consumers realize, when they buy lithium products, that depreciated lithium has a market value.

Lithium has an important role in a decarbonized economy. Nonetheless, lithium mining and waste management yield critical environmental impacts and social costs. In addition, the geographical concentration of lithium resources raises a concern about market power and strategic behavior by, for instance, lithium extractors. These are all important issues that may be considered in future research.

Acknowledgements The authors thank two anonymous reviewers for their valuable comments and suggestions on a previous version of this paper.

Appendix 1

Cost Function

To make the model fit better with the current situation in the lithium market, we add two cost elements for lithium extractors. In the numerical simulations, the cost function looks like:

$$c^E\left(A_{jt}\right) = c_{j0}e^{\eta_j A_{jt} - \tau_E} x_{jt} - c_j^T x_{jt} - c_{jt}^{add}\left(x_{jt}, x_{j0}\right)x_{jt} \tag{27}$$

So total cost depends on three parts. The first part, $(c_{j0}e^{\eta_j A_{jt} - \tau_E t} x_{jt})$ adopted from e.g. Grimsrud et al. (2016), assumes unit extraction costs (starting at c_{j0}) increase with accumulated supply (A_{jt}) and decrease with (exogenous) technological progress $\left(\tau_E = 0.05\right)$. The parameter η_j represents the rising costs rate as accumulated production increases and is calibrated to the initial stock levels of lithium resources for each producer. The second part, $(c_j^T x_{jt})$, is simply linear transportation costs to the world market. The third part, $c_{jt}^{add}\left(x_{jt}, x_{j0}\right)$, is a quadratic term to consider that it is costly to ramp up production substantially in the short to medium term, and also that sunk costs make sudden output reductions less profitable. One particular example is Bolivia, which has enormous and profitable lithium resources, but where production is close to zero due to institutional barriers such as constraints on property rights and on foreign investments. The term $c_{jt}^{add}\left(x_{jt}, x_{j0}\right)$ equals zero if production equals the base year output, is quadratic in deviation from the base year output, and reduces gradually over time.

The first order condition for producer j, subject to a positive outcome ($x_{jt} > 0$) is:

$$\frac{\delta c^E(A)}{\delta x} = c_{j0}e^{\eta_j A_{jt} - \tau_E} - c_j^T - c_{jt}^{add}\left(x_{jt}, x_{j0}\right) \tag{28}$$

Table 5 displays the value of a range of parameters applied in the numerical model.

Table 5 Parameters applied in the model

	Argentina	Australia	Bolivia	Chile	China	USA	Rest world	Total
Initial Extraction cost* (USD/kg)	2.8[a]	2.8[b]	3.9[c]	3.6[d]	3.9[e]	3.4[f]	6.6 [g]	3.8[§]
Transport cost (c_j^T)** (USD/kg)	2	2	2	2	1.25	2.5	1.25	

*Base year 2017. Correspond to "All-In Sustaining costs" which include capital expenditure and depreciation with other capital expenditure and rehabilitation. Data Source: we compare average extraction cost from operating mines published by Roskill (2019) with other sources [a]Orocobre (2015), [b]Galaxy (2015), [c]Comibol (2017), [d,e]Cochilco (2013), [f]Yaksic and Tilton (2009), [g]Nemaska-Lithium (2017)

[§]Average value among countries

**Hypothetical values. Assume that China and Rest sells to domestic market, while the others must export

Appendix 2

Utility and Demand Functions

We assume the following standard utility function for use of lithium y_{it} (in all consuming sectors i):

$$U_{it}\left(y_{it}\right) = \boldsymbol{\Phi}_i + \frac{\alpha_i}{1+\alpha_i} y_{i0}\sigma_{it}\left(\frac{y_{it}}{y_{i0}\sigma_{it}}\right)^{\frac{1+\alpha_i}{\alpha_i}} \tag{29}$$

where $\boldsymbol{\Phi}_i$ is a constant, α_i represents the (long-term) price elasticity of demand, and y_{i0} denotes the initial demand level. The factor σ_{it} is an exogenous growth function reflecting the underlying growth in demand. The elasticity α_i is -0.5 in the benchmark scenarios.[13] This gives the following marginal utility function:

$$U'_{it}\left(y_{it}\right) = \left(\frac{y_{it}}{y_{i0}\sigma_{it}}\right)^{\frac{1}{\alpha_i}} \tag{30}$$

And thereby the derived demand function that we use in the model numerical simulations:

$$y_{it} - y_{i0}\sigma_{it}\left(\frac{p_t}{p_0}\right)^{\alpha_i} \geq 0 \perp y_{it} \geq 0 \tag{31}$$

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[13] As far as we know, there exists no empirical studies of demand elasticities of lithium. Thus, the size of this elasticity is very uncertain, especially in the long run when the price sensitivity depends for instance, on the availability of substitutes. Therefore, we perform sensitivity analysis with respect to this elasticity.

Table 6 Annual Growth rate in lithium demand in sector i (given price in 2015)

	Transportation	Grid storage	Consumer electronics	Industrial applications
	(a)	(b)	(c)	(d)
Until 2025	25%	15%	10%	5%
2031–2050	7–10%	7–10%*	3%	3%
2051–2100	5%	5%	1%	1%
After 2101	1%	1%	1%	1%

* Assuming it follows EV sales growth (IEA 2018a, b)

(a) Based on IEA (2018a, b)

(b) Based on U.S. Geological Survey (2017)

(c) and (d) based on Kushnir and Sanden (2012)

Table 7 Parameters in the demand growth function

Parameter	Transportation	Grid Storage	Consumer Electronics	Industrial Applications
σ_{i1}	4982	2286	2636	2741
σ_{i2}	6.07	6.41	295	489
σ_{i3}	1113	1147	1229	2034
σ_{i4}	0.074	0.072	0.053	0.053
σ_{i5}	3863	1132	1112	218
σ_{i6}	0.10	0.10	0.10	0.10

The elasticity α_i is -0.5 in the benchmark scenarios.[14] The growth function σ_{it} is calibrated based on projections from the IEA (2018a, b) for the medium term to 2030, and Kushnir and Sanden (2012) for the longer term, using a logistic functional form with several parameters. Obviously, the long-run growth in demand is highly uncertain.

The demand growth factor σ_{it} is calibrated based on the growth rates shown in Table 6, and the following functional form:

$$\sigma_{it} = \frac{\sigma_{i1}}{\sigma_{i2} + \sigma_{i3}e^{-\sigma_{i4}t} + \sigma_{i5}e^{-\sigma_{i6}t^2}} \tag{32}$$

The calibrated parameters are displayed in Table 7.

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[14] As far as we know, there exists no empirical studies of demand elasticities of lithium. Thus, the size of this elasticity is very uncertain, especially in the long run when the price sensitivity depends for instance, on the availability of substitutes. Therefore, we perform sensitivity analysis with respect to this elasticity.

Appendix 3

Recycling Cost Function

From the recycling costs function (18) we derive the following first order conditions:

$$\frac{\delta CR}{\delta w} = e^{-\kappa_t}\left[cr_0 - \ln\left(1 - \left(\frac{w}{l}\right)^{\rho}\right)\right] + \frac{\rho e^{-\kappa_t}\left(\frac{w}{l}\right)^{\rho}}{1 - \left(\frac{w}{l}\right)^{\rho}} = P^L \tag{33}$$

$$\frac{\delta CR}{\delta l} = e^{-\kappa_t}\left[-\rho\frac{\left(\frac{w}{l}\right)^{\rho+1}}{1 - \left(\frac{w}{p}\right)^{\rho}}\right] \tag{34}$$

Or equivalent to

$$\frac{\delta CR}{\delta l} = e^{-\kappa_t}\left[\rho w\frac{\left(\frac{w}{l}\right)^{\rho}}{\left(\left(\frac{w}{p}\right)^{\rho} - 1\right)l}\right]$$

Table 8 displays the parameters value applied in the numerical calculation of equations (18), (33) and (34).

Table 8 Parameters in the recycling cost function

Description	Value
Lowest initial recycling unit cost (cr_0)	10 USD/ kg of LCE[a]
Parameter recycling cost function (ρ)	2*
Technological change recycling (κ)	0, 5%*
Discount rate	5%*
Initial quality factor (q_0)	1.1*

[a] Approximated recycling cost for an electric vehicle LiB battery. It varies among cathode chemistries and recycling methods (Zou et al. 2013; Kushnir and Sanden 2012)

*Hypothetical values

Appendix 4

Resources and Subsidies Analysis

Figure 8 shows accumulated extraction for individual countries in the benchmark scenario. It also shows, for each country, when accumulated extraction surpasses the currently identified resources. We see that Australia and Chile, the two biggest producers today, will run out of identified resources around 2065. Chile has large resources and continues as one of the largest producers throughout the century, whereas Australia has rather limited resources compared to the others. In the first half of our time horizon, Argentina and China also have large identified resources and are important suppliers. In the second half of this century, USA and the rest of the world become important suppliers and Bolivia is the biggest producer of lithium at the end of the century. Up to date, these estimates are susceptible to change when more resources are identified, and producers tend to accelerate their extraction rates.

Figure 9 shows the optimal subsidy rates in the transport sector across scenarios. We see that the subsidy rates in 2100 vary between 14 and 30 USD per kg of LCE. As a comparison, the initial price of lithium in 2016 is 8.7 USD per kg of LCE. However, until 2050 all subsidies remain below 7 USD per kg of LCE.

Figure 10 shows how net present value (NPV) of welfare gains (relative to unregulated market) and subsidy payments are affected if the optimal subsidies end prematurely in different years—in percent of the corresponding numbers in the efficient solution. For instance, whereas the welfare gains in the efficient solution (vis-à-vis market solution) is 4.5 billion USD, the welfare gain drops by almost 90 percent, to 0.5 billion USD, if the subsidies end in 2060. Total subsidy payments drop from 100 to around 25 billion USD. Hence, ending the subsidies prematurely implies that most of the welfare gains are lost. This shows the importance of establishing a market for recycled lithium, so that subsidies are no longer needed. The figure also shows the share of lithium being recycled in different years in the efficient solution. We see e.g. that in 2060, this share is 90 percent

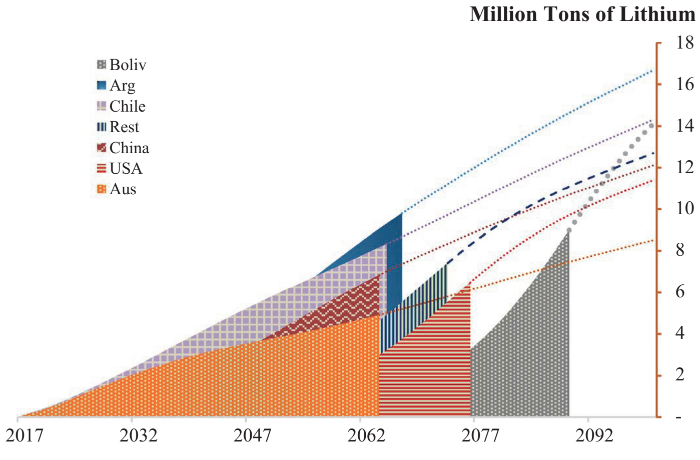

Fig. 8 Accumulated production and identified resources of lithium

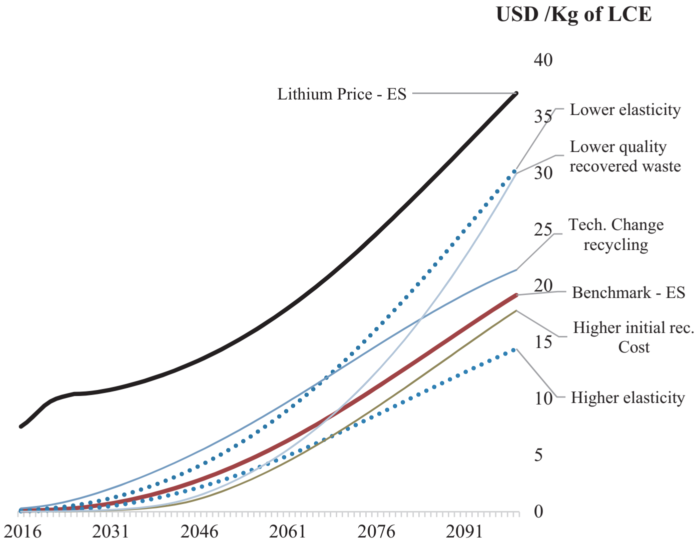

Fig. 9 Optimal subsidies (shadow price of lithium in use) in the Transport sector across scenarios

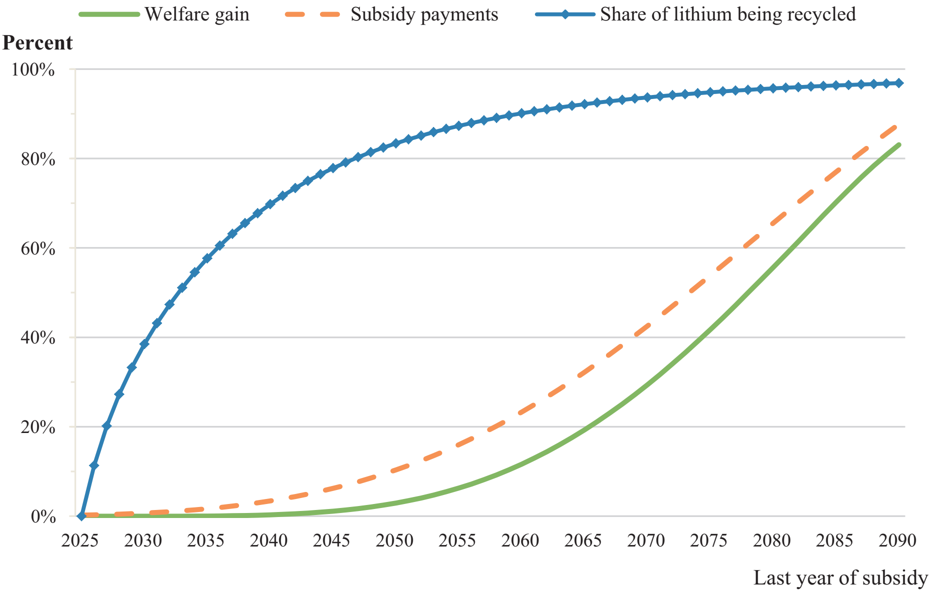

Fig. 10 NPV of welfare gains and subsidy payments if subsidies end prematurely in the given year. Percent of efficient solution (ES). Share of lithium being recycled in the efficient solution in the different years

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Paper 2

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ORIGINAL PAPER

Policies for Material Circularity: the Case of Lithium

Diana Roa[1] · **Knut Einar Rosendahl**[1]

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Abstract

Improper waste management carries social risks and dissipates high-value materials. Moreover, material market prices do not reflect these hidden costs and values. Two important questions are how prices can inform society about their resource use impact and how market-based policies optimize material circularity. This study adds to the literature by analyzing the effect of market-based policies aimed at promoting circular material reuse in a market defied by harmful waste but enhanced by recycling. The findings indicate that a landfill tax is a first-best policy since it targets the external costs of waste disposal, improves welfare, reduces damages, and boosts recycling. If a landfill tax is not feasible, other programs like taxes, subsidies, and a tax-subsidy scheme provide second-best results. Remarkably, recycling subsidies can stimulate higher raw material extraction and generate rebound effects. We also explore other non-market-based strategies to prevent waste and make recycling more cost-competitive and easier to recycle. The numerical results and sensitivity analysis of the lithium market illustrate the model's flexibility and prove why some policies are superior to others for reducing waste and creating value from used materials. Our study results serve as a guide to designing policies for optimal material circularity.

Keywords Critical raw material · Lithium · Recycling subsidy · Disposal charge · Material rebound · Dynamic optimization

Introduction

Material efficiency is crucial to support the transition towards a low-carbon, digital economy. Electronic devices and emerging technologies like electric vehicles and smart grid batteries require vast raw materials. A primary concern is that scarcity and supply risks may threaten to slow down the green and digital transitions [1–3]. However, recent research reveals that the rising demand for electronics is causing a surge in electronic waste (e-waste) [4]. To prevent social risks and limit valuable material losses, society must dispose of waste safely. Otherwise, as an environmental externality, waste impairs welfare and

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✉ Diana Roa
diana.marcela.roa.rubiano@nmbu.no

Knut Einar Rosendahl
knut.einar.rosendahl@nmbu.no

[1] Norwegian University of Life of Sciences, Ås, Norway

sustainability. Therefore, improper e-waste management undermines the promising benefits of the digital revolution and green shift.

This challenge calls for policy intervention. As a rule, waste management policy incentives upstream and downstream spheres [5–8]. Upstream refers to products designed with the environment in mind, and downstream aims at efficient recycling, diverting waste from landfills.[1] Fullerton and Wu [6] analyzed downstream policies and found that charging consumers the marginal social costs of disposal can correct the market failure and even persuade firms to design more recyclable products. Although their theoretical analysis proves how recyclability affects consumers' utility levels, in practice, consumers may be willing to recycle, but it will depend on better-organized recycling and collection systems [10, 11].

Recycling offers a way to manage harmful waste and exploit long-lasting materials once it becomes an attractive market. Unfortunately, recycling e-waste is seldom profitable due to costly and nascent reprocessing technologies compared to cheap and mature mining [12]. However, even unprofitable recycling can improve welfare when market prices do not reflect externalities [13]. A common government practice is subsidizing private recyclers to undertake risks and reduce cost pressures. Although research has backed that idea [14, 15] and suggests governments invest in research and improve technologies to make recycling more operational [16], there may be fiscal constraints that question to what extent recycling subsidies are the preferred policy compared to other measures.

The discussion so far highlights the difficulty of promoting policies that, in unison, steer producers, consumers, and recyclers' behavior and sustainably reorient public finances. Research suggests no single tool can solve multiple problems simultaneously, such as promoting recycling and reducing waste and damage [5–7, 17]. Some researchers find that disposal fees are insufficient without regulatory measures to ensure better product design [8]. Other studies argue that a tax-subsidy scheme can correct market failures related to waste disposal [5, 18]. In other cases, combining taxes on raw materials with subsidies for recycling does not work well due to distorting effects from the recycling subsidy [17]. Thus far, research has focused on optimizing inefficient markets and overemphasized recycling as a means of reducing material scarcity [19]. However, there is still a lack of thorough exploration of the cumulative effects of waste management policies on welfare and damages considering budget constraints. This paper, therefore, provides a quantitative analysis that complements previous mostly theoretical studies on waste management.

The term circular reuse throughout this paper implies reducing e-waste to a minimum and creating added value from used materials. With that in mind, this study cannot cover all environmental impacts at different stages of a materials' life cycle, as we are not looking at the environmental externalities of mining in ecologically sensitive areas or carbon emissions from material recycling. This study focuses only on end-of-life product externalities. Therefore, our policy analysis is strongly Pigouvian based on the user or polluter pays principle to internalize externalities from waste disposal, which can also stimulate material efficiency.

Our study aims to analyze the impact of market-based policies to promote material circular reuse in a market enhanced by recycling and defied by hazardous waste. We ask in this paper how prices can inform society about their resource use impact and how market-based policies can optimize material circularity. Our model incorporates a material balance

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[1] Take-back programs such as "Extended Producer Responsibility" encourage product weight reduction, product life extension, and warranty extension on repairs. In Europe, these measures have been updated to a new circular economy action plan [9].

condition, waste damage costs, and non-linear mining and recycling costs. By examining how producers, consumers, and recyclers behave under constraints, this study offers new insight into policy design for waste management. A first-best policy maximizes welfare and achieves efficient recycling levels to reduce waste. When that first-best is not feasible, we must rely on other policies denoted as second-best solutions. Our simulations of the lithium market[2] and a sensitivity analysis on key assumptions illustrate the model's flexibility. Lastly, we discuss why some strategies are superior to others and examine some of the policy counterfactual effects and implementation challenges.

Model Assumptions

Our analysis builds on the Hotelling model for non-renewable resources and introduces a material balance constraint, and non-linear extraction and recycling costs. This model extends the framework presented in Rosendahl and Rubiano [19] by including a negative externality from waste disposal. The approach uses a partial equilibrium analysis of a durable resource market to focus on two aspects: (i) the resource market equilibrium, including recycling, but disregarding interactions with other markets; (ii) the Marshallian aggregate surplus as a welfare measure to compare policies. The benefit of this method is that one can observe how the market works at suboptimal levels because prices do not reflect waste disposal costs ("Free Market Solution"). Then, by comparing the free market with the socially optimal solution ("Social Planner Solution"), we can introduce market-based policies to deal with market failures ("Market-Based Policies").

Figure 1 shows the relationship between ore resource stocks and material flows. After being mined, lithium metal becomes battery-grade material. The conceptual map below also summarizes the variables used in our model, which we measure in value terms, not physical terms. Notice that used material can be recycled and returned to the market or end up as an uneconomical waste.

Free Market Solution

In the unregulated market solution, no one considers waste damage costs in their decisions. We assume free entry and competitive behavior in the mining and recycling sectors.[3]

Let P^M denote the material market price, i.e., raw (x) or recycled material (z). Furthermore, let P^W be the waste price (w) collected from consumers by recyclers. This price can be positive or negative (see Eq. (3)).

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[2] Lithium is one of the 30 critical raw materials found in e-waste presenting supply risks and difficult recycling [20]. Until now, data and information about lithium material stocks and flows are the most reliable and publicly accessible. See Appendices.

[3] The effects of market power and strategic behavior have been studied extensively in previous studies (c.f. [21, 22]) concluding that a monopolistic industry will slow down extraction vis-à-vis the socially optimal solution when facing a potential recycler. Hoogmartens et al. [17] extend the analysis of strategic behavior to the possibility of a substitute material at a fixed price.

Recycling

The competitive recycling industry collects waste (w) from consumers at the price P^W. Whether the waste price (P^W) is positive or negative depends on recycling profitability versus the costs of delivering waste to the landfill (Eq. (3)). If landfill costs are high (e.g., due to a landfill tax), we assume that the recyclers cannot avoid this payment by throwing the waste elsewhere.[4]

An amount of recycled scrap ($z = \alpha w$) is sold in the market, while the remaining part ($(1-\alpha)w$) is delivered to the landfill at a price $P^{LF} \geq 0$. We assume that storing scrap is too costly to be profitable. Hence, recyclers do not face an intertemporal trade-off between current and future stocks, so their maximization problem is unconstrained from a stock variable. The recycling rate ($0 < \alpha < 1$) is endogenous, depending on recycling profitability.[5]

Recycling costs appear as $C^R(\alpha)z$, and marginal recycling costs are strictly increasing in the share of recycled output: $C^R_\alpha > 0$ and $C^R_{\alpha\alpha} > 0$. The term C^R_α can be interpreted as the long-run average unit costs and disregard economies of scale that may appear at initial recycling stages.[6] Moreover, we assume that $\lim_{\alpha \to 1} C^R_\alpha = \infty$ indicating that complete recycling is impossible because of the limits imposed by product design, recycling technologies, and thermodynamics of separation [25]. Therefore, we always have $\alpha < 1$. The recyclers' instantaneous profit maximization problem becomes[7]:

$$\max_{\alpha, w \geq 0} \pi^R = \left[P^M \alpha - P^W - C^R(\alpha)\alpha - (1-\alpha)P^{LF}\right] w \tag{1}$$

We maximize with respect to α and w:

$$\alpha : P^M = C^R_\alpha - P^{LF} \tag{2}$$

$$w : P^W = \alpha(P^M - C^R) - (1-\alpha)P^{LF} \tag{3}$$

As stated in Eq. (2), recycling is zero ($\alpha = 0$) if the material price (P^M) is too low to cover the marginal recycling cost (C^R_α) minus the private landfill cost (P^{LF}). Therefore, recycling levels depend not only on the remaining earnings from material prices and recycling costs but also on disposal costs.

Equation (3) provides the zero-profit condition. The price (P^W) that clears the market for scrap materials depends on recycling profits given market prices, recycling costs, and landfill costs. Without recycling ($\alpha = 0$), waste prices (P^W) equal landfill costs ($-P^{LF}$) and are hence zero or negative. If waste prices (P^W) are higher than the right-hand side of Eq. (3), no recyclers will buy any waste, and hence, P^W will drop. If waste prices are too low, it will bring excess demand for waste, and P^W will increase.

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[4] Illegal disposal and transboundary waste shipment are real but beyond the scope of this study. Ino [23] offers a framework to analyze how to prevent firms from disposing waste illegally.

[5] In our numerical simulations, we only consider lithium recycling from LIBs. Cobalt and nickel, however, can also be recycled simultaneously. In lab-scale recycling experiments, recycling efficiencies vary between materials (cobalt 89%), nickel 69%, and lithium 80%) [24]. For simplicity, we do not differentiate recycling efficiencies by technology (i.e., hydrometallurgical, pyrometallurgical, or direct recycling); nor do we differentiate recycling efficiency based on input scrap type or quality.

[6] Economies of scale are important at the initial stages of recycling business and recycling profits dependent greatly on the composition of the total scrap stream [24].

[7] Time index t is suppressed where it is not essential.

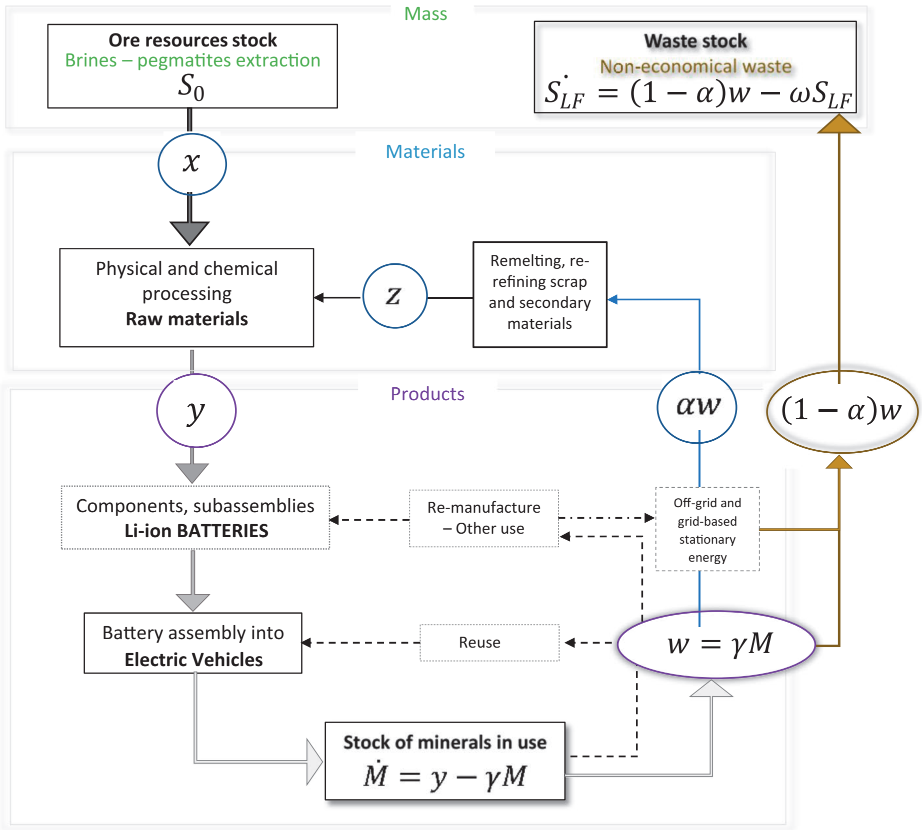

Fig. 1 Conceptual map: squared boxes represent materials or product stocks, and circles represent flow variables. Solid lines show what is included in this paper, while dashed lines display variables out of the scope of this study. We explain the variables and parameters in detail in "Free Market Solution"

We see that whether the waste price $\left(P^W\right)$ is positive or negative is in general ambiguous. With high recycling profits and lower disposal fees, the waste price tends to be positive. Likewise, with low profits and high disposal fees, waste prices $\left(P^W\right)$ tend to be negative. A negative waste price means that recyclers will not buy scrap materials, and consumers must pay to get rid of their depreciated materials.[8]

Consumers

A representative consumer chooses to demand raw (x) and recycled materials (z). Both goods are homogeneous; i.e., the recycled material is not a differentiated product from the pure material. Thus, disregarding resource storage, total consumption (y) should not exceed total supply, giving the following market balance condition:

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[8] Allowing consumers to deliver the material waste directly to the landfill, paying the price {P}^{LF}, would not change the outcome of our analysis (assuming they are not able to dump waste outside the landfill).

$$y \leq x + z \tag{4}$$

Let $U(y)$ denote the consumer's quasi-linear utility function (gross consumer surplus of consuming material),[9] and $MU\left(y_t\right)$ the marginal utility of consuming material, i.e., $U\left(y_t\right) = \int_0^{y_t} MU(s)ds$. Hence, $MU\left(y_t\right)$ represents the marginal willingness to pay for an additional unit of the resource.

The waste stock held by consumers and available to recyclers is defined by:

$$w = \gamma M \tag{5}$$

where γ denotes the annual depreciation rate of resource stocks in use; thus, $1/\gamma$ measures the resource lifetime before it is recycled or discarded. The material stock in use M_t develops according to[10]:

$$\dot{M} = y - \gamma M \tag{6}$$

Consumers have no choice but to let recyclers collect their material waste, also if they must pay ($P^W < 0$). The representative consumer faces the following problem to maximize its net Consumer Surplus CS subject to (6):

$$\max_{y \geq 0} CS = \int_0^\infty \left[U(y) - P^M y + P^W \gamma M\right] e^{-rt} dt \tag{7}$$

Now φ^c is the shadow price of the material stock in use (M), which could be either positive or negative depending on the future waste price (P^W). Thus, we have the following current-value Hamiltonian: $\mathcal{H}^c = U(y) - P^M y + P^W \gamma M + \varphi^C (y - \gamma M)$ and the necessary conditions for an interior solution ($y > 0$) give:

$$y : MU(y) = P^M - \varphi^c \tag{8}$$

$$M : \dot{\varphi}^c = (r + \gamma)\varphi^c - \gamma P^W \tag{9}$$

Equation (8) states that consumers will demand materials up until the point where their marginal utility $MU(y)$ equals the material price (P^M) minus the shadow price of resource stocks in use (φ^c). Thus, marginal utility can be either higher or lower than the market price, depending on the sign of φ^c. The dynamics of $\dot{\varphi}^c$ (Eq. (9)) depends on the discount and depreciation rates ($r + \gamma$), and on the future waste price adjusted by the annual depreciation rate of material stocks in use (γP^W). As time goes to infinity, we have that $\lim_{t \to \infty} e^{-rt} \varphi^c M_t = 0$.

Mining Industry

The competitive mining industry has property rights to ore resources. They extract metal minerals and transform them into materials before selling them directly to consumers. Although lithium is non-renewable, we do not consider them a finite resource stock.

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[9] Quasi-linear preferences are useful for isolating one sector and avoiding income effect feedback on the demand for other goods [26]. Quasi-linear utilities also make the externality optimal level independent of the consumers' wealth [27]. See Appendix 1.

[10] $\dot{M}$ means $\frac{dM}{dt}$, and the subscripts other than t denote the respective partial derivatives.

Instead, we assume that unit extraction cost $C^E\left(A_t\right)$ increases with accumulated extraction $A_t\left(C_A^E > 0\right)$, where accumulated extraction increases according to:

$$\dot{A} = x \tag{10}$$

Total extraction costs are then given by $C^E = C^E\left(A_t\right)x_t$. This cost function disregards short-term capacity constraints, as we are interested in the long-run effects.[11]We apply the following cost function, which also allows for technological change τ:

$$C^E\left(A_t\right) = C_0 e^{\eta A_t - \tau_t} \tag{11}$$

The parameter η represents the rising cost rate as accumulated production increases. We calibrate this parameter to the initial deposit stock levels for each producer.[12]To extract material volume x, a firm faces the following problem, subject to (10):

$$\max_{x \geq 0} \pi^E = \int_0^\infty \left[P^M x - C^E(A)x\right] e^{-rt} dt \tag{12}$$

The current-value Hamiltonian is: $\mathcal{H}_2 = P^M x - C^E(A)x - \lambda^E(x)$, where we have switched sign in front of the shadow price λ^E so that $\lambda^E \geq 0$ represents the resource rent.[13] Thus, the necessary conditions for an interior solution $(x_t > 0)$ are:

$$x : \lambda^E = P^M - C^E(A) \tag{13}$$

$$A : \dot{\lambda}^E = r\lambda^E - C_A^E x \tag{14}$$

Equation (13) states that extraction (x) should increase to the point where the material price equals unit extraction costs plus the resource rent. This resource rent also represents the shadow price of the resource property rights. The optimal path of the resource rent from future accessible resources $(\dot{\lambda}^E)$ will grow at a pace defined by the interest rate minus the change in marginal costs as extraction accumulates $(C_A^E = \eta C_0 e^{\eta A - \tau_t})$.[14] As time goes to infinity, $\lim_{t \to \infty} e^{-rt} \lambda A_t = 0$.

Social Planner Solution

Let us now turn to the welfare maximization problem. The social planner acknowledges waste impacts and seeks to correct the market failure by making explicit the costs from damaging waste into the welfare function. First, we assume that waste damage S_{LF}

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[11] This is a *rising supply cost* case, in which the marginal cost rises as the cheaper sources are depleted [28].

[12] The quality of ore may change in case of high-quality resource scarcity, but it is not observed at the moment. Nevertheless, our simulation accounts for cost differentiation due to the necessity of additional processes, transport costs, and the costs of readjusting output from the base year level to the optimal level (see Table 10in Appendix 2).

[13] As accumulated production imposes a constraint on the remaining profits, the costate variable ({\lambda }^{E}) would otherwise be negative.

[14] As extraction costs vary with ore grades, it is logical to deplete the cheapest resource first [29]. Once low-cost resources become exhausted, extraction turns towards deeper and costlier deposits. While extraction costs increase, scarcity rents may or may not decrease with time [30].

increases for each unit of non-recycled depreciated waste sent to landfills $(1-\alpha)w$,[15] and decreases at a natural degradation rate (ω):

$$\dot{S_{LF}} = (1-\alpha)w - \omega S_{LF} \tag{15}$$

The monetary cost of such impact is $D\left(S_{LF}\right)$, where $D', D'' \geq 0$. As explained in "Free Market Solution" above, consumers do not consider waste damages. Thus, damages may affect welfare but not individual behavior. The socially optimal solution is given by maximizing the following welfare expression related to a social discount rate ρ:

$$\max_{x,\alpha,y,w\geq 0} \Omega = \int_0^{\infty} \left[U(y) - c^E(A)x - C^R(\alpha)\alpha w - D\left(S_{LF}\right)\right]e^{-\rho t}dt \tag{16}$$

An additional constraint $w = \gamma M$ accounts for the waste allocation held by consumers and available to recyclers, with shadow price θ (can be positive or negative), and the constraint $y \leq x + \alpha w$ with its respective shadow price $\mu \geq 0$. Now given the constraints on stock variables $\dot{A}$, $\dot{M}, \dot{S_{LF}}$ with their respective shadow prices λ, φ, ξ, the current-value Hamiltonian is $\mathcal{H}_3 = U(y) - C^E(A)x - C^R(\alpha)\alpha w - D\left(S_{LF}\right) - \lambda(x) + \varphi(y-\gamma M) - \xi\left((1-\alpha)w - \omega S_{LF}\right) - \theta(w-\gamma M) - \mu(y-x-\alpha w)\cdot$

Table 1 shows the first-order conditions for the control and state variables with interior solutions $(x, \alpha, w, y > 0)$ and reveals the differences in prices between a private free market and a socially organized solution. A competitive and functioning market will solve those price differences and make $P^M = \mu$ and $P^W = \theta$. Besides the socio-environmental costs, the differences in shadow prices (λ, φ) between a free and a social market solution may also be due to differences between private (r) and social discount rates (ρ).[16]

Market-Based Policies

Before examining the government interventions to correct the market failure, it is important to recall that these are downstream measures aiming at efficient recycling to divert waste from landfills.

Landfill Tax

When market prices do not reflect the full external costs of waste disposal $(P^{LF} < \xi)$, there are "implicit subsidies" to material consumers at the expense of society, and the recycling share (if positive) is too low. Therefore, consumers have strong incentives to dump their waste in landfills at zero cost. Conversely, positive landfill taxes will lower the waste price P^W, so recyclers will be less willing to buy scrap materials, and consumers will have to spend more to get rid of depreciated materials. Thus, material demand will also decline despite the lower raw material market price. If material prices P^M are too low to cover recycling and landfill costs, the waste price P^W will be negative. Furthermore, only if the full cost of harmful waste disposal is internalized $(\widehat{P^{LF}} = \widehat{\xi})$, the efficient amount of recycling will be attained. In the numerical model, we assume that the marginal damage cost of waste is constant, $D'\left(S_{LF}\right) = \delta$, in which case the shadow price of harmful waste stock is:

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[15] In our model, landfill capacity is large enough to accommodate the recycling residues. However, the modelling framework can be extended to incorporate a landfill capacity constraint: $S_{\mathrm{LF}_t} \leq \overline{S_{\mathrm{LF}}}$ as suggested by Hoogmartens et al. [17].

[16] It is generally accepted that social discount rate should be lower than the private one [14, 17, 31].

Table 1 (A) The free market is unregulated, and no agents consider damage costs. (B) In a socially efficient solution, a social planner acknowledges material waste impact. (C) Market-based policies allow prices to change to internalize waste disposal costs fully.

		(A) Free market		(B) Socially efficient solution		(C) Market-based policies		
Material prices	Recycler	$P^M = C^R_\alpha - P^{LF}$; $P^{LF} = 0$ or $P^{LF} < \xi$	(2)	$\mu = C^R_\alpha - \xi$	(2a)	$P^M = C^R_\alpha - \widehat{P^{LF}}$, with $\widehat{P^{LF}} = \hat{\xi}$ $P^M + \hat{\vartheta} = C^R_\alpha - P^{LF}$, with $P^{LF} = 0$	(2b) (2c)	Landfill tax ($\hat{\xi}$) Recyclers' subsidy ($\hat{\vartheta}$)
	Consumer	$P^M = MU(y) + \varphi^C$	(8)	$\mu = MU(y) + \varphi$	(8a)	$\widehat{MU(y)} = P^M + P^T - \hat{\varphi}$	(8b)	Consumer Tax ($\hat{\varphi}$)
	Producer	$P^M = \lambda^E + C^E(A)$	(13)	$\mu = \lambda + C^E(A)$	(13a)	No policy (tax)		
Scrap material price		$P^W = \alpha P^M - \alpha C^R - (1-\alpha)P^{LF}$	(3)	$\theta = \alpha\mu - \alpha C^R - (1-\alpha)\xi$	(3a)	$\widehat{P^W} = \alpha P^M + \hat{\vartheta} - \alpha C^R - (1-\alpha)P^{LF}$, with $(P^{LF} = 0)$	(3b)	Recyclers' subsidy ($\hat{\vartheta}$)
Shadow prices	Valuable waste stock	$\dot{\varphi}^C = (r+\gamma)\varphi^C - \gamma P^W$	(9)	$\dot{\varphi} = (\rho+\gamma)\varphi - \gamma\theta$	(9a)	$\hat{\varphi}$		Consumer tax ($\hat{\varphi}$)
	Raw material deposits	$\dot{\lambda}^E = r\lambda^E - C^E_A x$	(14)	$\dot{\lambda} = \rho\lambda - C^E_A x$	(14a)	No policy (tax)		
	Harmful waste stock			$\dot{\xi} = (\rho+\omega)\xi - D'\left(S_{LF}\right)$	(9a)	$\hat{\xi}$		Landfill tax

$$\hat{\xi} = \delta\left(1 + \frac{1}{\rho + \omega}\right) \tag{17}$$

In addition, damages grow proportionally to the amount of harmful waste $D(S_{LF}) = \delta S_{LF}$ where $\delta > 0$ is the damage cost per ton of harmful waste. (See Appendix 3 for more details on our damage cost estimation).

Tax on Material Consumption — Advance Fee

A consumer tax could correct the negative externality if consumers pay the marginal social waste disposal costs, and recycling is non-viable. The tax, however, does not incentivize recycling. Still, we consider a consumer tax as an alternative policy, examining the second-best consumer tax path (in the absence of landfill tax). The tax can curb demand for materials by increasing consumer prices. Fullerton and W. Wu [6] find that if consumers must pay total marginal social costs of disposal, they will induce firms to design products that are easier to recycle. In practice, a better collection system and better information may lead to consumers recycling [11]. In our model, consumers do not have precise information and preferences on product recyclability that affect their utility levels. Thus, battery designs are controlled neither by consumers nor by recyclers. Battery recyclability is an exogenous parameter that influences recycling costs, and battery manufacturers are not considered in this model.[17]

Subsidies to Recycling

The free market can facilitate recycling, but government subsidies can accelerate it [14]. In contrast with Hoogmartens et al. [17] and Ino and Masueda [13], our subsidies $\hat{\vartheta}$ on recycling affect recycling efforts directly (α) as the subsidy is paid per recycled unit z processed, and not per unit of waste collected. Thus, subsidies are meant to stimulate waste processing rather than just collecting it for landfill disposal.

In the numerical analysis, we seek the second-best recycling subsidy path that maximizes welfare given the constraint of no landfill tax ($P^{LF} = 0$). When market prices do not reflect harmful waste costs, recycling subsidies become ineffective because it creates a rebound effect. In our model, a rebound occurs when a surge in waste prices (P^W) reduces the cost of using materials (increasing φ^c in Eq. (9)); then, material desirability will increase and, therefore, consumption (lower $MU(y)$ in Eq. (8)).

Combining Consumer Taxes and Recycling Subsidies

We also consider a fourth policy option, combining recycling subsidies and consumer taxes. This scheme is somewhat similar to a deposit-refund system when consumers who buy electronic products receive a deposit, and all or part of the deposit is later refunded when consumers return their products for reuse, recycling, or safe disposal. Producers (or retailers) may collect the deposit and repay it later. We do not model an explicit refund; instead, recycling subsidies tend to increase waste prices P^W and thus give consumers an

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[17] See Appendix 4.

implicit refund higher or lower than the deposit. We assume that this policy is fiscally neutral, meaning that the government's net revenue from the tax-subsidy scheme equals zero in each period. With two policy instruments available instead of just one, the welfare effects should be better, but this is not necessarily the case given the fiscal constraint.

Numerical Case Simulation

This section elaborates a numerical case simulation to understand the difference between a free market and a social planner solution and illustrate the effects of different policy scenarios. First, we show how recycling is affected in a free market with changing resource availability ("Free Markets and Resource Availability"). Then, we offer different policy outcomes ("Policy Scenarios"), and we run a sensitivity analysis to examine regulatory guidelines, i.e., standards for extended product lifespans and safer and environment-friendly design ("Sensitivity Analysis I: Non-market-Based Policies"). Lastly, we show how changes in the damage costs impact our conclusions drawn from the model ("Sensitivity Analysis II: Lower and Higher Damage Costs").

To calibrate the model, we use data from the global lithium market with the base year 2020 and use information from seven country suppliers (Argentina, Australia, Bolivia, Chile, China, USA, and the Rest of the World) and four main consumer sectors (electric vehicles, grid storage batteries, electronic devices, and other non-battery applications). In most sectors, material recycling is possible except for non-battery applications. The numerical optimization model was performed using GAMS 28.2.0 and adopted both mixed complementarity program (MPC) and non-linear program (NCP). (For data details, see Appendices 1, 2, and 3.)

Free Markets and Resource Availability

Let us now consider recycling in a free market with changing resource availability. In contrast to previous studies [19, 32], we find that resource scarcity should not be the main reason to promote recycling. Resources may be limited in the short term due to environmental regulations in mining, delays in concession bidding, or trade issues.[18] However, scarcity may not be a severe issue in the long term.[19] The most likely scenario is that exploration activities continue expanding material stocks. As a result, producers will undertake discovery projects even at a higher cost, putting more available resources at affordable prices in the market.

Figure 2 compares the effect on lithium market prices and recycling rates in a scarce and abundant resource scenario. In a scarcity scenario, the mining industry will exploit only economic reserves to date. When no more reserves are economically feasible, prices will

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[18] During 2020 and 2021, most industries experienced widespread supply chain disruptions due mostly to COVID-19 according to the USGS [33].

[19] To date, about 25% of identified lithium resources are economically feasible (so-called reserves). Nonetheless, identified lithium resources have doubled during the last 5 years going from 41 to 86 million tons [33]. In addition, new exploration projects grow in large numbers and will put more than 200 million tons of lithium resources available to the market within the coming years [34]. There are also economic concentrations of minerals, metals, and rare materials in the deep oceans, adding to the identify resource stock and sustainability challenge [35].

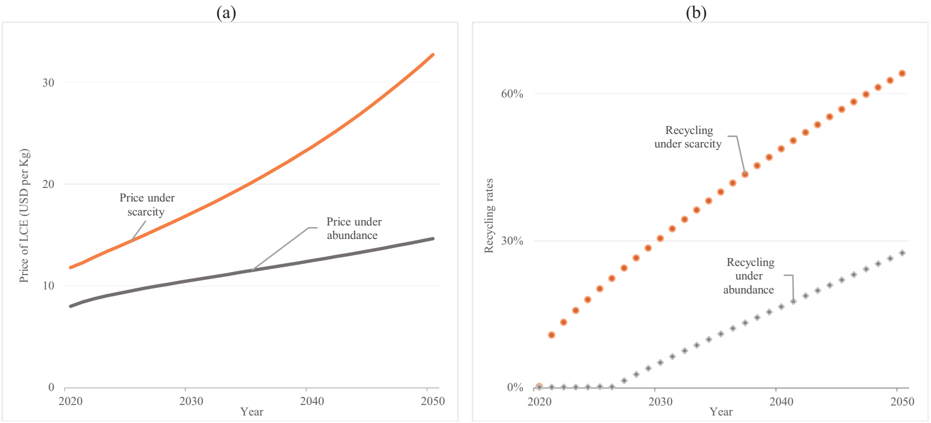

Fig. 2 Prices, recycling rates, and resource availability

range between USD 12 and 33, and recycling rates should start now at 11% to satisfy the swelling material demand. In contrast, in an abundance scenario, the mining industry can extract all identified resources; prices will range between USD 8 and 14 during the next 30 years, and recycling will not happen before 2027. Based on our estimates, exploration activity will likely expand material stocks, and without any public intervention, the market will determine very late when recycling becomes profitable regardless of harmful waste impacts.

Policy Scenarios

This section elaborates four policy scenarios and explains the effects of optimal and suboptimal solutions over material prices, recycling rates, waste, demand, supply, welfare, and damage levels. Market prices do not reflect waste's external costs and value in our benchmark scenario, and there is no policy intervention. Table 2 summarizes the four market-based policies presented in "Market-Based Policies" above.

Prices

The effect of market-based policies on material prices is shown in Fig. 3a. After implementing a landfill tax, material prices attain lower levels, reducing producers' incentives

Table 2 Policy scenarios

Policy scenario	Description	Symbol
Landfill tax	Pigouvian tax on landfill disposal (optimal solution, 1st best)	$\delta > 0$
Consumption tax	Tax on material consumption (suboptimal solution, 2nd best)	$\hat{\varphi} > 0$
Recycling subsidy	Subsidy to recycling (suboptimal solution, 2nd best)	$\hat{\vartheta} > 0$
Combining tax and subsidy	Tax on material consumption and subsidy to recycling, with subsidy payment not exceeding tax income for each sector (suboptimal solution, 2nd best)	$\hat{\varphi} > 0$ and $\hat{\vartheta} > 0$

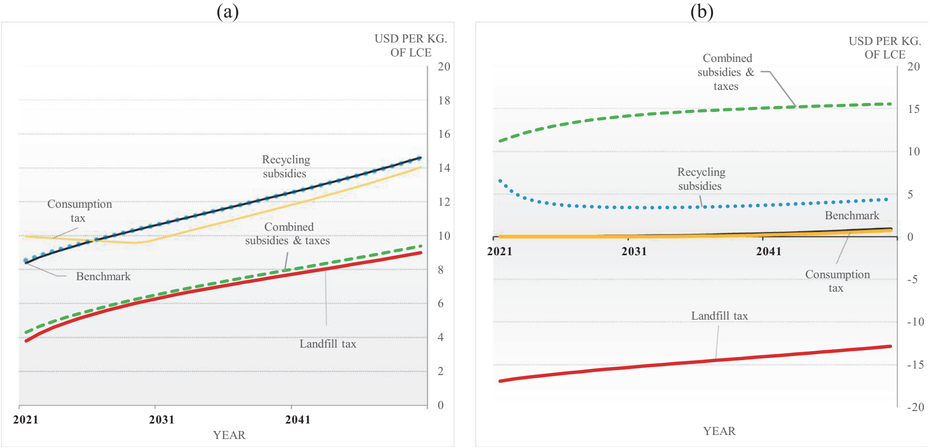

Fig. 3 **a** Raw material market price (P^M). **b** Waste market price (P^W)

to extract lithium. The landfill tax cumulative effect on material extraction is presented in Fig. 4c.

Figure 3a shows that lithium prices also decrease after applying consumption taxes, but consumers' purchase price (including the tax) increases. Hence, production and consumption are slightly depressed. Instead, recycling subsidies would cause the lithium market price to be close to the benchmark scenario. This effect may seem surprising at first, as an increased supply of recycled lithium would decrease lithium's market price. However, recycling subsidies also stimulate demand for lithium waste, increasing the waste price further increasing material demand. Thus, recycling subsidies encourage both supply and demand. This situation is illustrated in Fig. 4c.

Figure 3b shows that a positive landfill tax makes the waste price negative, meaning that recyclers will not be willing to buy scrap materials, and consumers must instead pay to get rid of their depreciated materials. As a result, material demand will also diminish despite the lower market price of raw materials. By contrast, recycling subsidies make the waste price positive, further increasing material demand as consumers find materials more valuable. But this situation only occurs when recycling is profitable and delivering non-recycled waste to the landfill has low or zero cost.

Under a tax-subsidy scheme, the market price declines, while the material waste price is highest among all scenarios. As a result, recyclers deliver much more output, and the greater consumption of recycled material compensates for lower raw material demand.[20]

Recycling Rates

The effect of market-based policies on recycling rates is shown in Fig. 4a. It shows that after a landfill tax is in place, recycling starts immediately, and recycling rates are consistently at much higher levels than in the benchmark because recyclers can reduce the pressure of additional tariffs by increasing the amount of waste recycled and, consequently, reducing the amount of waste sent to landfills. Therefore, a disposal fee provides higher incentives to recycle.

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[20] See Appendix 5 (Fig. 8) for additional results discriminated by consumer sector.

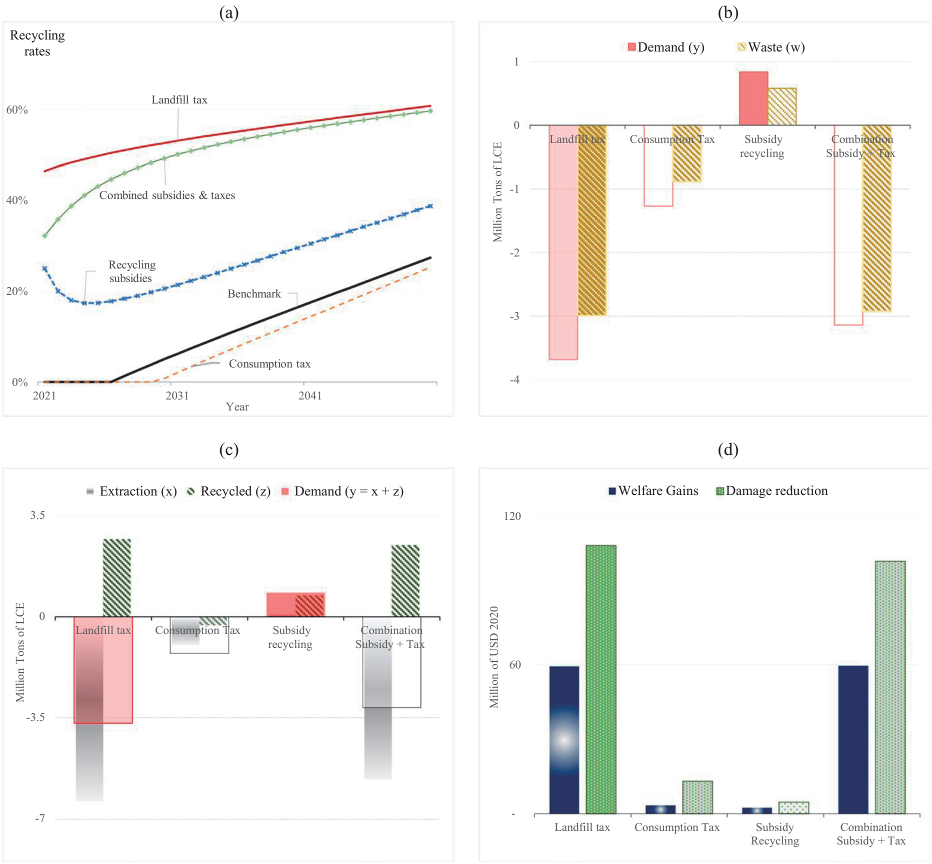

Fig. 4 **a** The recycling rates among policy scenarios compared to the benchmark or unregulated market. **b** The difference of accumulated demand and waste (2021–2040) among policies to the benchmark. **c** The difference in raw and recycled material production (accumulated until 2040) compared to the benchmark. **d** The welfare gains and damage reduction compared to the benchmark. Here, we calculate welfare and damages over a 100-year full-time horizon

What stands out in Fig. 4a is that after applying subsidies, recyclers hardly alter their output, and a large amount of waste ends up in the landfill despite the subsidy (after possibly being recycled one or more times). Government grants promote lower recycling rates and high waste volumes because the material market price does not change and remains as high as before any public intervention. Therefore, recyclers perceive a reasonable profit with less effort suggesting that subsidies to recycling, when implemented alone, should stay at a moderate level.

Closer inspection of Fig. 4a shows that when subsidies and consumption taxes are applied separately, recycling rates are lower than those obtained from a tax-subsidy scheme. One reason is that a consumer tax alone curbs demand but does not provide direct incentives to recycle. Another reason is that, with only the recycling subsidy in place, recyclers' profits are positively affected but not as much as when they are relieved from paying a landfill tax because the second-best recycling subsidy is not very high. However, when lithium demand decreases because of a consumption tax, subsidy levels can be increased, leading to higher recycling rates.

Demand and Waste

We turn now to analyze the accumulated effects of policy measures in the first 20 years. Figure 4b shows the total material demand (y), and waste (w) among policy scenarios. As mentioned above, a landfill tax reduces raw material prices, implying a material demand increase. However, despite the lower material price, demand also decreases because a positive landfill tax makes the waste price negative, which means that recyclers will not be willing to buy waste materials, and instead, consumers must pay to dispose of their waste. Likewise, consumer taxes increase purchasing material prices and depress material demand and waste.

Figure 4b highlights that a subsidy for recycling boosts waste and material demand. Recall that a recycling subsidy increases material prices (Eq. (2c) above) and waste prices (Eq. (3a) above), meaning that recyclers will be willing to buy waste as they benefit from higher material prices. As a result, consumers buy more materials and produce more waste. However, if governments combine recycling subsidies and consumption taxes with non-negative net government revenue constraints, the total cumulative demand and waste will be much lower than the benchmark scenario, and the policy will deliver later second-best results.

Raw Material Extraction and Recycling

We now evaluate how market price policies affect recycling and raw material supply. Figure 4c shows the total demand composed of raw and recycled materials. Extractive firms only receive incentives via market prices. As mentioned above, a landfill tax lowers material prices, reducing incentives to explore and extract raw materials. Recyclers still benefit from low but positive material prices and will process waste material to satisfy demand. The lithium market price also decreases after the government introduces consumption taxes, but consumers' purchase price indirectly increases via the added costs of disposing of the material waste. Hence, production and consumption are slightly depressed.

As we pointed out ("Demand and Waste" above), recycling subsidies increase material and waste prices. Due to higher prices, raw material extraction will be slightly higher during the first 20 years. Compared to the benchmark, the recycled output will increase due to higher waste prices. With higher raw material extraction and recycled material, total resource demand will be relatively high, with only small welfare gains and damage reduction (see Fig. 4d). In addition, a tax-subsidy scheme depresses raw material extraction and stimulates recycling, but the effects are not as large as with the landfill tax.

Welfare Gains and Damage Reduction

The differences in cumulative welfare gains and damage reduction relative to the benchmark are shown in Fig. 4d. Among market-based instruments, a landfill tax offers the most damage reductions and welfare gains because higher waste disposal costs make recycling more attractive. Therefore, a landfill tax can prevent products from being disposed of prematurely and orient waste collection towards recycling.

As shown in Fig. 4d, positive social benefits will also occur if the government implements a tax on consumers as an advance disposal fee. However, with recycling only as an option, such a tax has little effect on recycling and waste reduction. As a result, welfare gains and damage reduction resulting from consumer taxes are very marginal compared to a first-best landfill tax. In addition, subsidies to recycling are ineffective because subsidies alone stimulate too much material demand. The benefits in welfare gains and damage reduction are better when combining subsidies with a consumption tax. However, the tax-subsidy scheme requires zero net government revenues each year. The second-best tax helps keep consumption from being too high, and the second-best subsidies are higher than in the scenario with only subsidies.

The results in this chapter suggest that the recycling efficient level depends not only on the marginal disposal cost but also on profit conditions that rely on market price levels. The following section, therefore, moves on to test the model validity and robustness of the optimal solutions.

Sensitivity Analysis I: Non-market-Based Policies

This section elaborates a sensitivity analysis allowing decision-makers and modelers to select assumptions, as it illustrates how our model can accommodate different real-world situations. Table 3 describes three simulation scenarios. The first scenario involves government regulations limiting battery diversity and making more homogenous products, which reduces recycling costs. We double the *iota* (ι) parameter which represents the recyclability levels in this scenario.[21] In the second scenario, technological advances can lower recycling costs over time. To illustrate that situation, we increase the parameter *kapa* (κ) from 0.005 to 0.02, implying that recycling costs decrease by 2% instead of 0.5% per year.[22] In the third scenario, a policy can lengthen a product's lifespan to reduce waste production. In our model, the *gamma* (γ) parameter is halved, implying a double battery lifetime.[23] As a rule, improved recyclability, lower recycling costs, and extending the battery's lifetime by investing in technology and product design typically come with a cost, which we do not incorporate in our model. Therefore, these welfare results need to be interpreted with caution.

Figure 5a shows that technological change and better product design also stimulate recycling. However, the effects are less immediate than in the landfill tax or recycling subsidy scenarios (Fig. 4a). In our model, technological change takes time (by assumption) and better product design to extend battery longevity slightly decreases marginal recycling costs.

Figure 5b shows that when recycling costs diminish because of higher recyclability or improved technologies, more recycled output is available to consumers reducing material prices. As a result, total material demand increases jointly with more waste creation. Therefore, recycling rates will be higher than a free market solution but similar to recycling rate levels resulting from a subsidy policy, as presented in Fig. 4a. In addition, Fig. 5b shows that longer battery life can extend material use and decrease material demand and waste

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[21] See the Appendix 4, and Eq. (24).

[22] See the Appendix 4, and Eq. (25).

[23] See the Appendix 4, and Tables 12 and 13.

Table 3 Simulation scenarios and parameter changes

Simulation scenario	Description	Symbol
Recyclability	An exogenous increase in the parameter ι reduces recycling costs	ι increases from 1 to 2
Technological change	An exogenous increase in the parameter κ reduces recycling costs	κ increases from 0.05 to 0.02
Longer lifetime	An exogenous decrease in the parameter γ increases the lifetime	See Appendix Tables 12 and 13

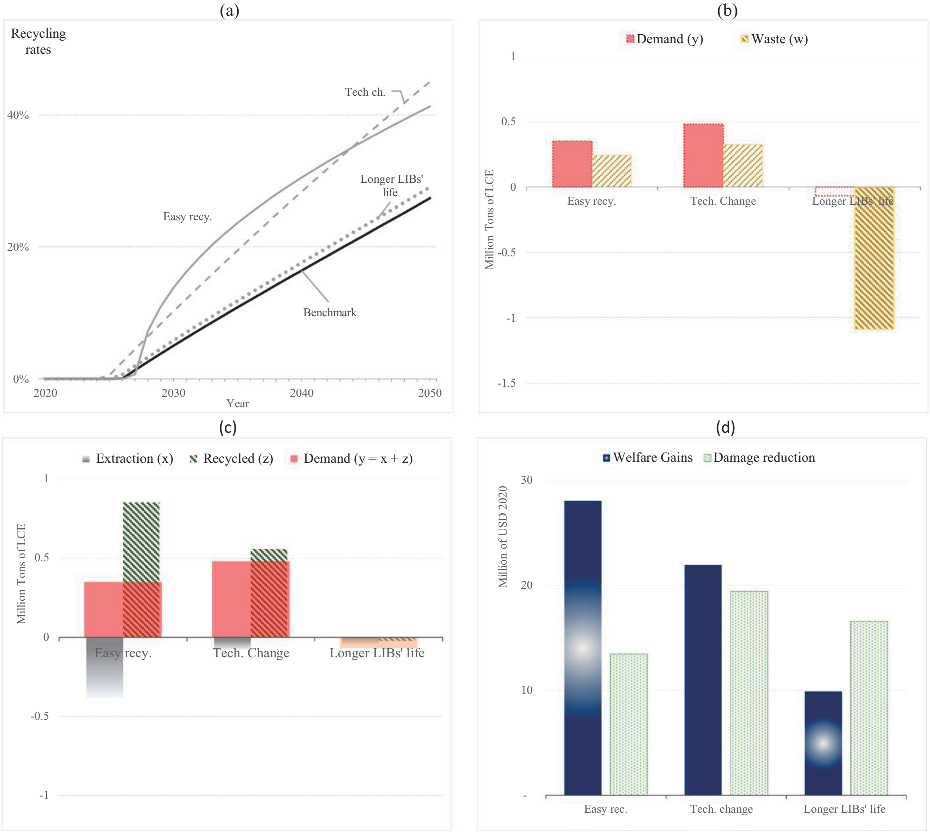

Fig. 5 **a** Recycling rates among scenarios: easy recyclability, technological changes, longer LIB's life. **b** The accumulated demand and waste (2021–2040) among scenarios compared to the benchmark. **c** The raw and recycled material production (accumulated until 2040) compared to the benchmark. **d** The welfare gains and damage reduction compared to the benchmark. Here, we calculate welfare and damages over a 100-year full-time horizon

vastly. Therefore, material circularity happens even if recycling rates are relatively low because longer battery life prevents waste accumulation.

Figure 5c illustrates that easy product recycling and technological change will lessen recyclers' costs and put more recycled output in consumers' hands. Therefore, material market prices decrease, and raw material supply reduces compared to the benchmark. It is essential to approach this account with caution because we do not include the cost of increasing recyclability as this model does not consider the battery production sector.[24]

Overall, welfare gains and damage reduction occur by extending the product lifetime or reducing recycling costs via better product design to easy recyclability and technological innovations. However, such measures *à la carrot* are not as effective as tax mechanisms to correct market prices and disincentivize waste production: *the stick*.

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[24] Battery costs have fallen and will continue falling markedly [36]. This sector is constantly working on reducing material content in batteries while optimizing performance. This may increase battery recyclability and extend battery lifetime.

Sensitivity Analysis II: Lower and Higher Damage Costs

This section performs a second sensitivity analysis to investigate how the optimal solution changes as damage costs change. In theory, landfill taxes should fully reflect the harmful waste cost. However, with limited data and research on the impact of electronic and battery waste, the costs of toxic waste damage are difficult to measure [37–39]. Therefore, in this study, we apply an approximate cost and the damage cost varies linearly with the amount of waste to simplify the model.

Figure 6a shows that higher damage costs imply higher recycling rates in response to higher landfill taxes. In the baseline scenario, the damage parameter delta is $\delta=1$. Figure 6b reveals that when we reduce the damage levels and half this parameter ($\delta=0.5$), cumulative demand and waste decrease 45% and 46%, respectively. By contrast, doubling damage levels ($\delta=2$) implies that cumulative demand and waste will be 32% higher than the benchmark scenario ($\delta=1$). Not surprisingly, the greater is the damage level, the lower is the effect of landfill taxes in terms of demand and waste reduction, and the sensitivity analysis suggests that the size of the damages has substantial impacts on the optimal level of material used.

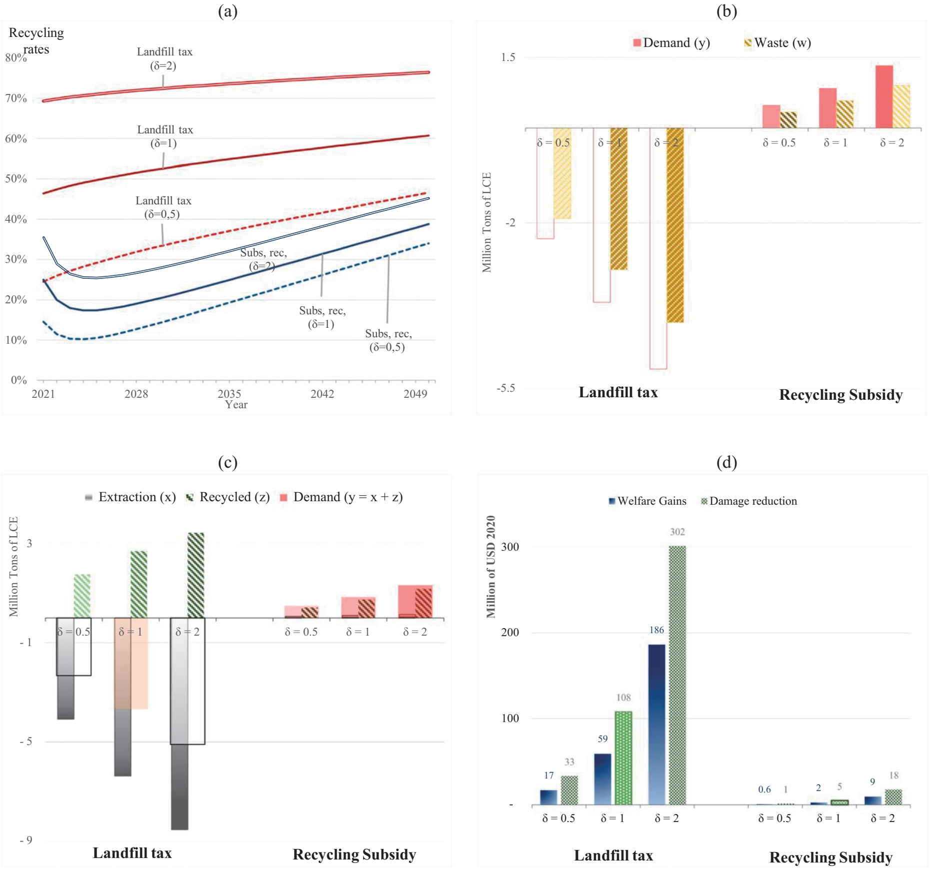

Fig. 6 **a** Recycling rates among scenarios with different values for the damage parameter delta (δ) . **b** The accumulated demand and waste (2021–2040) among scenarios compared to the benchmark, i.e., free/unregulated market solution. **c** The raw and recycled material production (accumulated until 2040) compared to the benchmark. **d** The welfare gains and damage reduction compared to the benchmark. Here, we calculate welfare and damages over a 100-year full-time horizon

Irrespective of damage levels, landfill taxes continue to reduce material extraction, and subsidies to recyclers continue to generate rebound effects, i.e., stimulating raw material extraction (Fig. 6c). Nonetheless, the greater is the damage level, the greater is the effect of landfill taxes on damage reduction and welfare gains (Fig. 6d).

Since we do not include externalities for raw material extraction, we do not apply Pigouvian taxes to the mining industry. However, the effect of a landfill tax on market prices is so pervasive that it reduces raw material supply and thus will also reduce externalities of raw material extraction.

Discussion and Policy Implementation Challenges

In reviewing the literature, no empirical evidence was found to understand the cumulative effects of waste management policies on welfare and damage reduction considering budget requirements. An initial objective of this study was to provide a quantitative analysis that supplements previous literature on economic policies for material reuse. We show that accounting for harmful waste impacts is necessary to attain efficient recycling levels. Our simulations showed that a landfill tax is a first-best policy because it attacks the externality directly, stimulates recycling, and reduces toxic waste from spent batteries while welfare reaches its highest level. This finding is consistent with that of Hoogmartens et al. [17], who found that by applying a constant landfill tax, it is possible to approximate the first-best welfare optimal outcome very closely in terms of externality costs and lower raw material exhaustion.

One unanticipated finding was that after a social planner introduces a landfill tax, total material demand is lowest among all alternatives and scenarios because landfill taxes depress demand for raw materials and deviate it to recycled materials. Lower material use is undesirable if it implies slower green energy and digital transitions. Although our model may not fully represent the welfare benefits and positive externalities from battery use, we show that even if a landfill tax reduces material demand, society still perceives welfare gains because recycling attains much higher levels than without market interventions. Therefore, in response to the sustainability challenge, it would be advantageous if battery producers could use less material per product while maintaining their performance level, and the landfill tax gives incentives for that.

Another important finding was the ambiguous relationship between material extraction and recycling. In the case of abundant ore resources, extraction increases, and raw material prices fall, which lowers the incentive for recycling because recycling is too costly and immature compared to low-cost, mature mining. However, it is not straightforward how recycling affects raw material extraction. When implementing a landfill tax, raw material extraction will be lower than in a free market, and more recycled materials will satisfy demand. By contrast, if recyclers benefit via subsidies, such policy can lead to more raw material extraction, suggesting that the subsidy policy benefits are relatively moderate. This is an example of a phenomenon known as the rebound effect [40].[25]

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[25] This rebound effect resembles the Jevons paradox; i.e., a more efficient resource use will accelerate resource exhaustion. This effect also shares similarities with the green paradox as pointed to by, e.g., [15]. The green paradox suggests that environmental policies may lead to accelerated extraction of fossil fuels, especially if fuel owners believe the policy to be strengthened over time. Although the mechanism is somewhat different in our model, we find that policies to increase circularity may in some instances accelerate extraction of raw materials.

In our model, a rebound occurs because subsidies to recyclers increase their demand for waste, increasing its price and reducing the cost of using materials, resulting in higher material consumption. Later, higher demand for materials leads to higher raw material prices, stimulating an initial raw material extraction. However, encouraging recycling in this way is not necessarily a welfare improver because the benefits in welfare gains and damage reduction are better if governments combine subsidies with a consumption tax. To some extent, the tax on consumers will dampen the subsidy rebound effect.

The parameter values and assumptions in this model are subject to uncertainty. With that in mind, we run a sensitivity analysis to investigate to what extent ambiguous information affects our results and conclusions, primarily related to the damage parameter. We demonstrated numerically that landfill taxes provide a consistent optimal solution with lower and higher damage levels. Since we do not include externalities of raw material extraction, we do not apply Pigouvian taxes to the mining industry. However, the effect of a landfill tax on market prices is so pervasive that it succeeds in reducing raw material extraction at all damage levels. By contrast, subsidies to recyclers continue to generate rebound effects by stimulating raw material extraction. Overall, this sensitivity analysis tests the robustness of the optimal solution and validates the model assumptions under poor information. However, policymakers should prioritize acquiring accurate data about damage levels to design more credible and proper policies.

In practice, an optimal market-based policy can bring counterfactual effects and implementation challenges. For example, charging waste holders directly for disposal costs may lead to illegal burning or dumping [41]. Likewise, implementing subsidies to recyclers may involve additional costs to monitor recycling firms' activities, and recycling subsidies may create market distortions and more damage when illegal dumping is an option. In such cases, the subsidy should vary considering the monitoring costs, disposal costs, and recycling technologies, and deposit refunds are second-best [13]. Nonetheless, several questions remain unanswered about how to implement a combination of taxes (deposit) and subsidies (refund) when consumers and recyclers have different geographical locations and uncontrolled transboundary waste movements exist.

This paper stresses the use of circular reuse to minimize e-waste and create added value from used materials. Therefore, the study is unable to capture all externalities at different stages of materials' life cycles associated with raw material extraction, recycling processes, and landfill pollution; it focuses only on the externalities of end-of-life products. However, avoiding the harmful effects of the entire life material cycle is crucial for a circular economy, so this is also an essential part of how policymakers should think about material circularity. Indeed, there are negative externalities from mining, and researchers have alerted that mining lithium can spoil unique landscapes and drain scarce water stocks [42]. In that case, implementing a Pigouvian tax on extraction, reflecting these environmental damages, would likely dampen raw material extraction, leading to higher market prices, stimulating recycling, and indirectly reducing landfill damages, too. Moreover, certain recycling processes can cause more harm than good [37], and the environmental benefits of recycling will depend on the recycling technology used and the material cocktails embedded in products [43–45]. Further research should be undertaken to integrate ecologically and carbon impacts across the material lifecycle and examine ways to make mining, recycling, and landfilling more sustainable.

Conclusions

This research aimed to examine how a set of market-based policies can promote material circular reuse and correct market failures caused by improper waste disposal. The findings indicate that irrespective of damage levels, a landfill tax is the most efficient policy, as it targets the hidden cost of waste disposal and promotes the best results in recycling levels, damage reduction, and welfare gains. If a landfill tax is not feasible, other policies such as taxes, subsidies, and a tax-subsidy scheme provide second-best results. The research also shows that a consumer tax alone curbs demand but does not provide recycling incentives; thus, other market-based policies should be pursued.

This study has raised important questions regarding recycling subsidies. In general, a subsidy will encourage recycling. But if market prices do not reflect the externality cost, a subsidy to recyclers can promote material overuse because the subsidy will increase waste prices, which increases material value to consumers and leads to higher demand and waste. As the price of raw materials rises with higher demand, the initial raw material extraction is stimulated. Therefore, irrespective of damage levels, a high recycling subsidy cannot be the optimal policy because it increases waste demand and causes a rebound effect.

If governments want to avoid rebound effects, they should consider combining second-best policies. The numerical simulations confirmed that consumer taxes and recycling subsidies have limited welfare gains when implemented alone, while a tax-subsidy scheme will enhance welfare and reduce harmful waste with a neutral impact on the government's budget. Subsidies alone will not be sufficient to curtail material demand and waste, and recycling will not reach optimal levels unless consumer taxes are applied with subsidies. That is why combining taxes and subsidies is more efficient than just one of the two policies.

Although this study focuses on the end-of-life externalities, the findings of combining economic policies may well have a bearing on the circular and sustainable use of materials. Notwithstanding the case of lithium, this work offers valuable insights into material and mineral markets, and the model framework can be applied with data of other critical raw materials. This research contributes to our understanding of why it may prove somewhat negligent to leave the market free and recycle adrift when society carries losses from harmful waste. The current findings support that recycling is essential for material circularity, but government intervention is required to moderate the material and recycling markets. By doing so, society can reap the benefits of reusing valuable materials and push forward sustainable energy and digital transitions.

Data and Code Availability

The GAMS code and input data employed in this study are available upon request.

Appendix 1. Demand function and data input

We assume the following utility function for the use of materials y_{it} at each period "t" in all-consuming sectors "i":

$$U_{it}\left(y_{it}\right) = \varsigma + \beta_t\left(y_{it}\right)^{\frac{1+\epsilon}{\epsilon}} \tag{18}$$

where ς is some constant, ϵ represents the (long-term) price elasticity of demand, and $\beta_t = \frac{\epsilon}{1+\epsilon}\left(\frac{1}{y_0\sigma_t}\right)^{\frac{1}{\epsilon}} p_0$. The term y_0 denotes the initial demand level, while σ_t is a function reflecting the underlying growth in demand. Plugging β_t in (18):

$$U_{it}\left(y_{it}\right) = \varsigma + \frac{\epsilon}{1+\epsilon} y_{i0} p_0 \sigma_t \left(\frac{y_{it}}{y_{i0}\sigma_t}\right)^{\frac{1+\epsilon}{\epsilon}} \tag{19}$$

Simplifying and making $\varsigma_i = 0$

$$U_{it}\left(y_{it}\right) = \frac{\epsilon y_{it}\left(\frac{y_{it}}{y_{i0}\sigma_t}\right)^{\frac{1}{\epsilon}} p_0}{(\epsilon + 1)} \tag{20}$$

This condition gives the following marginal utility function:

$$U_{it}{}'\left(y_{it}\right) = \left(\frac{y_{it}}{y_{i0}\sigma_t}\right)^{\frac{1}{\epsilon}} p_0 \tag{21}$$

Furthermore, the derived demand function, which is a price-dependent deterministic demand function that we use in the model numerical simulations, will take the following form:

$$y_{it} - y_{i0}\sigma_t\left(\frac{p_t}{p_0}\right)^{\epsilon} \geq 0 \perp y_{it} \geq 0 \tag{22}$$

The elasticity ϵ is a hypothetical value -0.5 in the benchmark scenarios.[26] We set the factor σ_t from an exogenous growth function and calibrate the demand growth function σ_t using several growth rates (see Table 4), and calibrated parameters (Table 5) following this functional form:

$$\sigma_{it} = \frac{\sigma_{i1}}{\sigma_{i2} + \sigma_{i3}e^{-\sigma_{i4}t} + \sigma_{i5}e^{-\sigma_{i6}t^2}} \tag{23}$$

Lithium raw materials vary significantly in their lithium content, chemical compositions, and final use (Table 6). Our sources of information report mineral ore and reserves for hard rock and brine projects in different unit metrics, for example: in ppm Li, in percentages of Li, and in Li2O. In this paper, we used lithium carbonate equivalent (LCE). Since we took different information sources with other metric units, we normalized this data to "lithium carbonate equivalent" or "LCE" based on the table below's conversion factors (Table 7). Lithium prices have fluctuated considerably over the last years (Table 8). In our simulations, we take 2020 as a base year.

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[26] As far as we know, there exist no empirical studies of demand elasticities of lithium. Thus, the size of this elasticity is very uncertain, especially in the long run when the price sensitivity depends, for instance, on the availability of substitutes. Therefore, we perform sensitivity analysis with respect to this elasticity.

Table 4 The annual growth rate in lithium demand in sector *i* (given price in 2020)

Period	Transportation	Grid storage	Consumer electronics	Industrial applications
	(a)	(b)	(c)	(d)
Until 2025	25%	15%	10%	5%
2031–2050	8.5%	8.5%	3%	3%
2051–2100	3.5%	3.5%	1%	1%
After 2101	0%	0%	0%	0%

(a) Electric car registrations continue growing despite the pandemic. Meeting the 2030 target of the IEA and Paris Agreement implies that the global stock of electric cars should maintain annual growth rates above 25% by 2025 and in the range of 7 to 10% between 2030 and 2050 [36]

(b) Smart charging is crucial to ensure that grid capacity does not constrain electronic vehicle (EV) uptake [36]

(c and d) Growth rates until 2025 are extrapolations based on historical data [33]. The rate numbers from 2031 are our assumptions.

Table 5 Parameters in the demand growth function and displays the calibrated parameters of Eq. (23)

Parameter	Transportation	Grid storage	Consumer electronics	Industrial applications
$\boldsymbol{\sigma}_{i1}$	4982	2293	2636	2741
$\boldsymbol{\sigma}_{i2}$	6.07	6.41	295	489
$\boldsymbol{\sigma}_{i3}$	1113	1147	1229	2034
$\boldsymbol{\sigma}_{i4}$	0.074	0.072	0.053	0.053
$\boldsymbol{\sigma}_{i5}$	3863	1132	1112	218
$\boldsymbol{\sigma}_{i6}$	0.10	0.10	0.10	0.10

Table 6 Demand for lithium in sector i (thousand tones — Kt — of lithium carbonate equivalent (LCE)). Source:[33, 36]

	Lithium in batteries from sales of EVs	Lithium in batteries from stocks of EVs	Grid storage	Consumers electronics (CE)	Non -battery use	Total
2015	7.80	24.2	0.9	60.2	103.3	172.2
2016	11.70	35.9	1.4	82.0	111.7	206.8
2017	16.90	52.8	4.1	185.8	162.4	369.2
2018	28.60	81.4	6.6	296.1	178.4	509.7
2019	32.50	113.9	6.9	285.7	132.8	457.8
2020e	34.92	109.1	7.4	267.6	126.6	436.5
Average		69.54	4.55	196.21	135.86	358.68

Table 7 Conversion factors for differing lithium data. Source: Savannah Resources

To convert from	Chemical abbreviation	To convert to:		
		Lithium (Li)	Lithium oxide (Li2O)	Lithium carbonate equivalent (LCE)
		Multiply by:		
Lithium	Li	1	2.153	5.323
Lithium oxide	Li2O	0.464	1	2.473
Lithium carbonate	Li2CO3	0.188	0.404	1
Lithium hydroxide monohydrate	LiOH.H20	0.165	0.356	0.880

Table 8 Price, annual average, battery grade of LCE in thousand USD per ton. Source: [33]

2014	2015	2016	2017	2018	2019	2020	Average 2014–2020
6.7	6.5	8.7	15.0	17.0	12.7	8.0	10.65

Appendix 2. Supply data input (Tables 9 and 10)

Table 9 Estimated production, reserves and resources in 2020 per country in thousand tons. Source: [33]

	Production		Reserves (economically extractable)		Identify resources (technically feasible)	
	Li	LCE	Li	LCE	Li	LCE
Argentina	5.9	31.4	1.9	10.1	19.3	102.7
Australia	39.7	211.3	4.7	25	6.4	34.1
Bolivia	0	0	0	0	21	111.2
Chile	21.5	114.4	9.2	49	9.6	51.1
China	13.3	70.8	1.5	8	5.1	27.2
USA	Withheld	Withheld	0.8	4	7.9	42.1
Rest World	2.1	11.8	2.9	15.7	16.7	88.9
Total	82.5	439.2	21	111.8	86	457.8

Table 10 Initial unit extraction costs in thousand USD per ton of LCE

	Argentina	Australia	Bolivia	Chile	China	USA	Rest world	Average
Initial extraction cost* (USD/kg)	2.5	4.2[a]	6.0	3.6	5.24	3.4	6.6*	4.42 §
Transport cost(c_j^T)(USD/kg)	0.4	0.67	0.96	0.58	0.84	0.54	1.05	0.8

*This value includes extraction and conversion costs. We compare average extraction cost from operating mines published by the Lithium Cost Model Service at Roskill and the Market Research at Deutsche Bank [34]

(a) Australia and the rest of the world produce spodumene lithium that needs to be refined into higher purity lithium products before being used in the battery supply chain. For example, China imports lithium concentrates and processes them in conversion plants

(§) Aritmetic mean value among countries

Appendix 3. Damage cost estimation

Upon disposal, the two main hazards that LIBs pose are the high concentrations of leachable metals they contain and a tendency to explode and catch fire when improperly handled [38]. However, standards and regulations can improve the safety of electronic products and classify waste as hazardous and universal waste.

Deposited electronics in landfills release heavy metals like mercury, arsenic, lead, and heavy metals toxic for humans and ecosystems. Likewise, incinerating electronics releases heavy metals and other toxins into the air besides the typical greenhouse gas emissions.

Table 11 shows the economic cost of human exposure to harmful electronic waste. Waste generation and monetary damages vary between countries and regions. Waste production and economic damages are greater in Asia than in the rest of the world. Africa has the lowest waste generation, and economic costs are lower than other developing countries, but the impact on their economies can be devastating when considering those damage expenses as a percentage of GDP. Europe and North America have a relatively low economic cost of e-waste, but they head first globally regarding e-waste production per capita.

Table 11 E-waste generation and economic cost of health damages by country

	E-waste generation million tons (A)	E-waste generation per capita kg	From which batteries tons (B)	Annual economic lost (LEP) (billion USD) (C)	% GDP (D)	Economic cost of harmful waste batteries (thousand USD/ton) (B) * (C)
Africa	2.9	2.5	14,500	18	4%	6.21
North America (USA, Canada)	7.7	20.2	38,500	51	0.33%	6.62
Central and South America	5.4	8	27,000	33	2.04%	6.11
Eastern Asia (China, Japan, Korea)	13.7	9	68,500	227	1.80%	16.57
West, Central and South Asia	11.2	5	56,000	236	1.80%	21.07
Europe	12	16.2	60,000	13	0.31%	1.08
Oceania	0.7	16	3500	NA	NA	
Total	53.6		264,500			10.93

A. [4]

B. Eurostat Statistics (2018)

C. Neurodevelopmental damages assessed as decrements (or reductions) in intelligence quotient (I.Q.) points are the most evident impact of harmful e-waste in human health. This damage is translated into decreased lifetime earning potential, assessed as lost lifetime economic productivity (LEP). Estimations based on [4, 46]

D. [4] and Eurostat Statistics (2018)

Appendix 4. Policy scenarios and waste stock ladder

Note that only disposal, recycling, and prevention are explicitly captured by our model (see Fig. 7), whereas we do not analyze material recovery and product reuse.[27] "Market-Based Policies" explains the logic of market-based policies (landfill taxes, consumption taxes, and subsidies to recyclers). In this Appendix, we describe other regulatory measures exogenously defined, for which we ignore the cost of such actions.

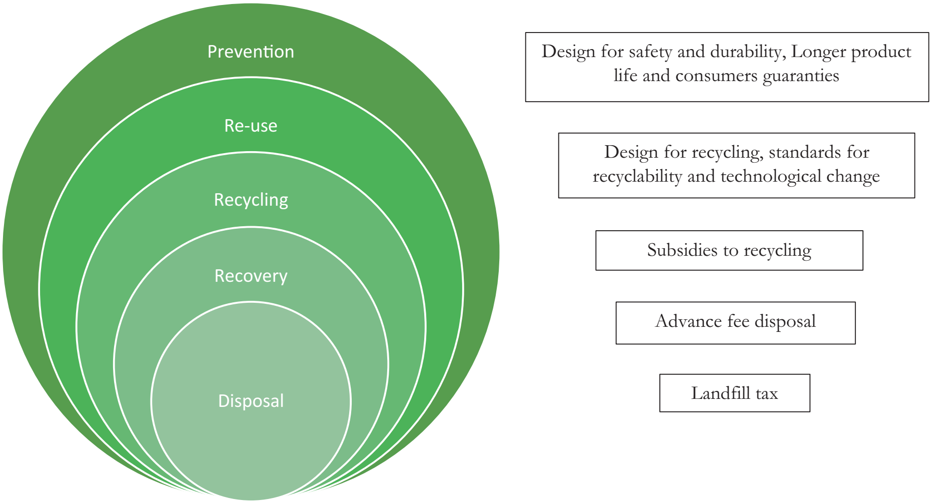

Fig. 7 Policies and waste stock ladder based on the Waste Framework Directive [47]. This figure shows overlapping relationships in waste management and emphasizes waste escalation from less desirable outcomes such as landfill disposal to preferable preventive waste management. However, the accompanying policies in each ladder do not necessarily suggest a better efficient or optimal level

Table 12 Policy scenarios and simulation parameters under free market and social planner solution

Scenario	Free market benchmark	Social solution
*Initial recycling costs**(cr_0)	10 (thousand USD per ton)	10 (thousand USD per ton)
Recyclability** (ι : *iota*)	$\iota = 1$	$\iota = 2$
Technological change** (κ : *kappa*)	$\kappa = 0.005$	$\kappa = 0.02$
Longer battery life	See table below	See table below

* This is the approximated cost of recycling 1-ton cathode materials from spent Li-ion batteries, including fixed and variable costs. It varies among cathode chemistries, recycling methods, and geographical location. Kushnir and Sanden [48] estimate an approximately recycling cost of between 6 and 10 thousand USD per ton of cathode materials from spent Li-ion batteries; Wang et al. [24] observe that for an existing recycling facility, the variable costs can vary from USD 1100 to USD 4500 per ton of recovered materials. They also assess that when total costs equal total revenue at a breakeven point, the unit value of recovered materials varies between 890 and 8900 USD per ton depending on the type of cathode chemistry. In the future, that cost may fall due to the increasing volume of collected EV. Li-ion batteries and advancements in recycling technologies

**Hypothetical values

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[27] When some material is difficult to recycle, it can be melted or transformed to use in other sectors like construction road. We refer to this as recovery.

Table 13 Battery lifetime in years and depreciation rate of lithium-ion batteries by sector. Own assumptions

	Electric vehicles		Grids		Consumer electronics	
	Years	Depreciation rate	Years	Depreciation rate	Years	Depreciation rate
Short lifetime	10	0.10	5	0.20	3	0.33
Long lifetime	20	0.05	10	0.10	6	0.17

Design for Recycling and Technological Changes

In our numerical analyses, we apply the following formulation of recycling costs, accounting for technological innovations via exogenous cost reductions over time:

$$C^R(\alpha) = cr_0\left[1 - \ln(1-\alpha^\iota)\right]e^{-\kappa t} \tag{24}$$

The cost of the cheapest unit of recycled output ($z = \alpha w$) is then $cr_0 \bullet e^{-\kappa t}$. When $\alpha \rightarrow 1$, we see that the (marginal) costs go towards infinity, as required above. The marginal recycling cost functions will be:

$$\frac{dC^R(\alpha)\alpha w}{d\alpha} = cr_0 e^{-\kappa t}\left[1 - \ln(1-a^\iota) + \frac{\iota a^\iota}{1-a^\iota}\right]w \tag{25}$$

In the lithium context, policies may enforce standards to reduce the immense variability of battery designs and enforce more recyclable batteries. The parameter ι(*iota*) determines this level or ease of recyclability. The higher is this parameter; the slower marginal recycling costs will increase. The recycling cost function also includes technological progress that reduces the unit costs exogenously over time through the parameter κ. Thus, the measures we consider here involve exogenously increases in ι (recyclability) and κ (technological change) (see Table 12).

Design for Safety — Consumer Guarantees and Longer Product Lifetime (Gamma)

In the waste management hierarchy, prevention is the most desirable way to manage waste. Here, policies may promote extended consumer guarantees offering options to repair and replace their batteries without any additional charge.[28]

The parameters γ used in Eqs. (5) and (6) denote the annual depreciation rate of material stocks in use (thus, $1/\gamma$ is a measure of the resource lifetime before it must be recycled or discarded). In our numerical simulation, we change this parameter to extend the product lifetime and calculate the respective effects on waste, welfare, and damages.

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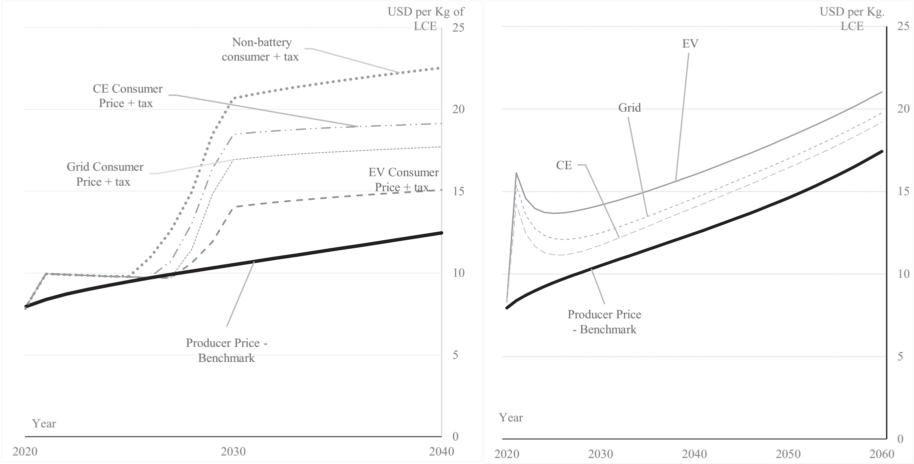
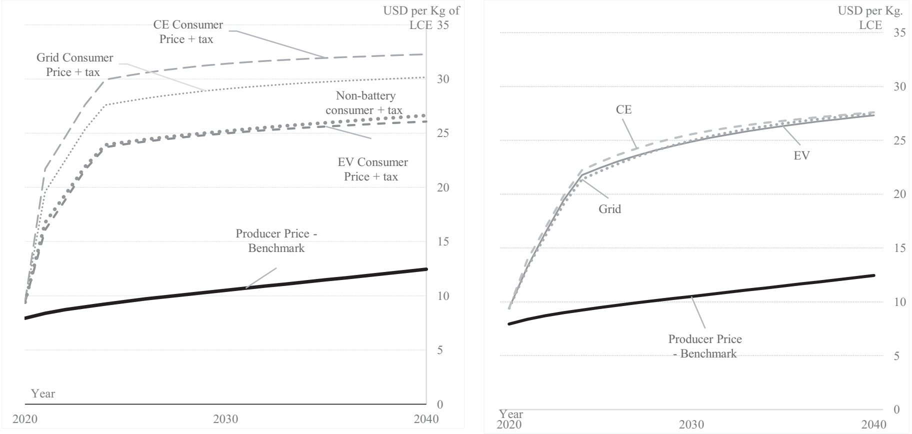
[28] The European Union promote this policy, but still it is not clear the scope and enforcement of such measures in the electronic market. See more at Europa.eu/consumer_garantees.

Appendix 5. Additional results (Fig. 8)



(a) Consumer material prices (P^M) after tax **(b) Recyclers material price (P^M) after subsidies**



(c) Consumer material prices (P^M) after the tax-subsidy scheme **(d) Recycler's material price (P^M) after the tax-subsidy scheme**

Fig. 8 Material prices after taxes and subsidies are applied individually (**a** and **b**) or combined (**c** and **d**). Notice that consumer prices after taxes (**a**) increase much more than recyclers' material prices after receiving a subsidy (**b**). However, both consumers' and recyclers' prices are much higher after governments implement a tax-subsidy scheme (**c** and **d**) compared to single tax and subsidy policies (**a** and **b**)

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Knut Einar Rosendahl: conceptualization, methodology, software, validation, formal analysis, writing review and editing, supervision.

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Declarations

Competing Interests The authors declare no competing interests.

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Paper 3

Accounting for unintended ecological effects of our electric future: Optimizing lithium mining and biodiversity preservation in the Chilean High-Andean wetlands

Diana Roa
Corresponding author
diru@nmbu.no
School of Economics and Business, Norwegian University of Life of Sciences, Ås, Norway
https://orcid.org/0000-0001-5234-8517

Ståle Navrud
stale.navrud@nmbu.no
School of Economics and Business, Norwegian University of Life of Sciences, Ås, Norway
https://orcid.org/0000-0002-6627-4595

Knut Einar Rosendahl
knut.einar.rosendahl@nmbu.no
School of Economics and Business, Norwegian University of Life of Sciences, Ås, Norway
https://orcid.org/0000-0002-8066-6261

Abstract

A low-carbon energy transition to fight climate change has intensified mineral and metal extraction and caused unintended ecological damage. Ecological conservation is challenged by the overlap between mining deposit areas and ecosystems, as in the case of lithium resources in the High-Andean wetlands of Chile. We show how accounting for the non-use values of biodiversity of these wetland ecosystems can change optimal mining patterns and enhance environmental conservation. We apply a meta-analytic benefit transfer function to estimate the non-use value of affected biodiversity and ecosystems. Then, we include these values in a competitive land use model that considers ecosystem services as assets and the opportunity costs of mining. Results show that accounting for wetland non-use values slows lithium extraction, varying with ecosystem values and resource rents. Based on these findings, policymakers can design a mineral extraction tax that minimizes wetland damages and maximizes the benefits of a mineral boom while promoting a sustainable energy transition.

Keywords: Ecosystem services, value transfer, wetlands, land use models, critical minerals

1. Introduction

Low-carbon technologies rely on massive critical raw materials. Consequently, a new global mining pattern is emerging, turning the focus to mineral-rich areas. In those areas, land and water use intensifies with mineral extraction. This resource-intensive pattern will continue pressuring the environment because increasing land and water use inevitably change ecosystem balances (Foley et al., 2005), leading to a classical trade-off problem between resource conservation and economic development. Therefore, a low-carbon transition presents us with a dilemma. It may enable us to fight climate change, but it may also have unintended consequences by intensifying natural resource exhaustion and exacerbating threats to biodiversity (Sonter et al., 2020). Thus, a critical question is how do we account for the ecological impact of mineral extraction to promote a sustainable energy transition? This paper aims to answer this question by applying a novel combination of a competing land use model (Barbier, 2011) and benefit transfer techniques (Johnston et al., 2021) to lithium mining in the High Andean wetlands in Chile. Thus, this paper contributes to the scarce literature on accounting for the economic value of ecological impacts of mining critical resources for the energy transition.

Ecological conservation is challenged by the overlap between mining resources and sensitive ecosystems. In Chile, High Andean lands feature some of the world's highest-grade lithium reserves and unique wetlands. It consists of saline and endorheic hydrological systems (Marazuela et al., 2019b), also known as *salares*; which describe salt lakes, marshes, shallow lakes, lagoons, and salt crust (Risacher et al., 2003).[1] The ecological richness of these ecosystems depends on the lagoons system (Valdivielso et al., 2022) and the complex hydrological system (Marazuela et al., 2019b). Moreover, the basin size also matters for lithium grade and profitability because the largest basin catchments hold the largest lithium concentrations (López Steinmetz & Salvi, 2021). This is, therefore, another interesting study case to investigate how ecosystem services and economic benefits compete and how this competition features conservation and mineral extraction policies.

About 50% of the Chilean salt flats area are wetlands declared as priority sites of national or international importance according to the Ramsar convention.[2] This declaration enhances awareness of wetlands' ecosystem services and functions. Economic pressures, however, question whether these conventions are sufficient in the long term (Bowman, 2013). The lack of specific national wetland policies, limited resources, inadequate infrastructure, and low monitoring capacity continue to threaten wetlands and Ramsar sites, especially in South America (Wittmann et al., 2015). In addition, the economic costs of environmental regulation and limited environmental research expenditure also overshadow conservation (Rosenbaum, 2019). For example, little knowledge about freshwater stocks in the High Andean lands led the Chilean government to award mining companies with more water rights than the natural recharge of the basins (Alam & Sepúlveda, 2022). Besides, there has been little quantitative analysis of the Chilean High Andean wetland values (Cerda et al., 2018). As a form of resource sovereignty, wetlands conservation begins with understanding what is owned and its competing value. (McNeish, 2021).

Yet the competition between use and non-use resource values will remain unfair as long as mining relies on cheap extraction that ignores environmental damages. Current brine extraction techniques are relatively low-cost compared to rock and deep sea sources (Xu et al., 2021). Underground brine is pumped to evaporation pools where lithium is gradually extracted from a vast mixture of particles, and the wastewater is reinjected (Flexer et al., 2018).[3] While some studies find that brine extraction modifies the area's natural balances (Flexer et al., 2018; Gajardo & Redón, 2019; Gutiérrez et al., 2018; Liu et al., 2019), other studies find that brine pumping has not shrunk lagoons surfaces (Guzmán et al., 2022) and highlight an increasing dampening capacity of salt flats despite of intense brine mining (Marazuela et al., 2019a). Although some research has been carried out on understanding the hydrodynamics of

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[1] Chile has classified 53 salt flats with a surface area of 582 500 hectares within a catchment area of 7 423 000 hectares Risacher, F., Alonso, H., & Salazar, C. (2003). The origin of brines and salts in Chilean salars: a hydrochemical review. *Earth-Science Reviews*, *63*(3), 249-293. https://doi.org/10.1016/S0012-8252(03)00037-0 . Catchment area is the area that serves to catch water from which rainfall flows into rivers, lakes, and water reservoirs. This catchment area in the Chilean High Andean lands is equivalent to the size of Italy.

[2] Seven wetland sites with an extension of 280 816 hectares have been declared by the Ramsar Convention that includes: Atacama-Soncor, Maricunga, Surire, Pujsa, Tara, Aguas Calientes IV, and Huasco.

[3] In 2020, one of the two major lithium companies in Chile, SQM, extracted approximately 55 million of m^3 of brine to produce 18000 tons of lithium carbonate equivalent -LCE-. It means that to produce a ton of lithium is required to extract 3050 m^3 of brine. The company has already announced a reduction of brine extraction by 50% by 2030 without any impact on production growth. https://www.sqmlithium.com/en/sqm-reducira-en-50-la-extraccion-del-salar-de-atacama/

some of the main Chilean salt flats, particularly the Atacama, the largest salt flat in Chile (Marazuela et al., 2019b; Schomberg et al., 2021; Valdivielso et al., 2022), researchers still do not fully understand how fresh groundwater interacts with salty brine water in distant wetlands (Blair et al., 2022).

Despite the inconclusive effects of mining on ecosystems from hydrological changes, other environmental factors can determine how wetlands are changing while mining is expanding. A study by Liu et al. (2019) observe a strong correlation between mining growth and environmental degradation during the last two decades in the Atacama salt flat. There has been a decline in vegetation near mining sites, higher daylight temperatures, lower soil moisture, and increased drought conditions (Liu et al., 2019). This correlation does not necessarily imply that underground (brine) changes cause over-ground (ecosystems) changes. Still, it makes evident that changing mining patterns might impact ecosystem services and their value. Thus, it is important to figure out how to translate these ecological impacts into economic damages.

Valuing ecosystem services is not a sufficient condition to conserve them (Gómez-Baggethun & Ruiz-Pérez, 2011). However, knowing ecosystems' values makes it possible to weigh them against other alternatives and make decisions accordingly (Pascual et al., 2012). Despite the critical importance of the High Andean wetlands, the value of these ecosystem services is largely unknown. Few published studies have estimated its non-use values by using Stated Preference (S.P.) methods of contingent valuation and choice experiments for part of Atacama's wetlands and services (Cerda et al., 2018) and similar wetlands in Bolivia (Gandarillas R et al., 2016).[4] Therefore, much work remains to be done to value the High Andean wetlands ecosystem services and understand how accounting for their value can influence regional mineral extraction paths.

Economic analysis of mineral extraction typically involves dynamic optimization methods. In this framework, the optimal extraction examines the opportunity cost of extraction today since fewer resources might be available tomorrow. Hence, there will be a resource rent in markets for minerals reflecting this opportunity cost. However, in this somewhat narrow sense, an optimal solution does not necessarily mean a sustainable one. Sustainability is multidimensional and relies on the nexus among different resources, like minerals, materials, land, water, and energy (Bleischwitz et al., 2018). Therefore, a sustainable resource use pathway should consider the linkage and co-dependency between two or more natural resources to deliver economic and non-economic benefits. Land use modeling is a standard method for assessing the impact on ecosystems given alternative land uses like crops, urban areas, grasslands, and forests. By adopting ecosystems landscapes as assets, Barbier (2011) proposed a land competing use model based on the Hotelling notion of resource use and subject to a constraint on ecosystems' land stock. Based on these approaches, research still has room to develop empirical studies and design policies that recognize the value of ecosystems and how they compete with the returns from mining in the long term.

This paper aims to analyze how accounting for ecosystem values influences mining paths. As a first step, we develop an analytical framework and adapt the competing land-use model of Barbier (2011) to the dynamics of mineral extraction and wetlands values (Section 2). Next, we estimate the value of the High Andean wetlands in Chile, particularly in the Atacama and Maricunga salt flats. Since the use and non-use values pertain to cultural ecosystem services, in this paper, we refer to the term *ecosystem value* for short in the rest of the article when we mean *cultural ecosystem service* as we value a change in an ecosystem service, not the entire ecosystem. Using a meta-regression analysis developed by Chaikumbung et al. (2016), we predict ecosystem values using the benefits transfer method. (Section 3). Then, we evaluate the mining and conservation paths numerically, considering how the mineral market and ecosystem values compete (Section 4). Our model provides an ecosystem conservation policy output based on the Pigouvian taxes to be applied for wetland losses due to mining. We finally discuss the implications of our findings and suggestions for future work (Section 5) and conclusions (Section 6).

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[4] In Latin America lithium reserves are concentrated in the High Andean salt flats with an extension of 2 481 900 hectares distributed in three countries: Argentina, Bolivia, and Chile. The Uyuni salt flat in Bolivia is the largest of the region (1 058 200 hectares). Salinas Grandes in Argentina is the second largest (600 000 hectares) and the Atacama salt flat in Chile is the third largest (305 100 hectares).

2. Model

The objective of the optimization model is to maximize the present value of the land stock, including the use and non-use values of ecosystem services it provides. Here we do not consider the possibility of a future ecological landscape restoration because, after mining resources, restoring the landscape is either technically infeasible or too expensive relative to the ecosystem benefits obtained. Following Barbier (2011), we adopt ecological landscapes, or land areas, as the basic unit and consider ecosystems as economic assets. This approach facilitates applying competing land-use models and treats landscapes, and all ecological systems within, as exhaustible stocks with a reserve value.

Let x_{it} and X_{it} denote mineral extraction and cumulative extraction at site *i* so that $\dot{X}_{it} = x_{it}$. Let $R(x_{it})$ be the periodic rent associated with the amount of mineral extracted, the international market price of minerals (P_t) and the mineral ore grade (g_i), where both the price and the ore grade are exogenous.[5] Thus, the periodic rent takes this form:

$$R_{it}(x_{it}) = P_t g_i x_{it} \qquad (1)$$

Additional profits can be derived from deposits of potash and magnesium, which accompany lithium concentrations. In this study, we focus on lithium's economic benefits.[6]

Total extraction costs depend on both current and cumulative extraction: $C(x_{it}, X_{it})$. Unit extraction cost is assumed to increase as the cumulative extraction surges[7], i.e., $\frac{\partial C}{\partial X_i} > 0$. We consider the following functional form for the extraction costs (see, e.g., (Rosendahl & Rubiano, 2019) and (Roa & Rosendahl, 2022)):

$$C_{it}(x_{it}, X_{it}) = c_0 e^{\omega_i X_{it} - \tau t} x_{it} \qquad (2)$$

where the parameter c_0 is the initial extraction cost, the parameter ω_i determines how fast unit extraction cost increases with cumulative extraction at each salt flat, and the parameter τ represents exogenous technological changes.

Let A_{ijt} be the area of an ecosystem's landscape j at extraction site i at time t. Each ecosystem will be affected by extraction as follows:

$$\dot{A}_{ijt} = -\delta_{ij} x_{it} \qquad (3)$$

where δ_{ij} may reflect both quantitative and qualitative depreciation of the ecosystems. The ecosystem landscapes provide a flow of non-use services or benefits, which vary among salt flats (i) and wetland areas (*j*). Let $B(A_{ij})$ be the periodic ecosystem service flow from the remaining wetland area. The larger the wetland area, the greater the benefits are, $\frac{\partial B}{\partial A_{ij}} > 0$, but those gains get smaller with further land extension $\frac{\partial^2 B}{\partial {A_{ij}}^2} < 0$. In other words, the marginal value of the wetland area increases if the ecosystem is depreciated.[8] We consider the following functional form for our ecosystem value function:

$$B_{ijt}(A_{ijt}) = B_{0ij} {A_{ijt}}^{\varepsilon_j} \qquad (4)$$

where B_{0ij} is a scale parameter (equal to the ecosystem value when $A_{ij} = 1$), and $0 < \varepsilon_j < 1$ is the elasticity of ecosystem value with respect to wetland size. Note that our variable A_{ijt} is the size of the surface ecosystem, and reductions in A_{ijt} can be a combination of quantitative and qualitative degradation. The reason is that the wetland and salt flats are linked through an underground hydrological system. Thus, extraction from the salt flats areas reduces the expansion and vitality of wetland areas.

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[5] See Appendix A for an extended presentation of lithium ore grades.

[6] Lithium mines produce potash as by-product. Chile can add important supply of potash, but the Chilean market share is relatively low, the market is quite competitive and potash prices are relatively stable.

[7] As noted by Bustos-Gallardo et al., (2021) the material form in which lithium is extracted (i.e., as brine) requires water. Then pumping and evaporation are degrading the water balance in the mining site, undercutting future brine production and increasing extraction costs.

[8] There is evidence supporting that wetlands value diminishes with scale (Woodward and Wui, 2001), (Ghermandi, 2010), (Brander, 2006), (Brander et al., 2013), (Chaikumbung et al., 2016). It means that an increase in wetland size pushes down the wetland value per hectare.

The decision-maker maximizes the present value of net returns from their natural resources and ecosystems assets, *V*, by choosing optimal levels of extraction, x_{it}.

$$\max_{x_{it}>0} V = \int_0^\infty \left[\sum_i R_{it}(x_{it}) - \sum_i C_{it}(x_{it}, X_{it}) + \sum_{ij} B_{ijt}(A_{ijt})\right] e^{-r} dt \tag{5}$$

subject to the dynamics of mineral resource depletion ($\dot{X_{it}} = x_{it}$) and the dynamics of ecosystem land transformation ($\dot{A}_{ijt} = -\delta_{ij} x_{it}$). If one disregards the values of ecosystems ($B\left(A_{ijt}\right) = 0$), then the only returns come from mineral extraction $R(x_{it})$ and ecosystem land transformation is irrelevant. With ecosystems at zero value, exhaustion continues steadily until further extraction is no longer profitable.

When maximizing (5), subject to the stocks $\dot{X_{it}}$ and $\dot{A}_{ijt}$, the current value Hamiltonian of the problem is:

$$\begin{aligned} H^C &= \sum_i R(x_{it}) - \sum_i C(x_{it}, X_{it}) + \sum_{ij} B\left(A_{ijt}\right) - \sum_i \lambda_{it} x_{it} - \sum_{ij} \mu_{ijt} \delta_{ij} x_{it} \\ &= \sum_i P_t g_i x_{it} - \sum_i c_0 e^{\omega_i X_{it} - \tau t} x_{it} + \sum_{ij} B_{0ij} {A_{ijt}}^{\varepsilon_j} - \sum_i \lambda_{it} x_{it} - \sum_{ij} \mu_{ijt} \delta_{ij} x_{it} \end{aligned} \tag{6}$$

Where $\lambda_{it} \geq 0$ and $\mu_{ijt} \geq 0$ are the shadow prices of the two-state variables X_{it} and A_{ijt}.[9] The current value first-order necessary conditions for an internal solution are:

$$x_{it}: \qquad P_t g_i - c_0 e^{\omega_i X_{it} - \tau t} - \lambda_{it} - \sum_j \mu_{ijt} \delta_{ij} = 0 \tag{7}$$

$$X_{it}: \qquad \dot{\lambda}_{it} = r\lambda_{it} - \omega_i c_0 e^{\omega_i X_{it} - \tau t} x_{it} \tag{8}$$

$$A_{ijt}: \qquad \dot{\mu}_{ijt} = r\mu_{ijt} - \varepsilon_j B_{0ij} {A_{ijt}}^{\varepsilon_j - 1} \tag{9}$$

$$\text{Terminal conditions } \lim_{t\to\infty} e^{-rt} \lambda_{it} X_{it} = 0 \quad \text{and} \quad \lim_{t\to\infty} e^{-rt} \mu_{ijt} A_{ijt} = 0 \tag{10}$$

Equation (7) states that extraction should continue if the net profit (two first terms) covers both the scarcity rent (λ_{it}) and all the shadow values of the affected ecosystems ($\mu_{ijt}\delta_{ij}$).

In a scenario when decision-makers do not account for the value of non-market ecosystem services ($B_{0ij}\left(A_{ijt}\right) = 0$), the rent from extraction ($\dot{\lambda}$) will grow at a pace defined by the interest rate (r) and the relationship between cumulative extraction and extraction costs (ω_i).

If decision-makers do account for the value of non-market ecosystem services and $B_{0ij}\left(A_{ijt}\right) > 0$, then the costate variable $\dot{\mu}$ (equation 9) provides the optimal time path of the wetland stock's *shadow value*. This formulation allows us to see the ecosystems as assets and calculate the reserve value of the remaining land discounted in each period. We can alternatively interpret this shadow value in three ways: (i) in equation (9), the term $\dot{\mu}_{ijt}$ can serve as a measure of "ecological wealth", which can be used to ration the wetland's use over time. (ii) In equation (7), the term $\sum_j \mu_{ijt}\delta_{ij}$ reflects the opportunity cost of mining, i.e., profits forgone for wetland preservation; (iii) Alternatively $\sum_j \mu_{ijt}\delta_{ij}$ can represent the Pigouvian tax for the potential biodiversity loss.

Note that the marginal ecosystem value (last term in equation (9)) goes towards infinity as A_{ijt} goes towards zero. Thus, we will assume that at some point in time *T*, further extraction is no longer desirable, in which case $\lambda_{it} = 0$ for $t \geq T$, and the shadow prices of the ecosystems remain constant (as A_{ijt} remains constant for $t \geq T$). Hence, from equation (9), we get that $r\mu_{ijt} = \varepsilon_j B_{0ij} {A_{ijt}}^{\varepsilon_j - 1}$ for $t \geq T$.

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[9] Note that we have changed the sign of the shadow price of X_{it}, so that this becomes positive instead of negative.

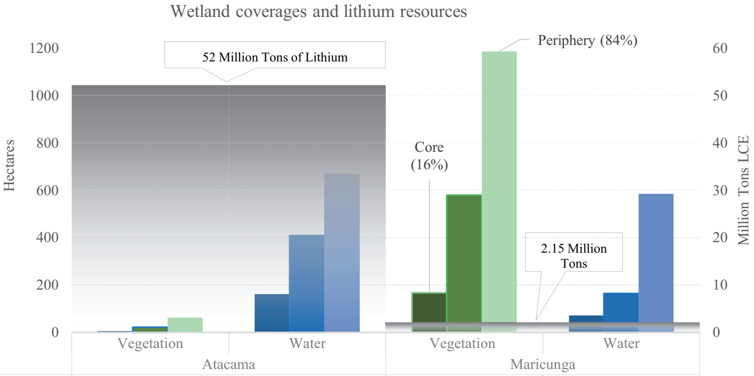
3. Data calibration

This section outlines how we calibrate the numerical model based on various data and previous studies.

3.1. Wetlands coverages and lithium resources

Our case study is two High-Andean wetlands in northern Chile, known as *Atacama* and *Maricunga* salt flats, and two types of wetland areas (vegetation and water) within these salt flats. The sites differ considerably concerning lithium reserves and ecosystem sizes (See Figure 1). Maricunga has much fewer reserves and a much larger ecosystem (at least for vegetation) than Atacama.

Wetlands are dynamic, and their size varies over time because of climate and seasonal changes (De la Fuente et al., 2021). Therefore, wetlands coverages can be categorized in percentiles of a frequency distribution, indicating how often a specific area is covered or not by vegetation or water. De la Fuente et al. (2021) distinguish between areas that are *not* covered less than 16%, 50%, and 84% of the time, respectively, and do this for vegetation and water. Thus, the former category (16%) only includes areas covered with vegetation or water most of the time (84% or more) and can be thought of as the core of the wetland. The latter category (84%) includes a much larger peripheric wetland sporadically covered with vegetation or water (but at least 16% of the time).[10] Figure 1 shows wetland endowments regarding vegetation patches, water coverage or shallow lakes in hectares (primary axis), and lithium resources per wetland in million tons (secondary axis).



	Atacama Vegetation	Atacama Water	Maricunga Vegetation	Maricunga Water
Core (16%)	5	160	168	72
Semi periphery 50%	22	409	579	165
Periphery (84%)	62	667	1185	585
Identified lithium resources	52.17	52.17	2.13	2.13

Figure 1. Wetland coverage (Core 16%, Semiperiphery 50%, and Periphery 84 %) in hectares and lithium reserves in million tons of Lithium Concentrated Equivalent LCE. Atacama holds approximately 52 million tons of identified lithium carbonate equivalent resources, and Maricunga has 2.15 million tons. Both High-Andean wetlands are located on high-ore-quality lithium with similar extraction costs. This graph is based on data from De la Fuente et al. (2021), USGS (2022), and (Lithium-Power, 2022)

The classification of wetlands size in percentiles allows us to consider three different conservation scenarios: (i) relaxed environmental restrictions implying the conservation of only the core of wetland coverage (16%, i.e., covered at least 84% of the time); (ii) a tighter conservation rule encouraging the preservation of semi-peripheric areas (50% coverage); and (iii) a strict conservation scenario urging decision-makers to conserve peripheral wetland coverage (84%, i.e., vegetation or water coverage at least 16% of the time).

An important but challenging parameter to calibrate is delta (*δ*), measuring the relationship between mineral extraction and ecosystem degradation. As explained in Section 2, we interpret this as a

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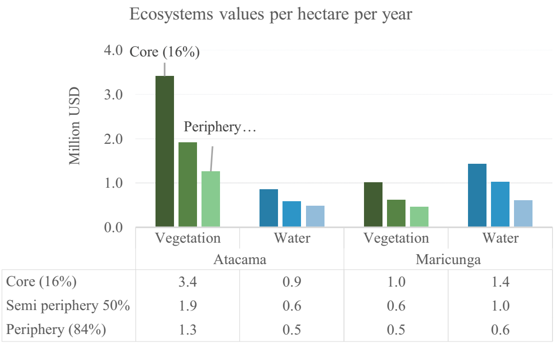
[10] De la Fuente et al (2021) also observe seasonal growth and shrinkage dynamics meaning that wetlands dimensions show maximum values during the austral winter (July-August when evaporation is the lowest) and minimum values during the austral summer (December- January when evaporation is the highest). See Appendix C, for a description of the indices to calculate vegetation coverages.

combination of quantitative and qualitative depreciation of the ecosystems. Liu et al. (2019) have analyzed the relationship between lithium mining in Atacama and environmental degradation in this area, considering, among other things, a Normalized Difference Vegetation Index (NDVI) and how it is related to the expansion of the mining area. They find that for four National Reserve areas nearby, the NDVI dropped on average by 0.0036 per year from 1997 to 2017. By combining this with information about lithium extraction in the same period, we can compute the change in NDVI per unit of extraction, and then we set δ equal to this value times the area size (see Appendix C for more details). Since the area size depends on the choice of coverage frequency (16%, 50%, or 84%), the calibrated value of delta δ also depends on this choice. Readers must remember that we extrapolate vegetation losses to Maricunga based on estimates from Atacama. It is beyond the scope of this study to measure the causal and physical effects of mineral extraction on ecosystems. Thus, some parameters, particularly delta (δ), are subject to uncertainty and focus of sensitivity analysis in Section 4.1.

3.2. Wetlands values

To estimate wetland values and calibrate the scale parameters B_{0ij}, we use a benefit transfer method (Johnston et al., 2021) to transfer values from previous environmental valuation studies of wetlands to assess the non-use value of the highland wetlands in northern Chile susceptible to being transformed by the lithium industry. There has been little quantitative analysis of ecosystem values in Chile. Although some research has been carried out on tourist preferences for ecosystem features in the Atacama desert (Cerda et al., 2018), no study has estimated the annual cultural ecosystem services value of the High Andean wetlands in northern Chile. Therefore, we use benefit transfer from a global meta-analysis of wetland valuation studies (Chaikumbung et al., 2016). Meta-analyses typically investigate collective insights from empirical literature; nonetheless, the resulting meta-analytic regressions can also be used to predict outcomes as an alternative to new costly and time-consuming valuation studies. More discussion about ecosystem services valuation and the validity and reliability of benefit transfer is available in the supplementary material in Appendix D, where we explain in detail how we derive our values of B_{0ij} and the size elasticity ε_j.

The most critical characteristic in wetland valuation is the wetland size. The standard metric used to measure ecosystem values is annual USD per hectare. Figure 2 shows the ecosystem values of vegetation and water coverages based on our meta-analytic benefit transfer estimations, following Chaikumbung et al. (2016).[11] Comparing Figures 1 and 2, one can observe that the larger the total wetland area, the lower the value per hectare. The explanation is that wetland values exhibit diminishing returns to scale, according to Chaikumbung et al. (2016) and other studies, cf. Appendix B. It means that an increase in wetland size pushes down the wetland value per hectare. Therefore, adding a hectare to a large wetland is likely to have less impact than adding one hectare to a small wetland. Still, the size elasticity is above zero, meaning that the *total* ecosystem value increases with size.



	Atacama		Maricunga	
	Vegetation	Water	Vegetation	Water
Core (16%)	3.4	0.9	1.0	1.4
Semi periphery 50%	1.9	0.6	0.6	1.0
Periphery (84%)	1.3	0.5	0.5	0.6

Figure 2. Benefit transfer exercise regarding non-use values of ecosystems per hectare per year; in Million USD in 2022.

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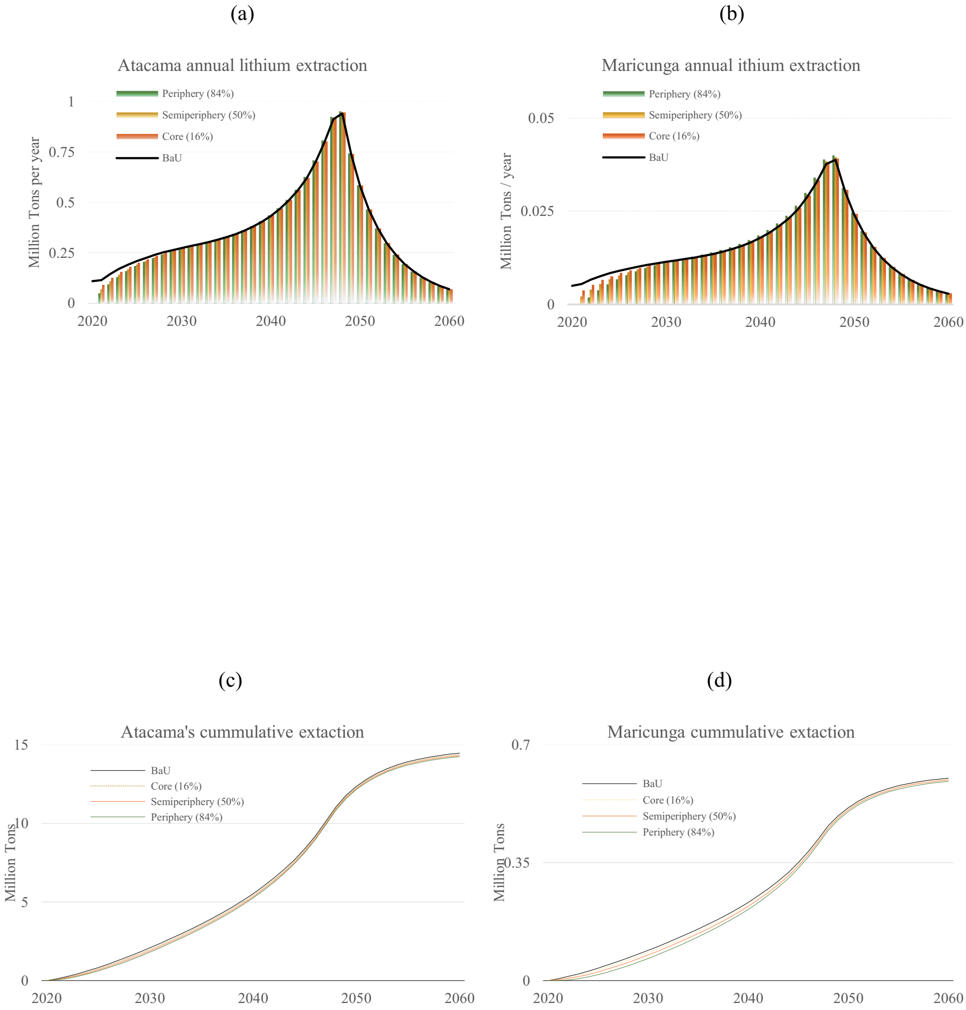
[11] Chaikumbung (2019) observes an average wetland size of 9605 hectares and estimates an average ecosystem value of $1998 USD per hectare per year (2002 prices) for wetlands in developing countries.

4. Results and discussion

The first objective of this study is to investigate how accounting for ecosystem values can alter mineral extraction paths. We perform the numerical analysis with the help of GAMS.[12]

4.1. Mineral extraction

Our simulations indicate that the mere recognition of an economically valuable portion of a wetland can slow mining extraction by approximately eight years (Figures 3a and 3b). This result is consistent with our analytical model presented in Section 2. In line with Barbier (2011), ecosystem valuation and changes in this value over time are crucial for determining the optimal time to exploit ecological landscapes. In our case, mineral extraction will be delayed, and the ecosystem valuation will have a larger impact initially in strict conservation scenarios with more extensive wetlands, as will happen in Maricunga. Despite this, extraction is similar after a decade and even higher in conservation scenarios than in Business-as-Usual (BaU), as shown in Figures 3a and 3b.


(a)

Atacama annual lithium extraction

(b)

Maricunga annual ithium extraction

(c)

Atacama's cummulative extaction

(d)

Maricunga cummulative extaction

*Figures **3a.** and **3b**. Lithium extraction paths under a BaU scenario compared to different ecosystem conservation policies in Atacama and Maricunga. Figure **3c.** and **3d.** Cumulative extraction paths, among other scenarios.*

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[12] The code program can be provided under request.

Figures 3c and 3d confirm that, in the long run, the total cumulative extraction of minerals is close to their BaU scenario, regardless of the environmental constraints. In the case of Maricunga, the value of the impacted ecosystems initially seems to reduce mineral extraction to a much larger extent than in Atacama. As shown in Figure 1, Section 3, Maricunga's peripheral wetlands (84%, i.e., vegetation covered at least 16% of the time) are approximately twenty times greater than Atacama's. For that reason, the average ecosystem value per hectare per year of Maricunga's wetlands is much lower than Atacama's. To determine whether larger wetland extensions with lower ecosystem values per hectare permit greater extraction growth thus requires a more detailed analysis.

4.2. Resource rents

Minerals resource rents can shed light on producers' extraction decisions with or without wetland conservation constraints. Figures 4a and 4b below show the resource rent level development for the two wetlands. In a BaU scenario, resource rents have a comparable growth (initial inverted U-shape) in both wetlands, as they have similar extraction costs.[13] However, conservation policies will initially have a lower effect on Atacama's resource rents than in Maricunga. Figures 4c and 4d show the rent differences after implementing a conservation policy at different wetlands sizes. Notice that wetland conservation policies initially reduce resource rents between 1% and 4% in Atacama, while in Maricunga, resource rents decrease between 2% and 7% in the first extraction period.

Nonetheless, that difference flattens gradually over time. After 20 years of lithium extraction, any environmental constraint on wetlands will make scarcity rents higher than in a BaU scenario because extraction costs are lower when cumulative extraction is lower. This explains why lithium extraction eventually multiplies, particularly in Maricunga (See Figure 3d above).

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[13] The U-shape is driven by the assumption of exponential growth in lithium prices until the price is twice as high as in the base year (which happens in 2048).

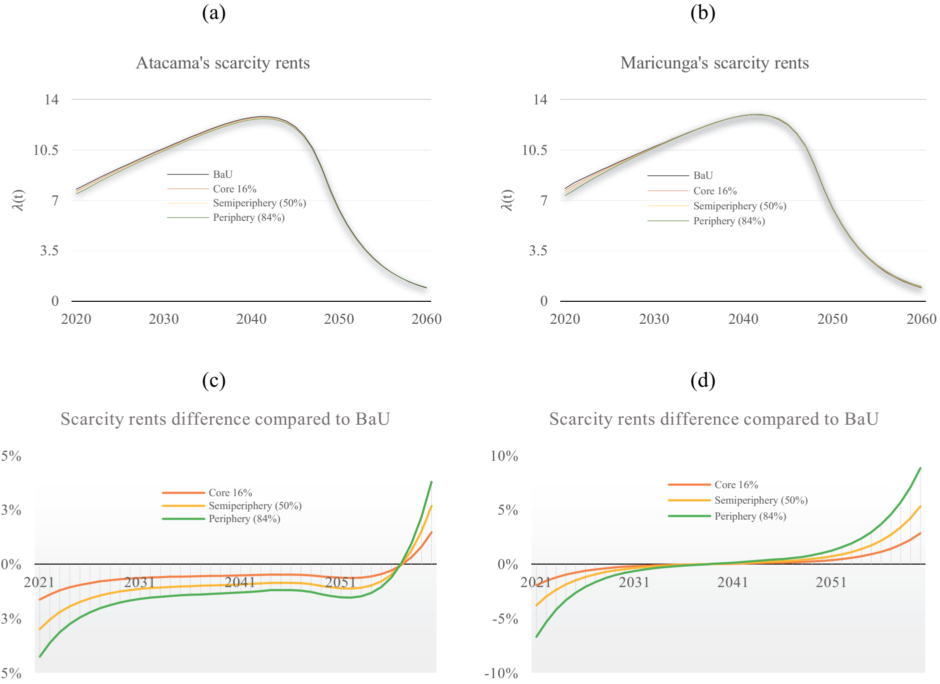


Figure 4a. Resource rent dynamics (λ_t). Figure 4b. Differences among scenarios with respect to BaU.

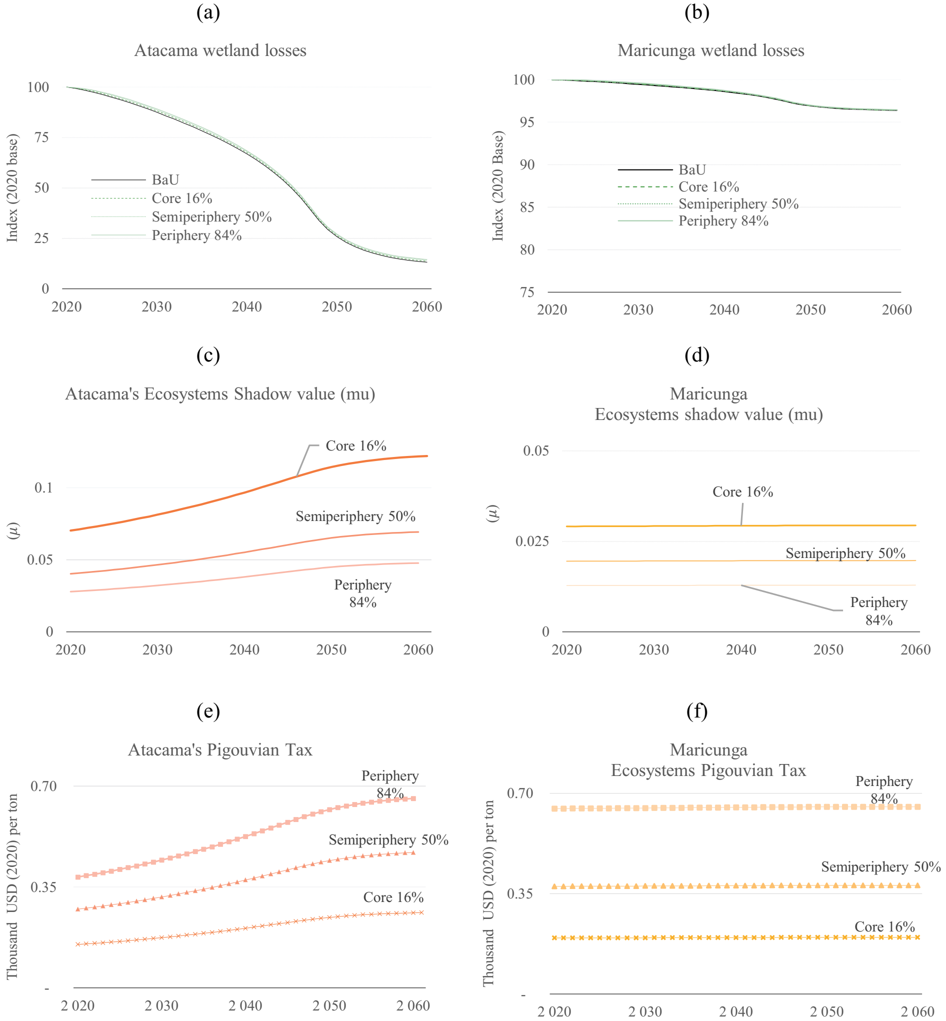
The results so far highlight that accounting for wetlands values can deaccelerate resource extraction, but it will greatly depend on the initial wetland size, the change in wetland non-use values, and how it affects resource rents. According to our analytical model, these effects are absorbed in the reserve ecosystem value (μ). As we demonstrated in Section 2, this shadow value (μ) can measure the "ecological wealth", which can be used to ration the wetland's use over time.

4.3. Ecosystems damages, shadow values, and Pigouvian taxes

Lithium mining will rapidly destroy the High Andean wetlands if no conservation policy is in place. Figures 5a and 5b show wetland coverage losses during 40 years of mineral extraction in the BaU scenario. Considering that it is an index change, these results are independent of which of the three coverages is considered in the BaU scenario. Figure 5a shows that by 2060, approximately 85% of Atacama's small vegetation and water coverages will be lost without any conservation policy. On the other hand, in Maricunga, only approximately 5% of vegetation coverages can disappear under continued lithium extraction. These results must be interpreted with caution because our assumptions on environmental degradation are extrapolated from the results of Liu et al. (2019). Their study focuses only on vegetation coverages in Atacama, and here we assumed that similar effects would be observed in Maricunga for both vegetation and water coverages.

Changes in wetlands endowments will lead to different shadow values. Figures 5c and 5d below show that ecosystems' shadow values, the sum of vegetation and water ($\sum \mu_{ij}$) values will evolve differently in these two wetlands. In Atacama, ecosystems' shadow values grow as ecosystem size decreases with increasing extraction. In contrast, in Maricunga, the ecosystem's shadow values will remain almost constant. A possible explanation for this pattern is that wetland coverages, mainly vegetation, are smaller in Atacama, while the lithium stocks are higher (52 million tons of LCE). In addition, the current lithium production level allows for more aggressive resource extraction in Atacama. Therefore, rapid resource extraction reduces (the small) wetland size quickly, and the respective shadow value increases with wetland depletion.

In contrast, in Maricunga, the wetlands' size is large, while the mineral stocks are relatively small (2.15 million tons of LCE), and mineral extraction will be relatively low compared to Atacama's. Therefore, wetland size decreases at a slower pace than in Atacama. (See Figures 5a and 5b).


(a) (b) (c) (d) (e) (f)

Figures 5a. and 5b. Wetland losses in Atacama and Maricunga under different conservation scenarios (Core 16%, Semiperiphery 50%, and Periphery 84%). Figures 5c. and 5d. Ecosystem's shadow value development for Atacama and Maricunga. Figures 5e. and 5f. Pigouvian tax for each ecosystem and extension to be protected.

Tax levels will depend on shadow values and ecosystems damages. As we presented in equation (7) when we combine the wetland shadow value with the quantitative and qualitative depreciation of ecosystems (δ_{ij}), we can obtain the equivalent Pigouvian tax for the potential biodiversity loss due to mineral extraction. In both wetlands, Pigouvian taxes follow the same pattern as their ecosystem shadow values, but the magnitude will vary with the ecosystem's depreciation rate (delta). Therefore, larger wetlands have a higher depreciation rate and higher taxes. Although ecosystem shadow values in Atacama (μ) are two or three times higher than in Maricunga, the Pigouvian taxes in Atacama are initially slightly lower than for Maricunga but gradually reach more similar tax levels at the end of the extraction period. The reason is that, in line with Barbier (2021), a tax on rent from land conversion varies with wetland size.[14] Note that the initial lithium price level is USD 17 000 per ton, the initial unit cost is USD 9 000 per ton, and tax under the stricter conservation policy that includes a large wetland periphery (84%) will start at USD 390 per ton, equivalent to 2% of the lithium selling price.

4.4. Mining profits

Now, we observe how ecosystem conservation alters profitability. Overall, our simulations have demonstrated that the mere recognition of a positive ecosystem value can initially lead to slow-paced or delayed mining for several years. However, despite environmental constraints, the large resource rents allow extraction to accelerate rapidly. In both Atacama and Maricunga, profitability is not affected, considering the net present value of mining revenues in the operation period (See Figure 6a). An intriguing finding is that valuing and considering ecosystems as assets can account for this ecological wealth, increase land values, and preserve more ecosystems (at least temporarily). Once ecosystems are accountable, the ecological wealth likely surpasses the economic benefits from mining extraction, as in the case of Maricunga (See Figure 6b). For Atacama, however, it is quite the opposite. These results, therefore, need to be interpreted with caution because we use a benefit transfer function to obtain an approximate estimation of ecosystem services, and it does not include the cost of preserving the environment. The ecosystem's valuation process is generally affected by uncertainties related to ecosystem dynamics, human preferences, and methodological issues.

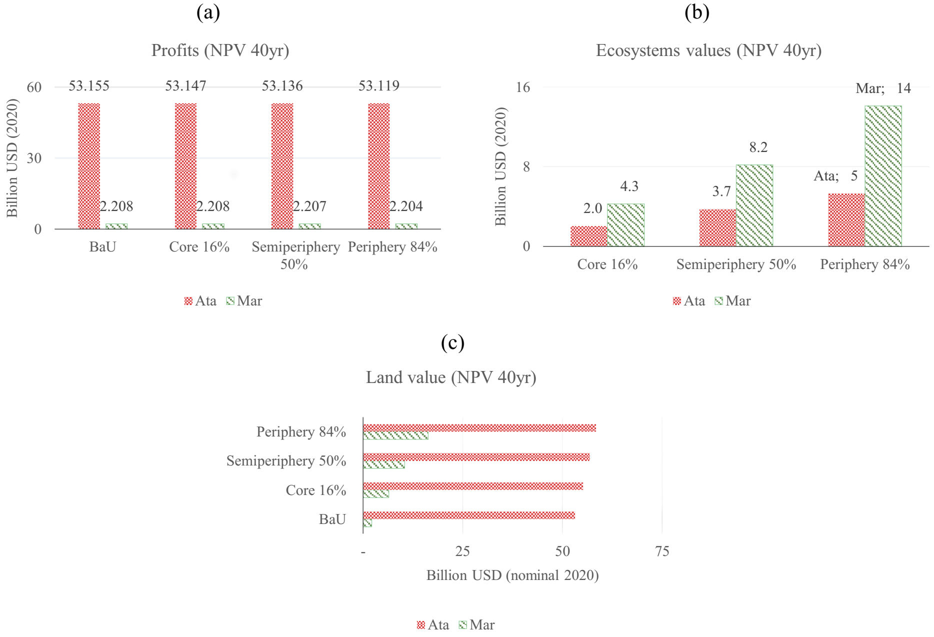


Figure 6a. Net present value -NPV- of profits in 50 years, comparing the BaU with the other policy scenarios (16%,50%, and 84%). Figure 6b. NPV of ecosystems for 50 years. In the BaU scenario, wetlands values are zero. Figure 6c. Total land value is the sum of the NPV of profits and ecosystem values.

In summary, when decision-makers consider ecosystem values and add them to profits from mining, the present value of net returns from their landscape stocks at any wetland coverage is higher than a BaU scenario (Figure 6c). Our simulations demonstrate that mining patterns will deaccelerate if ecosystem values are considered, and Pigouvian taxes are implemented. However, such measures should be revised periodically, as taxes will change with changes in ecosystem size and values.

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[14] In Appendix C, we present the calibration for the delta parameter which shows that the more extensive vegetation and water coverages, the larger the impact of lithium extraction, and therefore, the higher should be the tax imposed.

4.5. Sensitivity analysis I: higher ecosystems' values

This section elaborates on sensitivity analysis and simulates an alternative scenario where we assume higher ecosystem values. In our benchmark scenario, we took an ecosystem value with common wetland characteristics and ecosystem services such as water regulation and biodiversity. For this sensitivity analysis, we add some specific features that add more value to this wetland for being *lacustrine* and offering erosion control and cultural services, such as—opportunities for non-commercial uses, such as aesthetic, artistic, educational, spiritual, and sciences. In Appendix D, we explain how we derive these higher values, which are slightly more than twice the benchmark values. As expected, higher ecosystem value estimations mean mineral extraction will be more delayed and have a more considerable impact initially, especially in Maricunga (Figure 7b). Besides, the net present value of ecosystems will double marginally more for Atacama, which reflects the doubling of the ecosystem values (Figure 7d). Pigouvian taxes double across salt flats and wetland sizes (Figures 7e and 7f).

*Figures **7a.** and **7b.** Annual lithium extraction after doubling ecosystem values in Atacama and Maricunga. Figure **7c.** and **7d.** Profits and ecosystems values in Net Present Value – NPV- in 40 years and emphasize the difference between a scenario with higher ecosystems values concerning the benchmark scenario. Figure **7e.** and **7f.** Pigouvian taxes.*

4.6. Sensitivity analysis II: higher ecosystems' damages

This section investigates how extraction patterns may change with increased ecosystem damage. We assume a higher vegetation loss for this analysis, considering the maximum degradation level observed by Liu et al. (2019). See appendix C for more details on this environmental degradation estimate. Even if we apply the same environmental damage parameter (δ) in both wetlands, it is somewhat surprising that extraction patterns differ between salt flats. Atacama extraction is greatly affected by greater ecological damages and taxes. Profits are approximately 5% lower than the benchmark, irrespective of the wetland. With lower rents and profitability, extraction stops earlier than the BaU scenario.

In contrast, Maricunga's extraction patterns are almost the same as in the benchmark scenario, which does not affect profitability. An explanation might be that in larger wetland extensions, ecosystem values per hectare are low and economic rents allow steady extraction paths.

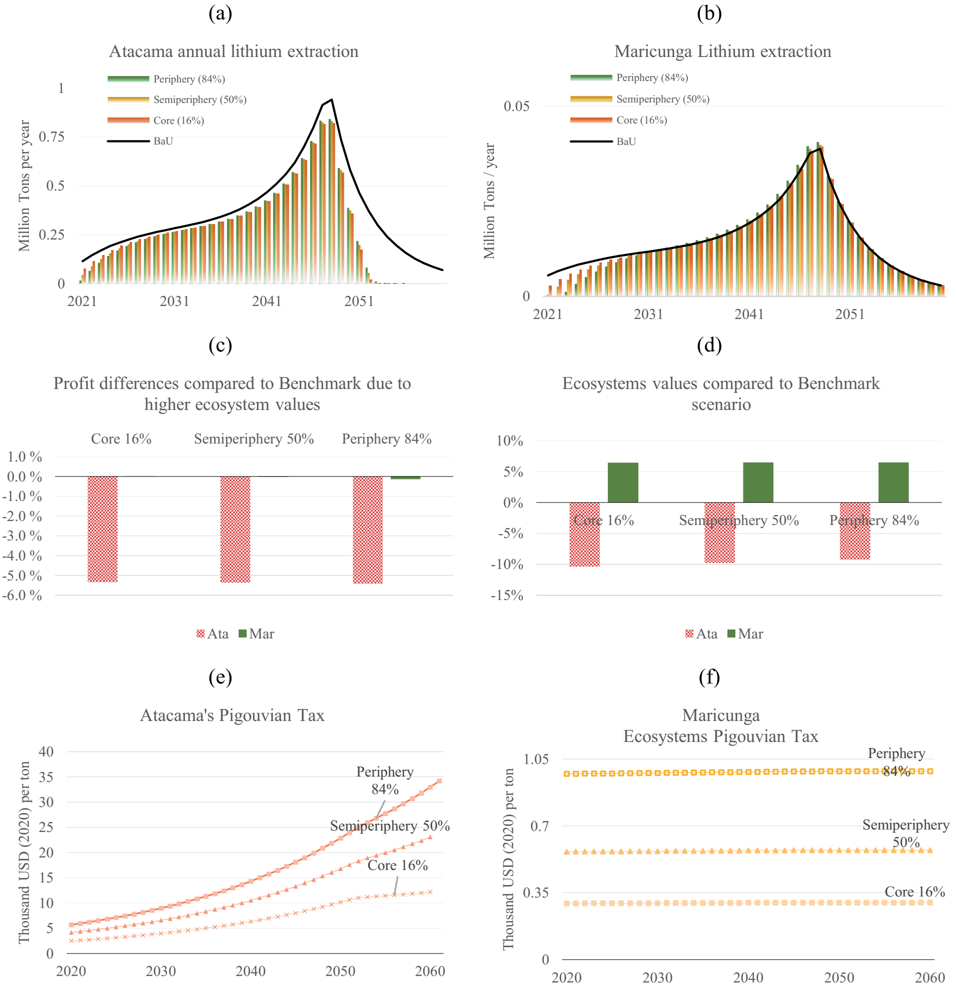

Figure 8. Second sensitivity analysis

Interestingly, the ecosystem's net present value in Maricunga increases with more serious ecological damages (Figure 8d). The reason is that despite the greater wetland losses, wetlands will not disappear, but they will become scarcer and more valuable in 40 years. As seen in Figure 8f, taxes in Maricunga will increase with increased environmental damages, but not as much as when the initial ecosystem value doubles, as presented in the previous section (Figure 7f). In contrast, Atacama's wetlands at all size levels can disappear around 2050, and their net present value will be lower than the benchmark (Figure 8d). In response to such environmental damage, higher taxes are imposed (See Figure 8e), and such taxes typically make extraction unprofitable after 2050.

5. Policy implications

Previous research revealed a strong negative relationship between lithium mining expansion and environmental degradation (Liu et al., 2019). The current paper aims to determine the competing land use between allocating wetland areas for lithium mining versus preserving these ecosystems. We use meta-analytic unit value benefit transfer to estimate the value of protecting the High Andean ecosystems and compare it with the expected lithium mining revenues. One interesting finding is that accounting for wetlands values can deaccelerate resource extraction paths. The higher the wetland values, the lower and more delayed the mineral extraction will be. However, it will greatly depend on the initial wetland size, the wetland ecosystem service values change, and how it affects resource rents. As demonstrated for Atacama and Maricunga, important differences in wetland sizes affect ecosystem values and resource rents. Therefore, any policy to control ecosystem loss, such as a tax on mineral extraction, should also vary with the wetland size the government decides to protect.

What is surprising from our results is that larger wetland areas with lower ecosystem values per hectare allow steady extraction paths, quite independent of the ecosystems' damage levels, as in the case of Maricunga. These results corroborate the findings of previous work linking wetland size with conservation measures (Barbier, 2021; Semlitsch & Bodie, 1998). Barbier (2021) states that no economic conversion should occur if the wetland area is too small. However, we find that in addition to the wetland size, the ecosystem damage level from mining is another critical factor in enforcing conservation policies. For instance, Atacama has relatively small vegetation coverage compared to Maricunga. Despite its relatively small size, mining can still take place in Atacama. Taxes in Atacama will initially be at a similar level to those imposed in Maricunga (See Figures 5e and 5f). However, if the damage level doubles and is much worse than the environmental degradation of the last 20 years, taxes will multiply and reach a much higher level, discouraging extraction for more extended periods, perhaps 25 or 30 years (as shown in Figures 8e and 8f). Government regulators have, therefore, reasons to shorten extraction period contracts to avoid complete wetland damage.

The High Andean wetland damages due to mining are very uncertain. We parameterized wetland size changes based on previous studies of the wetland surface dynamics (De la Fuente et al., 2021) and the historically strong correlation between environmental degradation and lithium expansion (Liu et al., 2019). However, according to Marazuela et al. (2019b), the ecosystem dynamics and surface effects depend greatly on underground hydrological changes, and there is no linear relationship between all forces (e.g., evaporation and recharge) that influence the water balance evolution. Climate change, human settlements, and recreation activities can also affect the ecosystem dynamics. Besides, lithium mining is expanding faster than ever. Still, better design and technological changes can make brine exploitation more sustainable (Marazuela et al., 2020). All these factors and a deeper understanding of the wetland surface-underground relationship are important topics for further research.

Our numerical simulations for Maricunga show that the ecosystem's net present value (NPV) surpasses mining profits (as opposed to Atacama). We have used a benefit transfer method to calculate ecosystem values for practical reasons. Therefore, this account must be approached with caution because ecosystem unit values are influenced by an extensive range of methodological and contextual factors. There is ample room for further primary research applying stated preference methods to estimate the non-use value of the High Andean wetlands in Latin America.

6. Conclusions

This study has examined the effects of ecosystems' values on mining paths. In general, the competition between mining resources and sensitive ecosystems challenges ecological conservation. The first step in wetlands conservation is understanding their functionality and economic and non-economic values. Despite limited research on the Chilean High Andean wetland values, brine pumping has adversely affected these ecosystems. The contribution of this study has been translating these ecological impacts into economic damages. Our model was designed to determine how mineral extraction impacts both quantitative and qualitative depreciation of the ecosystems. The findings of this study provide a new understanding of how ecosystem values compete with the long-term returns from mining.

The evidence from this study supports the idea that any policy to control ecosystem loss, such as a tax imposed on mineral extraction, should also vary with the wetland size. Further research is required to verify how brine pumping changes the underground hydrological balance and impacts sensitive ecosystems on the surface. This new knowledge should help to establish a consensus on the causal relationship between mining and environmental degradation. The ecosystem damage caused by mining is a crucial parameter for converting ecosystem damages into economic losses and determining the appropriate tax level.

To promote a sustainable energy transition, we need to account for the ecological impact of critical mineral extraction. Our findings provide insights into how policymakers can enforce control parameters to avoid complete wetland damages and still benefit from a mineral boom and increasing prices. Although this research focuses on lithium extraction and high Andean wetlands in Chile, the findings may well represent the broader challenge of sustainable mining and ecosystem conservation worldwide.

Appendix A

Ore grade and extraction costs

The Chilean government has prioritized lithium extraction by the potential of high ore grade and low-cost extraction. Mineral concentration is measured in terms of milligrams per Liter of Lithium salt. To calibrate this parameter, we calculate the *normalized* ore grade g as $g = \frac{x-\mu}{\delta}$, where x is ore grade, μ is the arithmetic mean, and δ the standard deviation value. Table 1. Column 6 displays the information on the calibrated ore quality parameter (g_i) presented in our model equation (1) and used in the numerical simulations in GAMS.

Table 1 Column 11 shows the calibrated parameter omega ω_i. In line with Bustos-Gallardo (2021), this parameter reflects how extraction costs are also affected by water balances, equal to precipitation minus evaporation divided by catchment area. The lower this parameter, the slower extraction costs will increase. We used this water balance as the calibrated omega parameter for Atacama $(\omega_{Atamcama})$. We calibrate the ω_i parameter for Maricunga considering the relative lithium resource stocks between these two salt flats like this: $\omega_{Maricunga} = \omega_{Atacama} R_{Atacama} / R_{Maricunga}$, and is presented in Table 1, Column 11.

Table I. Calibrated parameters

	1	2	3	4	5	6	7	8	9	10	11
	Potential	Salt pant - study case	Area in Hectare (Ha)	Lithium Carbonate Equivalent - LCE- Resources Million Tons	Ore grade Li (mg/L)	Normalize Ore grade (g_i)	Precip (mm/year)	Evap (mm/year)	Catchment area (Km2)	Water balance	Omega (ω_i)
1	**High**	**Atacama**	**305100**	**52.17**	**1500**	**0.98**	**160**	**1800**	**18100**	**0.09**	**0.09**
2	**High**	**Maricunga**	**14500**	**2.15**	**1647**	**0.99**	**120**	**1100**	**3045**	**0.32**	**2.20**
3	High	Pedernales	33800	7.49	423	0.46	125	1200	3620	0.30	0.63
4	Undefined	Punta Negra	25000	3.91	380	0.42	50	2000	4263	0.46	1.21
5	High	La Isla	15200	5.05	1150	0.93	130	1000	858	1.01	0.94
6	High	Aguas Calientes 2 - Sentrum	13400	1.03	220	0.29	150	1500	1168	1.16	4.60
7	High	Pajonales	10400	1.10	350	0.40	115	1350	1984	0.62	4.31
8	Medium	LoyoquesQuisquiro	8000	1.41	640	0.65	150	1500	676	2.00	3.36
9	Medium	Aguilar	7100	0.61	337	0.39	100	1100	589	1.70	7.72
10	Medium	Tara	4800	0.61	600	0.61	150	1500	2035	0.66	7.72
11	Low	Aguas Calientes 3 - Sur	4600	0.01	205	0.28	150	1500	476	2.84	472.70
12	Medium	Parinas	4000	0.41	477	0.51	140	1000	676	1.27	11.53
13	Low	Grande	2900	0.01	123	0.22	130	1000	867	1.00	472.70
14	Undefined	Capur	2700	0.13	50	0.18	150	1500	137	9.85	37.00
15	Low	Gorbea	2700	0.01	500	0.53	140	1000	324	2.65	472.70
16	Low	Agua Amarga	2300	0.01	61	0.19	120	1100	864	1.13	472.70
17	Low	Aguas Calientes 4-Sur-Sur	2000	0.05	8.5	0.16	180	1630	656	2.21	98.67
18	Low	Pujsa	1800	0.13	620	0.63	150	1500	634	2.13	37.00
19	Low	El Laco	1620	0.01	32.5	0.17	200	1500	306	4.25	472.70
20	Low	Aguas Calientes 1 - Norte	1500	0.04	290	0.35	150	1500	281	4.80	126.86
21	Undefined	Laguna Verde	1500	0.53	204	0.28	170	1000	1075	0.77	8.88

Appendix B

Diminishing returns to scale of wetland values

There is an agreement that wetland values exhibit diminishing returns to scale. Table II shows the regression coefficients from five studies' meta-regressions for wetland values per hectare. All coefficients display negative signs and are statistically significant. A negative coefficient means that an increase in wetland size pushes down the wetland value per hectare. This also suggests that adding a hectare to a large wetland is less important than adding a hectare to a small wetland. Note that the total value of a wetland increases with its size (since the coefficients are between 0 and -1) but at a diminishing rate as the per-hectare value decreases.

Table II. Wetland size and wetland values correlation parameters

Source	Coefficient Wetland size Log
(Woodward & Wui, 2001)	-0.16% to -0.28%
(Brander et al., 2006)	-0.11 %
(Ghermandi et al., 2010)	-0.25 %
(Brander et al., 2013)	-0.37 %
(Chaikumbung et al., 2016)	-0.41 %

In our numerical simulations, we use the estimated coefficient by Chaikumbung et al. (2016), which means that the parameter ε_j in equation (4) is set equal to 0.59 (ε_j = 1 – 0.41).

Appendix C

Environmental degradation

NDVI detects the response of vegetation varieties to the local environmental disturbance with a valid range from -1 to 1. The positive value from 0 to 1 corresponds to vegetation cover from sparse shrub or grassland to dense canopy, and a value of -1 indicates the absence of vegetation and the presence of water bodies. Hence, a negative change of NDVI in this study can imply the degradation from dense tree cover to shrubland, from shrub or grassland to barren soil, or from bare soil to mining operation ponds. The negative changes of NDVI are evident in environmental degradation from lithium extraction.

Previous studies (Liu et al., 2019) show that lithium operations expansion correlates strongly negatively with NDVI. The slope of the regression function indicates that while lithium operations expand by 1km, the average vegetation coverage measured by the NDVI decreases by 0.0014. The mining area is found to have a strong negative correlation with the means values of NDVI having detectable negative changes in the vegetation coverages.

To calculate the δ_{ij} parameters, we first consider the NDVI per year reported by Liu et al. (2019) for the four National Reserve areas (Table 1). Then, we take the average of these four areas, which is 0.00275 representing the change in NDVI per year.

We then calculated the average production per year in the same period (1997-2017) from lithium production data, which is 0.045 million tons. Then we can calculate the change in NDVI per mill tons extraction (0.00275/0.045 = 0.06). In GAMS, we set the parameter $\delta_{ij} = 0.06A_{ij0}$ for our benchmark scenario. For the second sensitivity analysis, we assume a higher vegetation loss and consider the maximum degradation level observed in certain ecosystem areas (e.g., this area is denominated sector 4 – S4) in Liu et al. (2019, page 153). Thus, the NDVI will be equal to 0.0039, and the parameter $\delta_{ij} = 0.09A_{ij0}$

Table III and IV below shows our estimations of δ_{ij}. We notice that the more extensive vegetation and water coverages, the larger the impact of lithium extraction.

Table III Delta parameter in Benchmark scenario
Vegetation coverage Hectare / Lithium Resources Tons

	16%		50%		84%	
	Veg	Water	Veg	Water	Veg	Water
Atacama	0.32	9.62	1.32	24.52	3.72	40.04
Maricunga	10.05	4.33	34.74	9.88	71.11	35.09

Table IV Delta parameter in II Sensitivity Analysis
Vegetation coverage Hectare / Lithium Resources Tons

	16%		50%		84%	
	Veg	Water	Veg	Water	Veg	Water
Atacama	0.48	14.43	1.98	36.77	5.58	60.07
Maricunga	15.08	6.50	52.11	14.81	106.66	52.63

Appendix D

Benefit transfer

In this section, we estimate the non-use values (existence and bequest values) of cultural ecosystem services at our policy site, the highland wetlands in northern Chile susceptible to being transformed by the lithium industry. Thus, following the recent best-practice guidance in benefit transfer (Johnston et al., 2021), we rely on the transfer of non-use values from a meta-analysis of existing valuation studies, particularly the one by Chaikumbung et al. (2016) of wetlands in the global south to make such out-of-sample predictions. We use their meta-regression function, keep the regression coefficients of the explanatory variables, and insert the values for the explanatory variables at our policy site to estimate these non-use values. To assess the quality and reliability of our benefit transfer estimates, we also compare our estimates to other meta-analyses of wetlands with broader scope both geographically and in terms of types of wetlands. Later this benefit transfer is combined with the structural form presented in section 2, equation (3). This combination incorporates the dynamics of the ecosystem in space and time, giving different extraction paths if the ecosystem values are taken into account by decision-makers.

Meta-regression function

To calibrate the ecosystem's value, we transfer the values and characteristics of the salt flats into the transfer regression function developed by Chaikumbung et al. (2016). Their study presents a meta-regression analysis based on 1432 estimates of the economic value of 379 wetlands in 50 countries in the global south. We selected this study because it covers most of our policy study's characteristics and publishes detailed information to replicate the estimations. It also offers a commodity consistency, allowing us to observe the annual ecosystem value in USD dollars per hectare. We, therefore, assess ecosystem value by giving the following benefit transfer function:

$$\ln V = \beta_0 + \beta_A ln x_A + \beta_w x_w + \beta_m x_m + \beta_c x_c + u \tag{11}$$

The dependent variable is the constant price dollar value per hectare of wetland per year or its natural logarithm transformation (denoted as $\ln V$). The explanatory variables x and their respective estimated coefficients β, are the following: the constant β_0; the size area in the logarithm $\beta_A ln x_A$; a vector of wetland characteristics ($\beta_w x_w$); a vector of valuation methods ($\beta_m x_m$); and a vector of context characteristics ($\beta_c x_c$). In addition, Chaikumbung et al. (2016) offer ten different meta-regression models of economic valuation studies of wetland ecosystem services, covering four estimation methods and six different wetlands subgroups. We choose only one estimation (Model (5), “Without marine”) that better represents our wetland’s characteristics. Table V. below shows the estimated coefficients of variables in the regression.

Table V. Meta-regression regressors and coefficients estimated by Chaikumbung et al. (2016) Model No. 5

		β_i	x_i			$\beta_i x_i$		
	Variable	Coefficient	Mean (Chaikumbung et al)	Atacama	Maricunga	Mean (Chaikumbung et al)	Atacama	Maricunga
	Constant	6.816**						
	Size (lnArea)	-0.404***	9.17	3.09	6.36	-3.70	-1.25	-2.57
Type	Lacustrine	0.024	0.13	0	0	0.003	0	0
	Palustrine	-1.54**	0.08	0	0	-0.12	0	0
Ecosystem service	Water regulation	1.697**	0.07	1	1	0.12	1.70	1.70
	Erosion control	0.483	0.07	1	1	0.034	0.483	0.483
	Biodiversity – Habitat	1.663***	0.30	1	1	0.50	1.66	1.66
	Culture	-0.241	0.04	1	1	-0.010	-0.241	-0.241
Valuation method	CVM	-1.853***	0.42	1	1	-0.78	-1.85	-1.85
	CE	-1.335*	0.08	1	1	-0.11	-1.34	-1.34
	HP	-2.082*	0.002	NA	NA	-0.004	-	-
	D.C. - Avoided damage cost	0.885*	0.15	1	1	0.13	0.89	0.89
Publication Status	Published	-0.567	0.48	0.48	0.48	-0.272	-0.272	-0.272
	Year of Survey	-0.102**	2.50	2.50	2.50	-0.26	-0.26	-0.26
Context	Protected	1.382	0.19	1	1	0.263	1.382	1.382
	Ramsar	-0.721	0.16	1	1	-0.115	-0.721	-0.721
	Urban	1.954**	0.07	NA	NA	0.14	-	-
	Ln GDP per capita	0.475	8.21	9.67	9.67	3.900	4.592	4.592
	Absolute Latitude	0.052**	15.01	23.418	26.95	0.78	1.22	1.40
	Africa	1.376**	0.17	0	0	0.23	0.23	0.23
	Latin America	1.555**	0.10	1	1	0.16	1.56	1.56
	No. of observations	896						
	No. of studies	262						
	Adjusted R^2	0.536						

* Denote statistically significant at *10%. ** 5% *** 1% level. “N.A.” means that the variable does Not Apply to our study case.

In our benchmark scenario, we consider mostly statistically significant variables to calculate wetland values. However, despite not being statistically significant, we decided to include some relevant variables in our estimations (e.g., Lacustrine, erosion control, protected, Ramsar) for sensitivity analysis. Note that when they are part of the estimation in Table V, they affect the estimated constant β_0. Thus, instead of using coefficients from the Atacama and Maricunga areas, we apply the mean values from the observations in Chaikumbung et al. (2016) for sensitivity analysis.

Next, we present reasons for the inclusion and exclusion of variables in our estimations:

Wetland Size: This is a crucial variable to define the magnitude of ecosystem values. We, therefore, include the coefficient of ln(Area), which is consistently negative and statistically significant across all models reported by Chaikumbung et al. (2016). The coefficient signs are also consistent with those reported in other meta-analyses by Woodward and Wui (2001) and Ghermandi et al. (2010).

Note, however, that since wetland size is a separate variable in our model (A_{ijt}), this coefficient is used to calibrate the elasticity ε_j, so that $\varepsilon_j = 1 - 0.404 = 0.596$. Therefore, wetland size is excluded from the estimation of the scale parameter B_{0ij}.

Wetland type: In this Andean ecosystem, wetlands are lacustrine sites with scarce vegetation that serve as key regulators of biotic and abiotic elements and are crucial habitats for the Andean gull, vicuñas and the threatened Andean flamingo (Marconi et al., 2022), and home of endemic species like the vicugna (*Vicugna*), llama (*Lama glama*), and alpaca (*Lama pacos*), and form the basis for the livelihoods and cultural heritage of the native Altiplano populations (Gandarillas R et al., 2016).[15]

In Chaikumburg et al. (2016), the coefficient for the *lacustrine* variable is inconsistent across models, being positive and negative, and is not statistically significant in the selected Model (5). In our benchmark scenario, we do not account for that characteristic. But in a sensitivity analysis, we include the average value of the lacustrine coefficient, as we want to simulate a scenario with higher wetland values.

Wetland ecosystems services: The wetlands offer multiple ecosystems, and we, therefore, proceed to analyze how those other services are more valuable to the baseline category recreation services:

(i) Water regulation: Atacama's wetland has a hydrological system comprising a series of surface channels and lagoon bodies. Around the Maricunga wetland, lagoons, aquifers, fluvial, alluvial, and saline deposits surround the salt flats, another flamingo's habitat. The corresponding coefficient of the *water regulation* variable is positive and statistically significant, suggesting that water regulation services are more valuable than the baseline category of recreational services. This variable equals one in the benefit transfer function for benchmark and sensitivity analysis scenarios.

(ii) Erosion control: In an arid region with low precipitation and high evaporation rates, soil erosion is crucial to land degradation and desertification. Chaikumbung et al. (2016) analyzed an important number of studies (43) and observations (102) studying the erosion control ecosystem service and found no statistical significance in this service value. We, therefore, set this variable equal to zero in the benchmark scenario. But we account for it and put it equal to one in the wetland value calculations for our first sensitivity analysis scenario.

(iii) Biodiversity - habitat: Chaikumbung et al. (2016) found that biodiversity and habitat are highly correlated. Thus, these two services were combined in a single variable. The coefficient is positive and statistically significant, suggesting that wetlands offering biodiversity and habitat are more valuable than those used for recreation. This variable coefficient is multiplied by one in the benefit transfer function for both the benchmark and first sensitivity analysis scenario.

(iv) Culture: Some indigenous populations consider the salt flats spiritual sanctuaries and defend their settlement and the right to continue using the salt flats and wetlands to manifest their traditional practices. The High Andean wetlands are also the habitat of stromatolites, exceptional and rare stones that provides records of ancient life on Earth (Flexer et al., 2018). Despite this unique feature, the variable is not statistically significant in the Chaikumbung et al. (2016) study and is therefore excluded from our benchmark and included in the sensitivity analysis.

Valuation method: As we want to estimate non-use values, we focus on the Stated Preference (S.P.) methods (Contingent Valuation (CV)- and choice experiments (CE). CV is the most frequently used method, with 155 studies and 603 estimates in Chaikumbung et al. (2016). There are 24 CE studies with 105 estimates. Both valuation methods assign lower ecosystem values than the baseline market price method. CV and CE are statistically significant variables in the meta-regression and therefore included

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[15] The Andean flamingo is presenting a decreasing population.Since 2006, the mining company SQM has monitored the variation of flamingos in Salar de Acatama. At least four different species have been identified (Phoenicoparrus Andinus, Jamesi, Chilense and Pollos de Flamenco). In 2015, the company observed approximately 3600 in the wetland. In 2021, they only observed 1593 flamingos. More information here: https://www.sqmsenlinea.com/monitoreo-biotico/fauna/aves-acuaticas-flamencos

in our calculations. Thus, we multiply the coefficients of CV and CE variables by the average values in both benchmark and sensitivity analysis scenarios.

Publication status: Chaikumbung et al. (2016) assess the quality of the studies by observing the publication status and valuation year. Both variables are negative and statistically significant across models. However, they are not statistically significant in Model (5) of Chaikumbung et al. (2016). Still, we included publication and year in our estimations, considering the mean values for both benchmark and sensitivity analysis.

Wetland context characteristics: In Atacama and Maricunga, lakes and hydrological systems are declared RAMSAR sites and hold national natural parks and reserve areas. Thus, even though both variables (protected and Ramsar) are not statistically significant, we included them with average values in the benchmark and dummy variables in the sensitivity analysis. Our wetlands are not located in urban areas, so even if "urban" is statistically significant, we set it equal to zero in the benefit transfer function.

GDP per capita is a proxy of income. The literature has extensively demonstrated that wetlands are a normal good and wetland values in developing countries are income elastic. The two wetlands are in two regions where mining is the main economic activity. Both have a relatively higher income than the rest of the country (for Atacama wetland, the GDP per capita in the region is USD 34 840; for Maricunga's area is USD 17 021; while Chile's national GDP per capita of USD 14 255). Despite these differences and the fact that this variable is not statistically significant in Model (5), we decided to include this variable and multiplied the coefficient by the national GDP.

Absolute latitude is included in our estimations. The farther wetland is from the equator, the more valuable it is. Maricunga is further south than the Atacama, so it has a higher coefficient value. Wetlands in Latin America have a greater ecosystem value than Southeast Asia's base category. We multiplied this variable coefficient by the mean value in benchmark and sensitivity analysis scenarios.

Benefit Transfer results

Table 2 presents the estimations from the benefit transfer application by using Chaikumbung et al. (2016) meta-regression function. The authors reported an observed average wetland value of 1998 USD (2002 prices) per hectare per year, with the median being 2192 USD per hectare per year. The observed values vary substantially, with some observations above 20 million USD per hectare. Chaikumbung et al. (2016) also reported the mean values for all observed variables, allowing us to replicate their model estimations. They also reported the estimates of the General OLS model that includes the entire group of observations and variables denominated as Model (1). By plugging these mean values into the model (1), we obtain an estimated average value of 2267 USD per hectare per year.

In Chaikumburg et al. (2016), the average wetland size, in logarithm, is 9.17 (approximately 9 605 hectares). As shown in Table VI, in our study case, the dimensions of Atacama and Maricunga are smaller than the average size of Chaikumbung et al. (2016); we, therefore, expect higher average unit wetland values.

Table VI. Vegetation and water coverage areas in logarithmic form

Area Vegetation (Ln)			Area water (Ln)		
Av 16%	**Av 50%**	**Av 84%**	**Aw 16%**	**Aw 50%**	**Aw 84%**
1.7	3.1	4.1	5.1	6.0	6.5
5.1	6.4	7.1	4.3	5.1	6.4

Table VII below presents the observed and estimated values reported by Chaikumburg et al. (2016) jointly with our estimations for benchmark and sensitivity analysis scenarios. Our calculations for Atacama and Maricunga do not include the effect of wetland size, as it will be calculated in our analytical model equation (4) and simulated like that in the numerical simulation in the GAMS program.

Table VII. Observed and estimated wetland values

	Benchmark scenario		**I Sensitivity analysis**	
	Ln	*USD*	*Ln*	*USD*
***Observed average by Chaikumbung et al. (2016)**	7.6	1998		
Estimated average with Chaikumbung et al. (2016) Model (1)	7.7	2267		
Maximum observed value	17	24 154 953		
Atacama	15.7	6 690 746	16.5	14 592 467
Maricunga	15.9	8 039 681	16.68	17 534 484

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Paper 4

How effective are environmental taxes in the mining industry?

Diana Roa
diru@nmbu.no
School of Economics and Business, Norwegian University of Life of Sciences, Ås, Norway
https://orcid.org/0000-0001-5234-8517

Abstract

Environmental taxes allow mineral-producing countries to account for their mining footprint. However, several factors can limit their effectiveness. This article uses a cash flow model to critically examine the principles of tax regimes and the obstacles to design and apply environmental taxes in mineral-rich developing countries. Resistance is the first obstacle, mostly in economies with high dependency on mineral earnings. That is because environmental taxes are regressive as they aim to discourage harmful behavior rather than increase public revenues. This corrective tax purpose will affect the tax system's progressivity, simplicity, and neutrality. Consequently, implementing environmental taxes suggests that governments should redefine priorities with less emphasis on maximizing revenue. Nonetheless, measuring most tax bases and rates is difficult, and environmental taxes are no exception. Furthermore, flaws in environmental tax design can reduce their effectiveness. For example, only if the tax rate is set at an appropriate level, environmental taxes will give enough incentives to pursue mitigation strategies to minimize damage. On the other hand, when applied as an *ad valorem* charge on production, such as a royalty, Pigouvian taxes can be affected by transfer pricing manipulation. Therefore, the opacity of market prices can also compromise the effectiveness of environmental taxes. The results of this study confirm that authorities cannot design environmental taxes in the mining sector in isolation from other taxes. It must consider existing and new distortions of the tax system. Although this study focuses on the lithium mining sector in Chile, the findings may have implications for global coordination to implement environmental taxes in the mining industry.

Keywords: Environmental tax, global carbon tax, mining impact, ecosystem preservation, fiscal policy

1. Motivation

Low-carbon technologies are driving the current minerals super-cycle. As mineral prices rise, mineral-rich countries tend to accelerate resource depletion and implement fiscal measures to increase public revenue. The windfall is apparent, but some mining costs remain hidden. Mineral exhaustion comes at an ecological cost that business as usual has failed to account for. However, policymakers can ensure that environmental impacts are minimized and, if possible, avoided. One way to do this is by implementing environmental taxes to deter the industry from harmful behavior and compensate society for eventual damages. Tax regimes can therefore enable mineral-rich countries to capture windfalls, transform their economies, and influence how extractive companies treat the environment. The critical questions are, what factors can limit the effectiveness of Pigouvian taxes? Moreover, what fiscal policies for the mining sector are most likely to facilitate social and economic transformations in a fair and sustainable manner? This paper aims to answer these questions and use a financial approach to analyze the impact of environmental taxes on the Chilean lithium sector.

One of the main obstacles to implementing environmental taxes is that it can reduce mineral production (Roa et al., 2023), which can result in a significant drop in GDP and a deficit in the balance of payments (Mardones, 2022). At the country level, those effects are unfavorable in an economy with a high dependency on mineral export earnings like Chile.[1] Globally, lower mineral availability is undesirable if it implies slower energy and digital transitions (Roa & Rosendahl, 2022).

Rather than market-based tools, command-and-control policies and corporate citizenship (e.g., benefit-sharing agreements) have been the dominant methods for bringing sustainable development priorities to the private sector. However, industry initiatives are voluntary and can be abandoned in difficult economic times; depending on the community's bargaining power, they vary greatly between companies and projects, and compliance can be an issue (O'Faircheallaigh, 2015). Therefore, non-market-based policies have yet to prove to be the most effective way to protect the environment and regulate the mining sector.

The rush to meet energy transition mineral demand has resulted in projects being "fast-tracked" without adequate consultation and licensing procedures (Owen et al., 2022) and leading to more mining licenses in jurisdictions with weak governance (Carballo & Sahla, 2022). In Chile, the government has recently published a guideline (SEA, 2021) requesting companies to list and classify the effects of lithium mining on the environment without asking for any economic quantification of damages. A lack of quantifying damages increases the risk of overlooking the severity of mining's environmental impact (Gavin, 2004), which can result in economic benefits exclusive to mining companies at the expense of ecological losses, liabilities to human health, deepening inequality, and triggering long-term conflicts.

Environmental issues often trigger conflicts between mining companies and communities, and mining companies fail to adequately factor in the costs of conflict (Franks et al., 2014). For example, the Maricunga project, the second-largest lithium reserve in Chile, has escalated from demonstrations to tribunals. The project generates controversy due to blind spots in the environmental impact assessment, ignoring and bypassing communities' consent and underestimating the project's impacts on ecosystems and their cultural values.[2] Evidence has shown that the mining sector has long harmed the High-Andean wetlands on a social and environmental level (Blair et al., 2022).

Strategies to enhance the sustainable use of critical minerals such as lithium require a long-term and holistic perspective. Lithium mining is essentially groundwater mining from beneath arid basins. The process generates large volumes of salt mixture waste, which is reinjected back into the ground. As a

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[1] Mining contributes 10% of the GDP and 52% of total exports. Critical materials such as copper and lithium are abundant in Chile, which makes it an important player in the global mineral market. According to the USGS (2022), Chile is the world leader in mine copper production (5.6 million tons in 2021) and the second-largest producer of lithium (26 thousand tons in 2021).

[2] More information about the Maricunga'a conflict can be consulted in Fundación Terra in this *link* (consulted in November 2022).

critical refuge for native and migratory species, this dry landscape includes internationally recognized (Ramsar) wetlands and protected areas. The vitality of ecosystems depends on water coverages and underground hydrological balances, and reservoirs may take decades to replenish (De la Fuente et al., 2021). Lithium mining expansion has already been correlated to environmental degradation during the last two decades in the Atacama salt flat in Chile (Liu et al., 2019). There is still uncertainty, however, on how brine extraction changes the underground hydrological balance and impacts sensitive ecosystems on the surface (Roa et al., 2023). The difficulty in accurately measuring the environmental impacts of mining operations can limit the effectiveness of any policy governing the mining sector.

The conflict in Maricunga is not an isolated case and may well represent common resistance to the extractivist aspects of the energy transition (Owen et al., 2022; Walter et al., 2021), and shows that traditional approaches to protect the environment and regulate the mining sector are insufficient to avoid conflict.[3] This issue also makes evident the need to translate social and environmental risks into business costs.[4] Indeed, when conflict costs are quantified, mining companies are more likely to reconsider corporate behavior and project design (Franks et al., 2014). It is, therefore, possible to investigate the opportunity costs of mining from a project and financial perspective, allowing us to explore the use of environmental taxes to strengthen mining regulations.

Tax reforms, however, may reduce mining profits, increasing the risk that companies will seek ways to minimize tax payments. Tax risks, like profit shifting along the extractives value chain, increase when foreign-owned companies have reserves, processing plants, and operations in different countries with substantial differences in tax regimes. In such conditions, mining companies have an easier time shifting profits to low-tax countries in order to minimize taxes (Beer & Devlin, 2021; Delis et al., 2022).

Discrepancies in regulations, like lack of transparency, exacerbate tax risks. In Chile, most major mining firms are multinational companies not obliged to disclose their financial accounts (Jorratt, 2022). At the same time, evidence that mining firms in Chile engage in profit-shifting has increased during the last decade (Solimano & Guajardo, 2018). While the debate continues about the effectiveness of government measures to deal with profit shifting (Bustos et al., 2022), researchers have yet to examine to what extent additional taxes, like environmental taxes, can aggravate this problem and create other distortions in the mining tax system.

To date, few studies have investigated how to account for the environmental impact of lithium mining (Roa et al., 2023). Other studies demonstrate that mining would be less financially affected by a global carbon tax than other industries because mineral extraction yields high economic rents (Cox et al., 2022). Although some research has been carried out on the economic rents and tax system of lithium mining in Latin America (Jorratt, 2022), the fiscal effects and challenges of enforcing environmental taxes on the lithium sector have yet to be discovered. It is still necessary to understand whether environmental taxes are effective in minimizing mining footprints and to what extent they encourage companies to do so.

This paper aims to critically examine the fiscal and financial aspects of taxing environmental damages. By employing a cashflow model, I analyze the Chilean lithium tax regime and look for generalizations that can be applied to the mining industry. I set an initial structure and level for carbon taxes and Pigouvian taxes for ecosystem damages (section 2). Then, (in section 3), I examine key features of tax systems such as progressivity as profits change, simplicity of tax bases, neutrality on new investments, and the reliability of the tax system at low-profit levels. In section 4, I discuss alternative scenarios for

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[3] According to the Environmental Justice Atlas and Mining Watch Canada (2021), in the Americas are registered forty-nine (49) conflicts around environmental issues of critical minerals extraction. Lithium projects have raised eighteen (18) conflicts, five (5) in Chile. Socio-environmental conflicts are defined as mobilizations by local communities and social movements, which might also include support of national or international networks against mining activities, infrastructure construction, or waste disposal whereby environmental impacts are a key element of their grievances. See more in https://ejatlas.org/

[4] The Maricunga mining project is supposed to start in March 2022 with a capital expenditure of US$627 million. The company may suffer roughly US$2.75 million per week of delayed production.

environmental tax reform in Chile, considering low and high tax levels and the possibility of reducing tax payments in legitimate and non-legitimate ways (section 5). I finally discuss the implications of this study and suggestions for future work and conclusions (Section 6).

Based on the Maricunga lithium mining site in Chile, this study focuses on project-level analyses. It cannot cover the regional and national impacts of the project. Welfare and revenue distribution measures are beyond the scope of this analysis.

1.1. A review of the fundamentals of environmental taxes in the mining industry

Environmental taxes can be used to determine the "true price" of mineral exhaustion. Because mining damages impose costs on others, the social marginal costs (SMC) are higher than the private costs. Thus, environmental taxes are intended to equalize social and private marginal costs. The most common environmental damages of mining exhaustion are deforestation, soil erosion, air and water pollution, and natural habitat devastation. Taxes, however, might not be suitable to minimize all mining damages.

Sustainable mining suggests defining thresholds where damages can be avoided, minimized, restored, compensated, and offset (Figure 1). The estimation of optimal environmental taxes can depart from such thresholds and guide the decision path to advance mitigation strategies. It means that taxes should be used after reasonable actions have been taken to avoid and minimize damages. Such actions suggest denying mining licenses when mining is unsafe and poses risks to highly vulnerable and valuable ecosystems. It might also be necessary to reduce the project size before it starts and set quotas to limit water and brine depletion, as in the case of lithium mining in the High-Andean wetlands.

Figure 1. ***Environmental and natural resource decision chain***

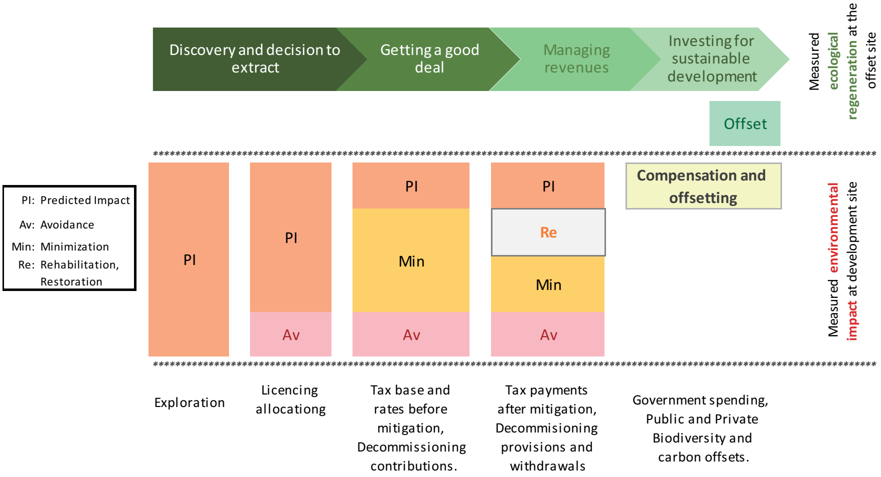

Fig. 1. Adapted from "The Natural Resource Charter" (NRGI, 2014); and "Biodiversity Offsets", Policy Highlights (OECD, 2016)

Environmental taxes must be justified primarily by the cost-effective achievement of environmental goals (Fullerton et al., 2008). If the tax rate is set at an appropriate level, environmental taxes will give enough incentives to pursue mitigation strategies to minimize damages. For example, brine lithium is processed using diesel-fueled thermal power plants. Suppose that alternative energy sources, like wind or solar power, are available and are cost-competitive. In that case, a certain part of the damage can be minimized, and in the end, it will reduce carbon tax payments. Other damages to habitat and ecosystem services might be irreversible, and the residual impact must be compensated with complementary instruments (e.g. carbon and biodiversity offsets).

Environmental taxes are regressive as they will likely deter low-grade, high-environmental-cost projects. When considering the whole tax system and profits on a lifetime basis, a regressive fiscal regime means an inverse relationship between profits changes and the government share of profits, i.e., the lower (higher) project's profits, the higher (lower) the government share. Lower profitability may come from lower prices or higher costs. And environmental damages are an additional and hidden cost of mining independent of the mineral market value.

In contrast to regressivity, a tax regime can be progressive if it considers that profit levels can change across the lifetime of a project and vary across different projects. Progressivity also implies a direct relationship between profits changes and the government share of profits, i.e., the higher (lower) are project's profits, the higher (lower) the government share or tax revenue. The literature (Daniel & Goldsworthy, 2010; IMF, 2022) suggests that progressive rate schedules may have appeal in terms of political economy, being more robust against political pressures in the event of high return outcomes than regressive schemes. Chilean big business, like mining, has had a long-standing and major influence on public policy and opposition to increasing tax burdens (Fisse & Thomas, 2014; Solimano & Guajardo, 2018). Thus, implementing regressive policies, such as environmental taxes, may meet with controversy and resistance from mining companies.

Government can still justify a less progressive system when pursuing further objectives (Wen, 2018). Despite profit distortions, an environmental tax can contribute to economic welfare if it provides environmental benefits, i.e., reduces pollution, and enhances ecological conservation. (Perman, 2003). Ultimately, environmental taxes have a regressive component by design because their goal is to discourage harmful behavior rather than increase public revenues. Therefore, tax regimes can be an instrument to enhance environmental preservation while seeking to maximize welfare rather than revenue.

Revenues from environmental taxes can be unpredictable and unstable. The tax base can be eroded due to mitigation actions by mining companies. Still, additional environmental tax revenues can possibly create distortions in the tax system. For example, Pigouvian tax revenues may exceed other public revenue sources (e.g., profit or income taxes) and crowd out other government sources of income. In Chile, there is evidence that mining tax windfalls have crowded out local revenue, promoting tax laziness among municipalities (Oyarzo & Paredes, 2019). One way to avoid distortions from environmental taxes is to put them back into the economy in a lump-sum way (Oates, 1995). For example, Pigouvian taxes can compensate victims for irreversible damages; and to finance all the supportive services related to it (e.g., capacity building in environmental agencies, R&D, infrastructure to monitor ecosystem changes, and data collection).

Environmental taxes not only induce mitigation damage and generate potential revenues but may also reduce the costs of the tax system. This is the so-called "double dividend" hypothesis. According to this hypothesis, revenue from environmental taxes can be earmarked or redirected to reduce other taxes. If those other taxes have distortionary effects, reducing their rate will create efficiency gains (Perman, 2003). Extensive theoretical studies support the double dividend hypothesis (Fullerton et al., 2008; Goulder, 1994; Oates, 1995; Perman, 2003). However, despite environmental benefits usually being achieved, the economic dividends of environmental taxes remain ambiguous and require further study (Freire-González, 2018; Patuelli et al., 2005).[5]

Although market instruments entail risks, tax policies are critical to environmental regulation since they allow governments to prioritize the most pressing issues (Taylor et al., 2012). A global concern on

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[5] In praxis, it is hard to see the number of tax reforms that have implemented environmental taxes and in parallel, reduced other taxes. In Australia, discrete tax concessions related to environmental matters have been enacted, e.g. a concessional WHT rate of 10% can apply to distributions from a managed investment trust (MIT) that holds only 'clean buildings' (*see* here *for further details*).The reduction occurs despite the fact that Australia does not impose a tax on carbon emissions or have an emissions trading scheme either.

climate change has focused on greenhouse gases, particularly carbon emissions; therefore, carbon taxes have been a prominent research topic.

The mining sector globally contributes to an important share of carbon emissions. At the same time, many mining industry products have an exceptionally high value per ton of CO2 emissions compared to other sectors (e.g., agriculture and construction) (Cox et al., 2022). That high added value can be associated with high economic rents of mineral extraction, which implies that the mining industry would be less financially affected if a global carbon tax were introduced compared to other sectors (Cox et al., 2022).

In contrast to carbon taxes, up to now, far too little attention has been paid to taxes for ecosystems damages. To my knowledge, no mineral resource-rich country has implemented environmental taxes associated with ecosystem damage or water pollution. Although challenging, the potential ecological wealth losses from mining activities can be quantified, making it possible to calculate optimal tax rates that reflect the marginal environmental damage and subsequently calculate the mining profits forgone for ecosystem preservation.

Overall, environmental taxes can be an efficient solution to reduce the environmental impact of mining operations, but their effectiveness depends on several factors. There remain numerous aspects of the financial and fiscal implications of environmental taxes on which this research is focused.

2. Financial models and input data

Recent advances in financial cashflows models have assisted the analysis of fiscal reforms in extractive industries (Tarras-Wahlberg, 2022). The benefit of this approach is that it allows the design and evaluation of a fiscal regime by assessing a mining project's economic and financial characteristics. Another advantage is that it allows estimating the government and investor participation in a resource project, thus providing indicators and results in language understandable to business and financial analysts and government professionals. Currently, there are three well-known models publicly available. The first model is the "Fiscal Analysis Resource Industries" – FARI – by the International Monetary Fund.[6] The second model was developed by the Natural Resource Governance Institute (NRGI)[7]; the third one was developed by the ECLAC (United Nations)[8]. This study uses the FARI model to estimate the effects of environmental taxes, including sensitivity analysis, and I use the other two models to compare and verify preliminary estimations on project profitability and tax burden.

In this study, the input data comes from the Maricunga lithium project in Chile developed by the Company Minera Salar Blanco S.A.[9]. At full capacity, during 20 years of operation, Maricunga can provide roughly 4% of the global lithium supply.[10] The model inputs on fiscal regime parameters are presented in Appendices.[11]

The implications of changing fiscal regimes consider investors' and government's perspectives. From an investor's perspective, two key indicators are the project's post-tax net present value (NPV) and the post-tax internal rate of return (IRR). From a government perspective, two key indicators are the average effective tax rate (AETR) and government tax revenues. The AETR results from dividing the government

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[6] The IMF model is available at: https://www.imf.org/en/Topics/fiscal-policies/fiscal-analysis-of-resource-industries

[7] The NRGI model is available at: https://resourcegovernance.org/economic-models

[8] The ECLAC – United Nations – model is available here: https://repositorio.cepal.org/handle/11362/47807

[9] Minera Salar Blanco S.A. (MSB) is a Chilean joint venture created in 2016 to explore and develop the Maricunga lithium project, in the Atacama Region, northern Chile. The company is owned by the Australian international firm Lithium Power International Limited (51%), the Chilean mining company Minera Salar Blanco S.p.A. (31%) and the Canadian Bearing Lithium Corp. (18%).

[10] According to USGS (2022), world lithium production was around 430 thousand tons of LCE in 2021. That year, Chile provided around 26% of that total production. The Maricunga project will produce 18 thousand tons, when at full capacity, increasing the Chilean global supply share by up to 30%.

[11] The data and excel model can be available under request.

tax revenues by the project cash flows. Table I displays a summary of the Maricunga project cashflows. The first column is the company estimations, and the following three columns are own estimations.

Table I. *Comparison of Maricunga's project financial indicators among sources and models' output*

	Company estimations	*Own estimations by model*		
Participants cashflows *(US$ Million NPV 8% real)*	Minera Salar Blanco S.A.	FARI (IMF)	NRGI	ECLAC (UN)[a]
Project pre-tax net cash flow	1 971	1 971	1 970	2 209
Government tax revenues	559	1 370	1 332	1 429
Government share (AETR discounted 8%)	28%	71.5%	67.6%	64.7%
Pre-tax IRR (Project's IRR)*	44.5%	35.1%	35.1%	30.9%
Post-tax IRR (Mining company's IRR)**	39.6%	18.6%	19.5%	19.1%

[a] *Nominal values without inflation effects*

**Project cashflow before taxes and decommissioning fund*

*** Net cashflow after fiscal regime: (Parent company returns excluding loan and related financial costs)*

The Company Minera Salar Blanco S.A. calculations come from their investor reports for 2022.[12] Following the Company's assumptions, all model estimations are based on an average lithium price[13] of US$ 24 000 per ton of LCE (constant 2022 USD) and assume no borrowing funds to leverage initial capital investments.

Table I illustrates the sensitivity of the project's financial results subject to methodological differences and data assumptions. The NRGI is derived from the FARI model, so both have a very similar structure, and the main differences lie in how the models treat the variable royalty rule, tax refunding (VAT), and depreciation schedules. The ECLAC model has a more robust assessment of the Chilean tax system and depreciation estimations. However, it only allows estimations for a 40-year period, does not assume equity and leverage shares, and all values are nominal without inflation effects. The FARI model considers carbon taxes and allows plugging other Pigouvian taxes into the analysis. Therefore, the rest of the estimates presented in sections 3 and 4 are based on the FARI model.

Decommissioning costs are another important source of difference in estimates. The Company does not present a plan to stabilize and rehabilitate the exploitation and production area after the mining closure. Therefore, it does not recognize the associated decommissioning costs. Financial management of closure costs and provisions affects capital, financial costs, and tax payments. For illustrative purposes, this study considers a decommissioning cost of US$33 million distributed over the last three years of operation.

Waste is a critical source of environmental damage since lithium extraction is chemical-intensive and generates large volumes of water and solid waste. However, the Company does not present information on recovery rates or a waste management plan. They only mention that solid waste will be sent by trucks to discard piles, and it will be handled following the current regulations of Chile. Such rules apply to copper waste and tailing management but not to lithium.

The lack of disclosed information and limited scientific knowledge makes it problematic to assess the entire lifecycle environmental impact of lithium mining. Due to practical limitations, this study focuses on environmental impacts related to ecosystem damage and direct carbon emissions from lithium production.

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[12] The data used for this exercise comes from the investor's reports of the Lithium International available at their website https://lithiumpowerinternational.com/maricunga-chile/, consulted on January, 2023.

[13] According to the USGS Mineral commodity Survey (2023), the estimated lithium price per metric ton of LCE is US$ 37 000 during 2022. According to the Central Bank of Chile, the average lithium price received from lithium exports during the first semester of 2022 has been US$ 49 000 per ton and it is expected to observe an average of US$ 24 000 per ton by the end of 2022. (cf. Indicadores de Comercio Exterior segundo trimestre 2022, consulted on February, 2023.

2.1. Pigouvian taxes for ecosystems damages

Without any conservation policy, lithium mining may destroy overlapping ecosystems. A way to minimize wetlands damage can be by imposing a tax that deaccelerate mineral extraction paths and reduces environmental damage (Roa et al., 2023). This section presents the tax base and rates of Pigouvian taxes for ecosystem damages.

Maricunga is one of the highest ore grades mining sites at current lithium prices, holding the second-largest lithium reserves after Atacama (Figure 2). Among seven salt flats in Chile where lithium has been discovered, Maricunga is the third largest wetland size. Economic rents, wetland size, ecosystem values, and damage levels are all important factors in determining the corresponding Pigouvian tax rate to compensate for ecological damages (Roa et al., 2023).[14]

Figure 2. ***Mineral revenues, ecosystem size and ecosystem values in seven salt flats in Chile***

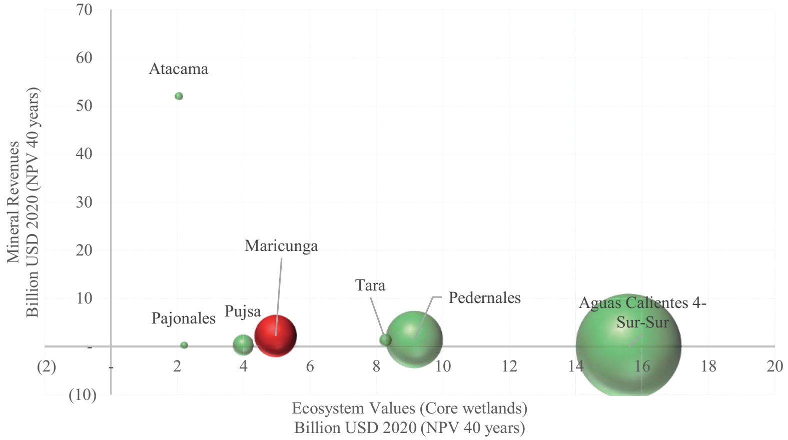

Table II shows how taxes for ecosystem damages in Maricunga vary with wetland size, ecosystem values, and damage level.[15] Estimations are based on Roa et al. (2023).

Table II. *Tax levels and rates by wetland size and ecosystems values and damages (USD per Ton and % of lithium price)**

Wetland coverage	*Average tax*	*Tax for high ecosystem damage*	*Tax for high ecosystems values*
Core (small)	197 (1.2%)	300 (1.8%)	430 (2.5%)
Semi-periphery (medium)	380 (2.2%)	570 (3.4%)	830 (4.9%)
Periphery (large)	650 (3.8%)	980 (5.8%)	1430 (8.4%)

** Estimations are presented by wetland coverage in USD per ton of lithium produced and as a lithium price percentage (current 2021 US 17 000 per ton). According to the USGS survey, during the last eight (8) years, around US$ 12 000 per ton, with a minimum of US$ 6000 per ton and a maximum of US$17 000.*

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[14] In Chile, the largest reserves of lithium are placed in the Atacama salt flat where two companies have been producing lithium during the last decade. The second largest lithium reserves are in the Maricunga salt flat where other companies are preparing to starting lithium production in 2023.

[15] According to De la Fuente (2021), wetlands dynamics in the High Andean Chile depends on seasonal evaporation and precipitation rates and groundwater recharging. Wetlands' size can be distinguished between areas that are not covered less than 16%, 50%, and 84% of the time. The former category (16%) only includes areas covered with vegetation or water most of the time (84% or more) and can be thought of as the core of the wetland. The latter category (84%) includes a much larger *peripheric* wetland sporadically covered with vegetation or water (but at least 16% of the time).

Table II shows that the tax range goes from 1.2% to 8.4% of the lithium price, depending on assumptions about the wetland coverage, ecosystem values, and damages. These rates are comparable to the estimations by Tost et al. (2020), who assume that the cost of ecosystem damage can be passed on to consumers through higher mineral prices. Such prices can increase between 0.8% and 7.9%. In the analysis in sections 3 and 4, I use only the minimum (1.2%) and maximum (8.4%) tax rates to show the fiscal implications of environmental taxes. The behavioral responses to low and high environmental taxes are presented in Section 4.2. and 4.3., and the effects on revenues in section 4.4.

2.2. Carbon taxes

In 2019, Chile's total CO2 emissions were the fourth largest in Latin America, after Mexico, Brazil, and Argentina. Considering the emissions per unit of GDP (kg per PPP of GDP), the Chilean economy is the most polluting in the Latin American region.[16] When counting direct and indirect emissions, mining is the third most pollutive sector in Chile, with 20% of the total CO2 emissions, after the transport sector (29%) and industry (37%) (Avilés-Lucero et al., 2021). These estimates reflect how important it is to decarbonize the mining sector and trace the path to decarbonizing one of the largest economies in Latin America.

In Chile, carbon taxes were implemented in 2017, with an average tax rate of US$ 5 per ton of CO2, much below the average social cost of carbon estimated by the Chilean government[17] (US$ 32.6 per ton of CO2) and recommended by consultancy companies (US$ 40 per ton of CO2).[18] By 2020, just two copper companies had paid carbon taxes, which suggests that the majority opted for tax deductions via carbon offsets (Mardones, 2022).

In this analysis, the carbon tax applies to direct emissions from lithium production. In a hypothetical low-tax scenario, the carbon tax is US$ 30 per ton of CO2, with an annual increase of 2% above inflation. In a high tax scenario, the carbon tax is US$ 180 per ton of CO2 and increases by 7% every year (Table III). In the financial model, carbon taxes are deductible for the tax base calculations of corporate income tax (CIT) and resource rent tax (RRT).

Table III *Carbon tax estimations in a low and high carbon tax scenario without any mitigation policy*

	Low Tax		High Tax	
	Yearly	Total during 20 years of operation	Yearly	Total during 20 years of operation
CO2 emissions for diesel combustion (Million Ton CO2 equivalent)	0.052	1.04	0.052	1.04
Carbon tax rate applicable (US $ per ton of CO2)	30	64 (last year)*	180	948 (last year)*
Annual increase above inflation (%)	2%		7%	
Carbon tax as a share of sales revenue (net)	0.69%		7.22%	
Carbon tax as a share of operating costs	3.05%		31.78%	

**Constant US$ 2021 after inflation adjustments*

According to the company investors' report, the project uses diesel to fuel light vehicles, trucks, machinery, and heavy equipment, corresponding to approximately 90 m^3/month of diesel consumption. The machinery includes salt harvest transport trucks, harvested salts handling trucks, and soda ash transport trucks, among others. In the production plant, diesel will be used mainly for steam boilers, and

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[16] Data source is the Climate Watch. 2020. GHG Emissions. Washington, DC: World Resources Institute. Website, consulted on February, 2023.

[17] The Chilean government carbon price estimates are published in the Ministry of Social Development website, consulted in January, 2023.

[18] Deloitte and the Santiago Climate Exchange has published a report called "Radiography 2022: Corporate Vulnerability to Climate Change of the 100 largest companies in Chile" published at the Santiago Climate Exchange, SCX Website, consulted on February, 2023.

the diesel consumption is estimated at 1500 m^3/ month. Table III above presents the estimations of direct CO2 emissions (scope 1) after applying the corresponding energy combustion factors. The respective carbon tax during the total operational period (20 years) is assessed as a share of net sales and operational costs and deducted from the tax base to calculate income (profit) taxes.

The Company's diesel consumption in the production plant is the major component of operational expenses (about US$ 13 million per year), representing over 20% of the project's estimated cash operating costs. Table III shows that if a low carbon tax is implemented, the energy and emissions expenses will increase from 20% to 23.05%. With a high carbon tax, those expenses can go up from 20% to 52% during the entire operation period. These are a maximum estimate of the Company's expenses for the carbon tax, assuming that the Company does not take action to reduce its emissions. See section 4.3. for an alternative scenario when mitigation strategies take place.

3. Fiscal regimes among lithium-producing countries

The first part of this section briefly describes the evolution of the Chilean tax system in the lithium industry during the last two decades and compares their tax regime with other countries in the region. The rest of this section analyzes how environmental taxes affect the tax system in terms of progressivity, simplicity, neutrality, and reliability at low-profit levels.

3.1. Tax burden and mineral price gaps

Before discussing the fiscal implications of environmental taxes, it is essential to look at how the Chilean taxes on the mining industry have reached the current level. Since the 2000s, Chile has signed contracts with private companies to explore and exploit lithium resources. Therefore, the profits from mineral production have been absorbed mainly through taxes and not through ownership participation. As a rule, the Chilean mining fiscal regime's goal has been two-fold: (i) attracting foreign investments and (ii) maximizing government revenue over the project lifetime. The first goal reveals concerns about the country's sensitivity to international competition. The second goal explains why the Chilean government has taken advantage of the mineral prices' super cycles to increase the tax burden and secure an early and timely source of revenue.

In 2006, after a steady increase in copper prices, the Chilean government implemented tax reforms in the mining sector and applied a resource rent tax (RRT). Later, the government raised tax rates again in all sectors to cover the emergency of the 2010 earthquake. In 2018, the government negotiated new lithium contracts introducing variable royalties based on prices. More recently, the pandemic induced a temporary reduction in corporate tax -CIT- from 27% to 10% to encourage employment and new investments. This reduction was offset by a higher royalty rate that increased with higher mineral prices.

Figure 3 shows the average effective tax rate (AETR) evolution compared to lithium market prices. The AETR is the government's share of a project's pre-tax profits over its lifetime. The estimates consider observed mineral prices for each year and assume that all other cost variables do not change, i.e., *ceteris paribus*. Therefore, the increases in AETR reflect both an increase in the price and the changes to the actual tax terms. At current tax terms, and with an estimated lithium price of USD 37 000 per ton of lithium carbonate equivalent -LCE- for 2022, the undiscounted AETR in the Chilean lithium sector is 62.3%. At the time of this publication, the Chilean Parliament is discussing an additional 3% (flat) royalty in the mining sector, which could result in an even higher AETR.

Figure 3. Tax regime (AETR) changes due to changes in lithium price and tax terms

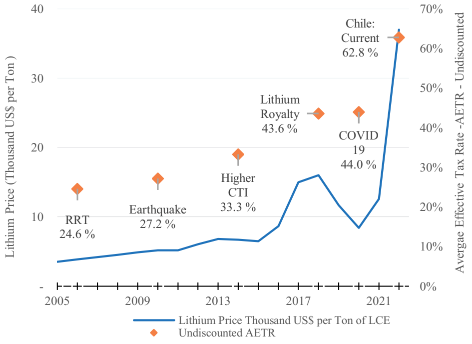

Figure 4. Chilean lithium exports and the difference in lithium market prices and export prices

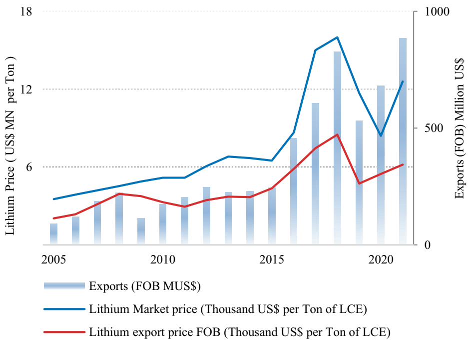

Figure 3. *Lithium prices are annual average-nominal, battery-grade lithium carbonate dollars per metric ton published by USGS (2023). See Appendix 1, Table 1 for more details of the current Chilean mining fiscal regime.* ***Figure 4.*** *For fiscal model evaluation, it may not be necessary to differentiate between production and actual sales or exports. Lithium export data are in LCE units from Cochilco (2022). Lithium export prices (FOB) come from dividing export values in FOB (MUS$) by total lithium production in metric tons of lithium carbonate.*

Figure 4 shows that the prices of Chilean exports are significantly lower than the market prices reported by the USGS each year.[19] Export prices are the companies' sales or book value reported in invoices or export declarations (FOB value). What is interesting about the data in Figure 4 is that the higher the lithium market price, the higher its difference with respect to export (FOB) prices. When comparing Figures 3 and 4, it is possible to notice that despite a sharp increase in lithium market prices and tax rates, the companies' sales (export) prices increase less.

Lithium is an example of a market with incomplete information. Market price opacity can be seen by the fact that lithium is not traded in major stock markets and, therefore, does not have spot prices or future contracts, which makes it difficult to predict and compare prices. The absence of lithium commodities in stock markets also reinforces market concentration in a few highly diversified multinationals.[20] Preliminary research by Jorrat (2022) suggests that the lithium price disparity is due to transfer pricing. Transfer pricing occurs when companies underreport the quantity, quality, or market value of the product or fail to declare valuable by-products. If mining companies intentionally understate market prices and project revenues that affect profit-based taxes, this practice is known as transfer mispricing. See a further discussion on this topic in section 5.

3.1.1. Tax effects on foreign investments and international coordination

On the question of tax burden and foreign investments, a high AETR in the Chilean lithium sector, too far above those available in other countries, create concerns about discouraging foreign investments. Figure 5 shows that the current tax burden in Chile is higher among the peer group and will be even higher if (low) environmental taxes are implemented (See section 4.2. for details on environmental tax levels). At first sight, it can make Chile less competitive in attracting exploration investments and more exposed to tax minimization, e.g., inflating costs and sending profits abroad to subsidiaries in low-tax jurisdictions.

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[19] The same trend has been observed in Argentina, where export prices are in average 58% lower than the market prices reported by the USGS (cf. Jorrat, 2021, page 40).

[20] In Chile, the two leading lithium companies are Albemarle and SQM. The former owns lithium brine operations in Chile, USA and Australia. The later, SQM has primary business in Chile and has expanded operations to Australia and Argentina. Both companies have a long worldwide chain of corporate sales.

Figure 5. ***Average Effective Tax Rates – AETR- Country and lithium mining sector***

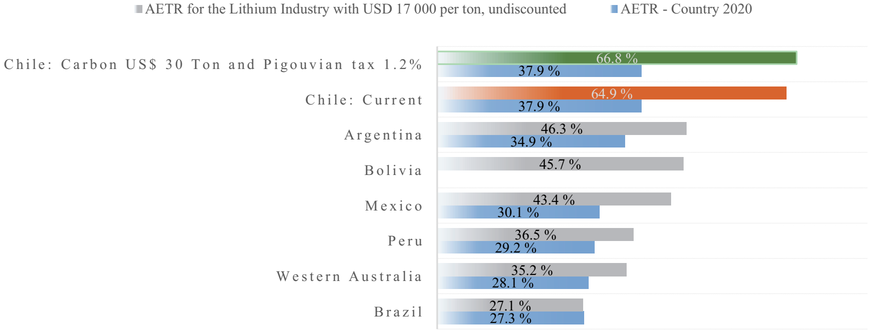

Figure 5. Fiscal regimes can be compared with international peers considering that investment projects (price, cost, production level) are the same as in the Maricunga project. Thus, the project's Pre-tax IRR and NPV will remain the same across countries and scenarios. However, the government share and AETR will change among countries and tax regimes. The lithium industry AETR 2022 was estimated with a nominal lithium price of US$ 17 000 per ton of LCE. The country AETR 2020 comes from the OECD Statistics database. There is no available information about the country AETR for Bolivia.

Using the AERT as a proxy of competitiveness should be viewed with caution because the choice of price and cost assumptions, including depreciation schedules, debt, and equity assumptions, heavily influences the AERT.[21] Thus, to analyze countries' competitiveness and attractiveness to investors, it is important to consider tax and non-tax factors along with other metrics. For example, Chile's lithium resources are highly profitable because of relatively high ore grades and low extraction costs.[22] Besides, Chile has been one of the most prosperous and stable economies in Latin America, which is also an essential factor for risk assessments. However, any additional tax, whether a new royalty or a relatively low environmental tax, will increase the mining sector tax burden and open the door to detrimental effects on investment decisions. Such trade-offs open two questions: (i) to what extent is it necessary for international coordination to tax the lithium sector? Moreover, (ii) how can governments tax the environmental impact of mining without exacerbating the possible disadvantages of their fiscal regimes?

Regarding international coordination to tax profits, persistent tax risks have justified the possibility of applying a global minimum corporate tax rate (of least 15%) (Delis et al., 2022; OECD, 2022). Research has shown that neither Chile nor neighboring countries need to engage in harmful tax competition because there is no evidence of geographical spillover effects after changing the Chilean mining tax system (Castillo, 2021). However, little is known about the additional implications of a global minimum corporate tax rate in the mining industry.

Regarding environmental policy coordination, it is common knowledge that carbon emissions are a global externality with widespread damage, and collective and harmonized action is urgent. Implementing a global carbon tax in the mining industry is, in theory, feasible as mining products have a high value per ton of CO^2 emissions and would be less financially impacted by additional carbon taxes than other industries (Cox et al., 2022). In contrast to carbon emissions, the ecological impact of mining is local and

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[21] The estimations also vary by model type. For example, the FARI model allows us to consider whether the Value Added Tax applies from exploration or further production and the effects of refunding delays. When considering VAT refunding options and levies breaks, the AETR decreases considerably.

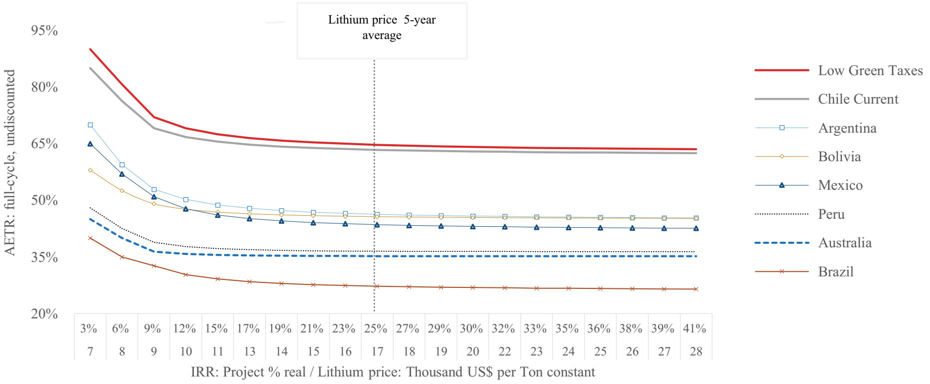
[22] According to the Frazer Institute (2021), many investment decisions are often based on the project's pure mineral potential. In line with that, Chile offers the greatest geological attractiveness among the Latin American lithium producers on top of its competitors Bolivia, Argentina, and Peru. (Junis, J., & Aliakbari, E. (2022). *Fraser Institute Annual Survey of Mining Companies 2021*. https://www.fraserinstitute.org/sites/default/files/annual-survey-of-mining-companies-2021.pdf).

context-dependent, and Pigouvian taxes can slow down production and reduce profitability (Roa et al., 2022). However, lithium reserves in Latin America comprise Argentina, Bolivia, and Chile, a region known as the Andean Altiplano Puna, which ecosystems are deeply connected by underground hydrological systems whose geographic boundaries do not correspond to the geopolitical ones (García-Sanz et al., 2021). Therefore, ecosystem taxes may have environmental benefits not only for Chile but for the Andean region as well.

3.2. Progressivity as profits change

This section discusses how environmental taxes affect the tax system's progressivity and how it compares with other countries' tax regimes. In a progressive tax regime, the government's share of revenue is smaller when profits are low and larger when profits are high. Figure 6 below shows how the AETR representing the government's share of revenue, varies with profitability in terms of the pre-tax internal rate of return (IRR) (which again varies with the lithium price levels). In this study, all countries provide similar conditions (extraction cost, production schedules) to develop a lithium project like Maricunga. Thus, the cash flows and pre-tax returns (IRR) of the projects are identical among countries, and the differences lie in their tax regimes.

Figure 6. ***Progressivity analysis across a range of lithium prices***



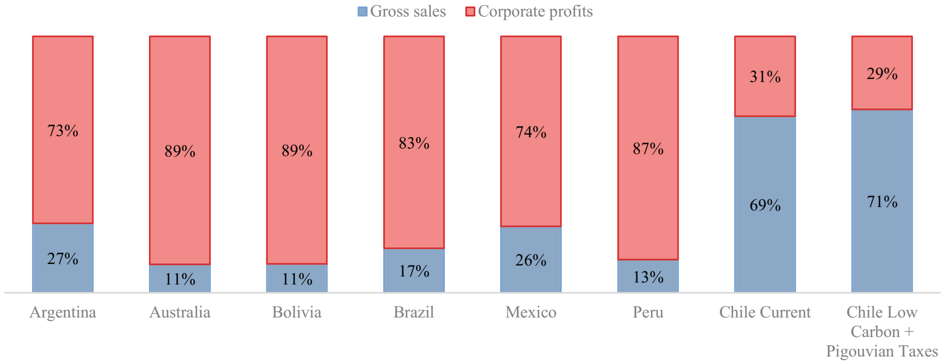
Lithium prices have skyrocketed recently, rising from US$ 6000 in 2012 to US$ 37000 in 2022. Increasing mineral demand can sustain high lithium prices. However, as discussed in section 3.1, the opacity of market prices adds uncertainty to profit levels, making it difficult to anticipate the tax system's progressivity.

In all cases, the progressivity or regressivity level can be defined by the sensitivity of the AETR with respect to changes in mineral prices. That sensitivity level will depend on the price threshold that we consider in the analysis. The average lithium price over the last five years is US$ 17000. Below that price, the Chilean AETR curve extends downward, suggesting that the tax system is more regressive to low mineral prices, especially after introducing environmental taxes. What is striking among the different tax systems is that the higher the AETR, the more sensitive to low mineral prices. These estimates consider that profit margins vary with changing prices and constant extraction costs. However, in practice, extraction costs can increase due to higher energy and operational costs or when the mine operations get deeper, and lithium becomes more difficult to extract.

3.2. Simplicity and tax bases

Increasing profit taxes (like withholding and corporate income taxes) increases the difficulty of measuring tax bases. In Chile, tax bases and rates for the mining industry have become more challenging to measure, and tax regulations have been circumvented by the companies' sophisticated tax planning practices (Bustos et al., 2022). However, despite the high tax levels and mounting tax planning, the Chilean lithium tax system is apparently simpler among its peer countries because it relies mainly on gross sales tax bases. Figure 7 below shows the proportion of taxes based on profitability (in red) and gross sales (in blue).

Figure 7. ***The proportion of government revenues by tax type and tax base simplicity across countries and fiscal regimes****



**The last scenario considers a Carbon tax of USD 30 per CO2 ton and a Pigouvian tax for ecosystem damages of 1.2%*

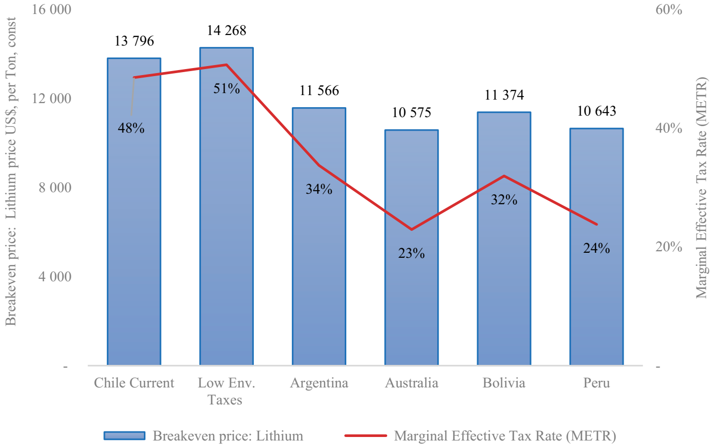
The simplicity of the tax bases is, therefore, essential when designing a new tax, like royalties or environmental taxes. Pigouvian and carbon taxes are not related to the project's profitability but to production and input intensity. As shown in Figure 7 above, environmental taxes would increase the proportion of revenues from a gross sales tax base, but this does not necessarily mean an increase in the tax system's simplicity.

Measuring carbon taxes has become, to some extent, easier to calculate as more tools and calculation standards become available. In contrast, Pigouvian taxes for ecosystem damages depend on the context and require a comprehensive assessment of ecosystem dynamics. Moreover, implementing and enforcing environmental taxes require monitoring of mining activities on the ground and implies coordination with environmental institutions, which could add transaction costs and make the tax system less simple.

3.4. Neutrality on new investments

Neutrality refers to the tax cost of investing an additional dollar to increase mineral extraction. It is, therefore, an essential criterion for attracting new investments. One indicator of the tax system neutrality is the marginal effective tax rate (METR). The METR is the proportion of pre-tax profits on the marginal unit of production taxed. According to Figure 8 below, the Chilean fiscal regime has a higher METR than other lithium-producing countries, which can be seen as a disincentive for new investments to expand lithium production in Chile. The reason is the large proportion of taxes on gross sales that do not consider capital and financial costs. Therefore, the simplicity of the tax system opposes its neutrality.

Figure 8. ***Marginal effective tax rate (METR) and breakeven mineral price***

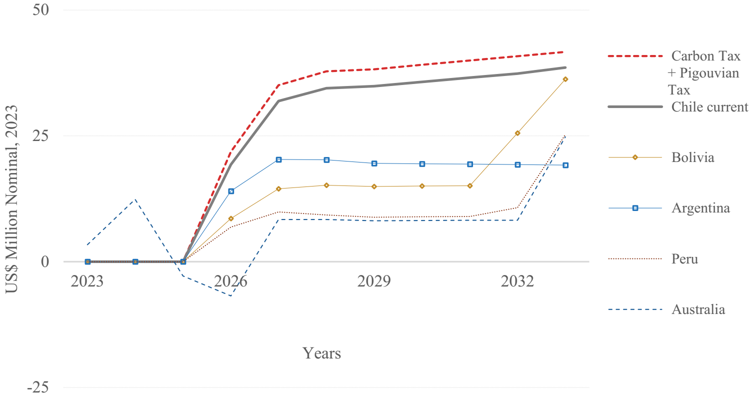


A complementary indicator to the METR is the breakeven price which represents the minimum price needed to yield a specific post-tax return on capital over the project's entire lifecycle. As shown in Figure 8 above, a new lithium project is viable in any of the lithium-producing countries because the breakeven price of all countries is below the reference price of US$ 17 000 per ton. Suppose Chile implements low environmental taxes, and new investments are needed to increase lithium production. In that case, the tax system will impose additional constraints (higher MERT and breakeven price) compared to its peer countries. Therefore, once environmental taxes are applied, the decision to invest and increase lithium production has additional (capital and tax) costs. Likewise, businesses with environmental tax costs are more susceptible to low lithium prices (below US$14 268 dollars) than their counterparts without such taxes.

3.5. Reliability at low-profit levels

Governments whose budgets are heavily dependent on the mining sector often favor regimes that generate at least a certain amount of government revenue each year, regardless of whether the mines generate profit. Like most mining projects, a new lithium project will generate limited or no profit in its first few years of development. In these years, the public revenue collected in the project's early years can give an idea of the regime's ability to generate revenue at a low or zero profit level. Figure 9 below shows how the government revenues profile follows the project cash flow and production schedule. According to the mining company Minera Salar Blanco (2022), lithium production in Maricunga will double in the second year of production and will gradually ramp up. See vary with hydrological conditions.

Figure 9. ***Government revenues profile during the first ten years of operations***



As mentioned in section 3.2., this study assumes that all countries have the same production schedules and cost conditions to develop a lithium project like Maricunga. For illustrative purposes, in all cases, taxes begin when production starts (in 2026) except for Australia. In this country, the government will secure early revenues, despite zero or no profits during the development phase. However, once production begins, and project earnings are positive, government revenues will be negative due to tax credits from past negative financial results. In Chile, a new royalty or a relatively low carbon or environmental tax does not prevent the mine from operating. Furthermore, suppose Pigouvian taxes do not provide sufficient incentives to mitigate damages. In that case, additional environmental taxes will increase overall government revenues, even at low-profit levels during the early years of production.

4. Alternative scenarios for Chile

This section describes the alternative scenarios for the Chilean tax regime, which include a new royalty of 3%; and the implementation of low and high environmental taxes, with and without mitigation policies. Table IV below summarizes the assumptions used to simulate these scenarios.

Table IV. *Alternative scenarios and main assumptions*

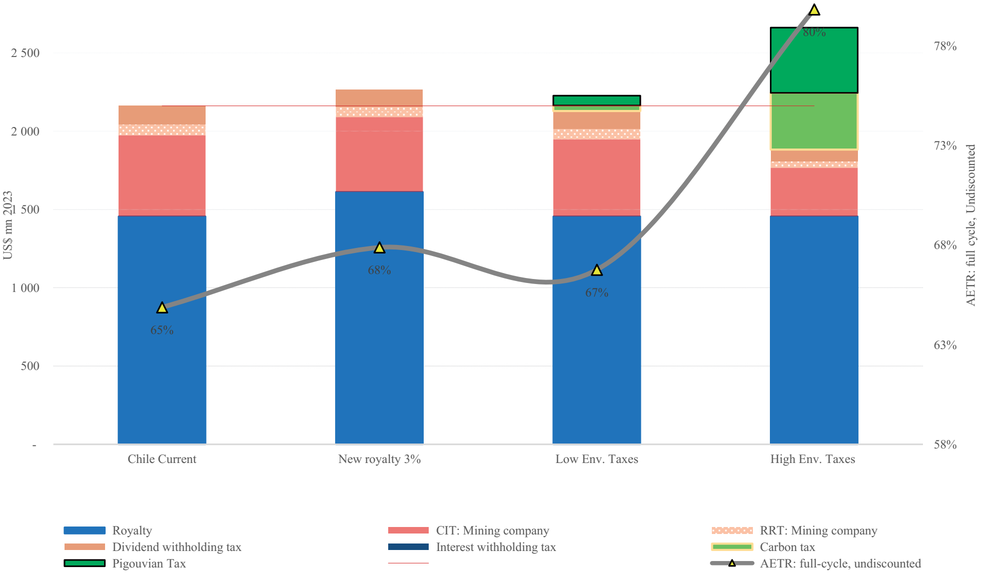
	Chile Current	*New Royalty 3%*	*Low Environmental Taxes*	*High Environmental Taxes*
Pigouvian (Ecosystem) tax rate	0%	0%	1.2%	8%
Carbon tax	0	0	US$ 30 ton of CO2	US$ 180 ton of CO2
*Royalty rate**	Variable	Variable plus a flat rate of 3%	Variable	Variable

** See Tables X and XI in the Appendix for more details about the price-variable royalty rate and profit taxes.*

4.1. New royalty

Amid the current mining boost and following the principle of revenue maximization, Chile aims to increase the public share of resources revenues by introducing an additional royalty tax of 3% on gross sales. The royalty will be new for the copper mining sector, which tax base has relied mostly on profits. Meanwhile, for the lithium sector, the royalty reform will add a flat rate to the current price-variable royalty. The proposal does not dismantle the previous special tax, resource rent tax, or variable royalty tax for the lithium sector. Thus, it is expected that the legislation might declare a hybrid tax model with both the new royalty and previous taxes. Still, many Chilean scholars consider that any additional taxes should be implemented only after the mining sector has improved its transparency. They also argue that a new tax system should encourage exporting more added-value materials, such as cathodes, instead of refined and unwrought minerals.[23]

Figure 10. ***Chilean government revenues under alternative regimes without environmental mitigation policies****



** In this financial analysis, royalties and Pigouvian taxes are deducted from the tax base to calculate corporate income tax (CIT) and resource rent taxes (RRT).*

From Figure 10 above, we can see that the new royalty elevates the tax burden (AETR increases from 63% to 66%). Since the project's overall profitability does not change, that additional government revenue will reduce private benefits (Figure 11). The new royalty scheme can potentially capture a greater proportion of the total value of Chilean resources, which is particularly beneficial during long-term high mineral prices. However, the royalty is regressive as it does not adequately address the costs of staying in business with depressed mineral prices.

4.2. Low environmental taxes

Carbon taxes are a form of Pigouvian tax. However, it is not the economic damages caused by emissions that determine the cost of carbon, but rather the cost of reaching a climate target. In a scenario where the government responds to environmental concerns with modest goals on emissions reduction, a starting point can be to incorporate a low carbon tax (US$ 30 per ton CO2). Notice that carbon taxes are applied to (fossil) energy inputs and are deducted from the tax base to calculate income (profit) taxes.

If carbon taxes exceed the marginal costs of reducing CO2 emissions, companies may reduce their direct emissions. Thus, it is important to know the relative costs of fossil energy compared to renewable energy. Table V below shows carbon emissions and carbon tax payments with low and high taxes. Such emissions will decrease if companies have incentives to invest in renewable energy, because of high carbon taxes or high diesel prices.

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[23] cf. an analysis by Luis Felipe Orellana, ¿El royalty minero acabará con la inversión? published in this Website, on May, 2021.

In a low-tax scenario, companies will not have incentives to reduce emissions because replacing their energy source during the first year can exceed the corresponding (low) carbon tax expenses during twenty years of operation (Table V). In an alternative scenario with a higher carbon tax, companies may have better incentives to look for renewable energy, but that will greatly depend on diesel prices relative to renewable energy prices, including installation and maintenance costs of low-carbon technologies. Table V below shows the diesel and carbon tax expenses compared to the cost of using wind power in the production plan. It disregards the cost of electrifying the transport fleet. Only a small share of diesel (6%) is used from transportation – the very large share (94%) is used for electricity generation.

Table V. *Carbon tax estimations in low and high carbon tax expenses compared to renewable energy costs.*

	Low Tax		**High tax no renewable energy investments**		**High tax WITH renewable energy investments**	
	First year of operation	Total during 20 years of operation	First year of operation	Total during 20 years of operation	First year of operation	Total during 20 years of operation
CO2 Emissions for diesel combustion (Tons)						
Transport	2 949	58 980	2 949	58 980	2 949	58 980
Production Plant	49 148	**982 960**	49 148	**982 960**	49 148	**217696**
Carbon Tax Payments (US$ Million Nominal 2023)	$1,6	$36	$9,4	$362	$9,4	$76
Carbon tax as a share of sales revenue (net)	0.69%		7.22%		1.1%	
Carbon tax as a share of operating costs	3.05%		31.78%		5.2%	

Emissions avoided by ONE wind turbine (metric tons CO2/year/wind turbine installed)	**3 679*** (7% of total annual emissions)	
Cost of Wind turbines installation, operation, and maintenance	$5 Million per wind turbine**	$70 Million for 14 wind turbines to operate the production plant
Costs of diesel (US$ Million) [†]	$ 12.5 Million per year	$ 250 Million during 20 years of operation

* Estimations based on the conversion factors used in the GHG emissions calculator by the United States Environmental Protection Agency https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results

** Source: Weather Guard Wind, costs in 2021. Including maintenance costs.

[†] Estimations based on the Company's investors report (January 2022) data with diesel price was $ 2.5. By March 2023, that price has doubled.

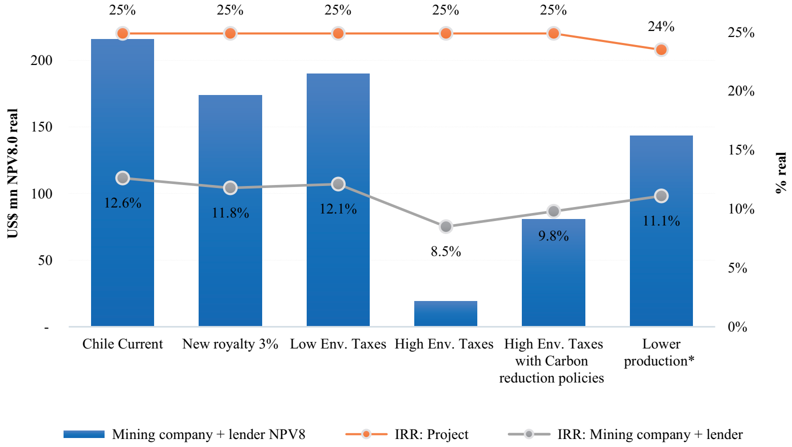
Regarding Pigouvian taxes for ecosystem damages, if these taxes were designed based on competing uses of landscapes for lithium mining versus ecosystem values per area, the first way to reduce ecological damage would be to reduce the amount of land extracted, thereby reducing production. According to Roa et al. (2023), without any intervention, between 5 and 35 hectares of Maricunga's wetland landscape can disappear during 20 years of the mining operation. Their study also suggests that in case the government enforces a low Pigouvian tax (1.2%), that additional cost will constrain the Company to cut five thousand tons (1.43%) of the total accumulated lithium production in 20 years of mining operations. The measure will likely result in the protection of 0.07 hectares of the core wetland during the entire period of mining operations.

In principle, the additional Pigouvian tax cost will discourage the project from getting too large. Although low environmental taxes will increase the tax burden (AETR increases from 63% to 65%), it does not affect private benefits to a significant degree, not as much as a royalty could do it. Figure 11 below shows how investors' NPV and post-tax IRR will change under alternative tax regimes.

Usually, any IRR above the discount rate will make the project feasible. In this study, both government and investors assume a discount rate of 8%. However, it is generally accepted that social discount rates are lower than private return rates. According to Lopez (2008), the social discount rate for the Chilean economy would be in the range of 3% and 5%, considering past economic performance and an investment horizon between 10 to 25 years. On the other hand, investors may have a different (higher) rate of return from investments, i.e., the hurdle rate. This rate considers capital costs, the country risk involved, the returns of business expansion, and the opportunity cost of similar investments elsewhere. A proxy to the hurdle rate is the weighted average cost of capital (WACC). According to Jorrat (2022), the average

WACC for the lithium mining companies operating in Chile between 2000 and 2019 was 6.6%. The importance of knowing these return rate levels is that if the private (hurdle) discount rate is set too high, this is likely to lead to the false rejection of projects that will aid in social development (Møller-Sneum et al., 2022). In our case study, the project's real post-tax IRR is higher than our hypothetical real discount rate of 8% and even higher than the proxy hurdle rate (6.6%). Therefore, the project is cost-effective in all alternative scenarios (Figure 11).

Figure 11. ***Investors' NPV and IRR under alternative regimes (real discount rate 8%)***



** In this scenario, instead of the Pigouvian tax, the government reduces the project size. A high carbon tax with its subsequent carbon reduction is still applied.*

Thus far, mining companies may have less resistance to low environmental taxes because it does not prevent a lithium mine like Maricunga from operating. However, low environmental taxes do not seem to provide sufficient incentives for companies to reduce damages, nor are they a guarantee that ecological benefits will be realized. So, a remaining question to explore is how high these taxes should be to influence the mining companies' polluting behavior.

4.3. High environmental taxes

This section assesses the tax level necessary to persuade mining companies' behavior to mitigate damages. If decarbonization is a matter of human survival, then the level and path price of carbon prices should be consistent with limiting global average temperatures to 1.5°C. Many international mining companies, including the Chilean lithium company SQM, have made public commitments to carbon neutrality by 2050. However, local authorities remain silent on such targets and on the corresponding mitigation measures.

A discussion about the implications of carbon taxation in the mining industry was presented by Cox et al. (2022), showing that the mining industry would be less affected financially if a global carbon tax were introduced compared to other industries, even if tax level were USD 150 per ton of CO2. Other researchers have concluded that the recommended cost of carbon is USD 180 per ton of CO2 equivalent in 2025, with annual growth of 7.2% (Wangsness & Rosendahl, 2022). This cost of carbon can be applied in a cost-benefit analysis throughout the economy independent of trading system regulations (i.e., European ETS). They also point out that, *a priori,* it seems reasonable for developing countries to have lower CO2 prices than industrialized countries. This may, however, encourage excessive investment in high-emitting projects in developing countries (Íbid, 2022, p. 7). A side note is that the lithium industry is not a local business but an international industry where few multinationals trade commodities at international market prices.

Figure 12 below provides the results of implementing a high carbon tax of USD 180 per CO2 ton, growing 7.2% annually. Without surprise, a high carbon tax will lead to an even higher AETR. If companies do not undertake mitigation policies, high environmental taxes will generate some additional government revenues. Despite meager benefits to investors (Figure 11), a high carbon tax does not prevent the mine from operating. And the mine could emit approximately one million tons of CO2 during twenty years of operation by running their business as usual. If environmental taxes do not deter the industry from harmful behavior, the proposed tax payments are to compensate for damages, not prevent them. Companies may still avoid such payments through tax minimization practices such as transfer mispricing. (See discussion in section 5 below).

Nevertheless, a high carbon tax can greatly exceed the investment cost of renewable energy (Table V above), which provides good reasons to switch to renewable energy sources and reduce emissions. In that case, government revenues from carbon taxes will gradually vanish while the mining site becomes carbon neutral, which can happen before 2050.

Figure 12. ***Chilean government revenues under alternative regimes with and without environmental mitigation policies***

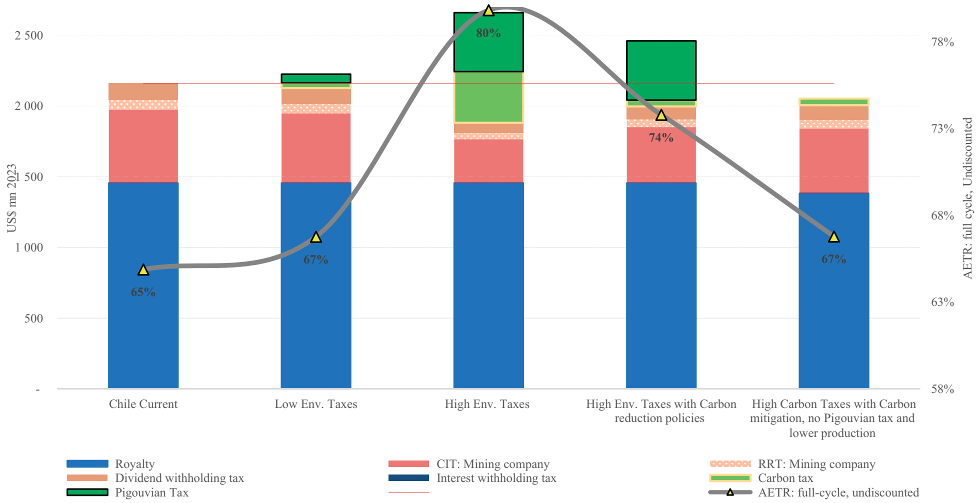


Table VI. *Environmental damage reduction from policy intervention*

Environmental Benefits	Low Env. Taxes – *No mitigation strategies*	High Env. Taxes – *No mitigation strategies*	High Env. Taxes With Carbon Reduction Measures	High Carbon Taxes With Carbon Reduction Measures, No Pigouvian Taxes, And Lower Production (5% less than business as usual)
CO2 Emissions Reduction	0	0	73 %	73 % †
Wetlands Damaged (Hectares-Ha-)	5-35 Ha	5-35 Ha	5-35 Ha	4-30 Ha

† It may vary with production levels, but we assume emissions are related to production plant operations independent of production level.

Regarding ecosystem damage, the ad valorem Pigouvian tax is intended to constrain the project size with additional costs and prevent too much damage to ecosystems. A high Pigouvian tax (8%) will reduce investors' benefits but do not prevent the mine from operating (Figure 11). Therefore, the tax payments will serve to compensate for damages to ecosystems. If the Pigouvian tax could more directly target input levels (i.e., brine extraction), firms might have incentives to reduce damage while maintaining production levels.

If Pigouvian taxes are difficult to implement or are suspected to be ineffective, the only way to prevent ecological damages is to reduce mining projects and leave mineral resources in the ground at the expense of less public and private revenue. Thus, instead of a high Pigouvian tax, the government can reduce the project size from the beginning by, for example, 5% of the total accumulated production. Following Roa et al. (2023), a reduced accumulated production will protect a small wetland area (between 0.1 and 5 Hectares), reducing at the same time project cash flows, mining project profitability, and government revenues (Figure 12). At this point, policymakers are facing a trade-off: hopefully, less environmental damage but less mining revenues.

Figure 12 shows the results of constraining production by 5%. In that case, both public and private benefits from mineral extraction will decrease. Still, according to Roa et al. (2023), within 20 years of operation, with and without taxes, mining will inevitably create some damage to the ecosystem. Table VI presents the damage reduction from each intervention.

Overall, the extent of carbon emissions reduction will depend on tax levels. Low carbon taxes do not necessarily give incentives to undertake mitigation policies. Moreover, carbon taxes have a low financial impact on project profitability. Therefore, it is possible to set a high carbon tax, making investments in renewable energy more attractive. The main implication of high carbon taxes is that they will allow the mining industry to shift to responsible energy substitutes and drive innovation to decarbonize mining operations.

On the other hand, high Pigouvian taxes for ecosystem damage will not necessarily prevent those damage from happening. Still, it will prevent the project from getting too large and guarantee fair compensation for potential damages. Instead of Pigouvian taxes, an alternative will be to reduce the project size. Then, the opportunity cost of preserving ecosystems will be less private and public revenues.

4.4. Revenue management

Concerning revenue management, in the case of Chile, there is little denying that mining has brought considerable economic gains reflected in their macroeconomic indicators and central government budget management (Solimano & Guajardo, 2018).[24] However, the literature suggests that fiscal policy has failed to incorporate local government (Oyarzo & Paredes, 2019). Chile is a highly centralized country, implying that revenues are distributed from the capital city of Santiago de Chile. Decentralization suggests non-uniform provisions that better match the needs and preferences of citizens (Breton, 2002). Nevertheless, a failure of decentralization in tax revenue management may neglect to compensate those directly affected by mining. Most mining damage to water, land use, and ecosystems is localized and unevenly distributed. There is a question, however, as to whether environmental taxes can be effective in strengthening natural resource governance beyond ensuring fair and direct damage compensation.

Environmental taxes provide additional public revenue, but they will vary when mitigation policies are implemented. Table VII. below displays the differences in project returns (Post-tax IRR) and cash flows (Million US$, NPV 8%) and the changes in public revenues under alternative tax reforms. Notice that all alternatives, except at lower environmental taxes, will provide lower Post tax IRRs than the one under the current tax regime (13.8%). Figure 13 shows that in most cases, the additional revenue from environmental taxes is significantly higher than the reduction in project profits. However, the government's additional *net* tax revenue will be proportional to the reduction in profits, i.e., excess tax burden. An exceptional case is the last scenario when companies are forced to reduce production.

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[24] For decades, Chile has shown exceptional mining revenue management. Their strategy includes a fiscal rule, a stabilization fund under a flexible exchange rate, and an inflation-targeting regime (Solimano and Guajardo, 2018).

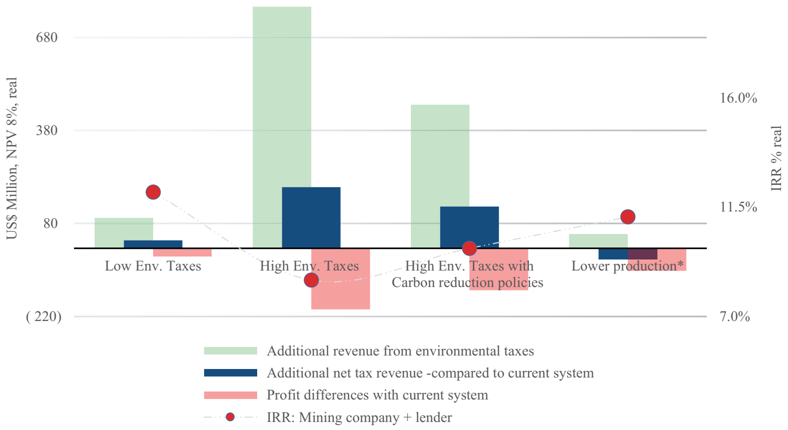
Table VII. *Profit losses and additional tax revenues (US$ Million Nominal, NPV 8%, real) compared to the current tax regime*

	Low Env. Taxes	High Env. Taxes	High Env. Taxes with Carbon reduction policies	High Carbon Tax, mitigation, and lower production
Post-tax IRR (%) *	12.1%	8.5%	9.8%	11.1%
Profit differences with the current system**	(26)	(197)	(135)	(73)
Additional revenue from environmental taxes	98	780	463	46
Additional net tax revenue -compared to the current system	26	197	135	(36)

* *The Post tax IRR* is for the Mining company and lender considering capital costs.***Numbers in brackets mean negative values.*

From Figure 13 below, we can see that the subsequent profit reduction (red bar) is equivalent to the increased net government revenues (blue bar), but these net changes are lower than the environmental tax (green bar). In most cases, the excess burden, or the additional net tax revenue, will equal the profit reduction. Again, the lower production scenario is an exception because the profit loss will double the additional government revenue, and the additional environmental revenue will be marginal.

Figure 13. ***Excess bu***



Regarding the entire mine lifecycle, environmental management can influence decommissioning costs, including closure and remediation expenses at the final stage of mining operations. In the case of the Maricunga project, the financial and technical planning for decommissioning and remediation have yet to be adequately considered. In Chile, a legacy of closed and decommissioned copper mines has secured an environmental debt. To my knowledge, no clear responsible parties or funds are designated for addressing decommissioning issues.[25] Since decommissioning funds management affects the project's net cash flows and related tax provisions, it is therefore important to investigate to what extent how decommissioning funds and environmental taxes payments may interact and determine the best mechanism to administer them.

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[25] Today, there mapped 740 mining tailings, from which 170 are abandoned, 101 are active, and 469 are inactive. Researchers have shown that living near tailings vicinities can result in severe health and environmental problems (F. Campos Medina et al., 2022). The location maps of tailing are publicly available on the Sernageomin website, consulted in January 2023.

5. Transfer mispricing

Companies can reduce their environmental tax payments by adopting mitigation strategies to minimize environmental impacts. However, there is always a possibility of reducing tax payments in non-legitimate ways. As explained in section 3.1., although production and export levels grow following a sharp increase in lithium market prices, a gap exists between lithium market prices and export (sale) prices, suggesting the possibility of transfer pricing. This section extends the analysis of how the effectiveness of environmental taxes can be affected by tax planning practices like transfer pricing.

Multinational enterprises use transfer pricing to determine the prices for the goods, services, and intangibles that are transferred among their subsidiaries. For example, in the mining industry, companies frequently sell minerals in the form of concentrate or mineral compounds to related parties abroad for further processing.[26] To ensure that transfer pricing is fair and reasonable, and that profits are allocated appropriately, the multinational should apply the "arm’s length” principle. According to this principle, in a transaction between two related parties, the agreed price must be the same as the market price in a comparable transaction between two unrelated parties (Readhead, 2016). However, if the parties negotiate that transaction at an artificially lower price with the intention of minimizing their taxes, this fraudulent behavior is considered transfer mispricing.

Transfer mispricing will erode tax bases and reduce government revenues. Production and sale prices can be under-reported by, for example, non-reporting of by-products or by selling minerals to related marketing hubs at a discount.[27] Tax base erosion can also occur when companies over-report project costs by setting illegible costs, [28] inflating goods and services, and debt terms.

During the last decade, the Chilean lithium export sale prices have been on average 40% lower than the market prices (See Figure 4 above).[29] For illustrative purposes, and in line with Jorrat (2022), it is possible to assume that despite all government measures to deal with transfer mispricing, mining companies can still report a sale price 20% lower than the market price.

Table VIII. *Differences in taxes, projects, and government share metrics with a 20% transfer mispricing*

Fiscal regime	Chile current system	Low environmental taxes	High environmental taxes	High env. Taxes and Carbon mitigation	Lower production
Royalty	-29 %	-29 %	-29 %	-29 %	-34%
Carbon tax (input)	0	0	0	0	0
Pigouvian Tax (*ad-valorem*)	0	-20%	-20 %	-20 %	0
CIT: Mining company	-32 %	-33 %	-46 %	-36 %	-35%
RRT: Mining company	-32 %	-33 %	-46 %	-36 %	-35 %
Dividend withholding tax	-30 %	-31 %	-44 %	-34 %	-32 %
Total Revenue Loss	**-29.7%**	**-29.3%**	**-26.2%**	**-28.3%**	**-29.8%**

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[26] Albemarle is the second largest lithium mining firms with mineral resources and conversions plants in Atacama, Chile. The company has also a lithium production plant in Langelsheim, Germany, and laboratories in USA and India. The company itself describes its Chinese headquarters as cost-effective flexible platforms. See albermarle.com/locations. Consulted in January 2023.

[27] Fair taxation requires not only monitoring production, but also applying it to each relevant tax instrument. In Chile, an investigation in 2012 discovered that some companies were paying resource rent tax -RRT- only on minerals extracted from new mines but not on minerals produced from old tailings (cf. Hubert, D., 2017)

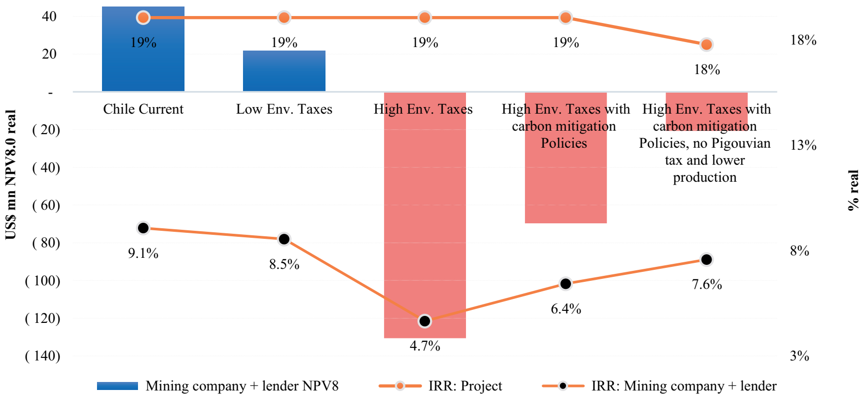
[28] In 2017, the Chilean lithium company SQM paid more than $15 million in criminal penalties for committing tax fraud by claiming non-existent costs and false invoices for transfers to Chilean politicians. (cf. The United States Department of Justice, Office of Public Affairs, Criminal Fraud Section in this link, consulted in January 2023.)

[29] An special parliamentarian commission has raised questions about distrustful transactions between SQM Chile and its affiliates in Europe with sales prices below market prices, both for lithium and its by-products such as potassium, which could result in underreporting tax payments to Chilean government agencies (CORFO), (cf. Comision Investigadora de Litio, Camara de Diputados, Congreso de Chile, Junio 2016)

Table VIII above shows the government revenues implications under transfer mispricing. In the presence of transfer mispricing, royalties will change more than proportionally, given the price-variable royalty rule. What is striking from the results is the large reduction of profit tax payments (e.g., CIT, RRT, and Dividend withholding taxes). The reason is that in the current system case, companies will perform a transfer mispricing twice, first in the royalty tax base, then by deducting mispriced royalties from a lower profit tax base. Notice that carbon tax payments are the only charge not affected by transfer mispricing as it is independent of lithium prices. The carbon tax base depends directly on fossil energy use. Thus, the revenues from carbon taxes are not sensitive to the volatility and transparency of mineral market prices.

In contrast, a Pigouvian tax base similar to an *ad valorem* royalty will vary with mineral market values and be susceptible to transfer mispricing. Therefore, flaws in environmental tax design can also reduce their effectiveness. Moreover, in the presence of transfer mispricing, implementing high environmental taxes would make this mining project unfeasible (Figure 14).[30] Once again, it is important to know more precisely the private hurdle and discount rates because if set too high, they will likely lead to false rejection of projects that will help social development. See Appendix II for additional results with lower discount rates.

Figure 14. ***Changes in Investors' benefits in the presence of transfer mispricing (20%)***



As a standard regulatory measure, it has been suggested that establishing a reference price to calculate royalty and tax payments may be more effective than attempting to ensure actual sales reflect fair market value.[31] Still, for environmental tax purpose, a first-best Pigouvian tax should instead consider the non-market resource values and a tax base that reflect the direct input and damages of resource extraction. A compromise between market value and environmental damage would be to use tons of production as the tax base. So, the tax is more targeted than the market value, and one also avoids the transfer pricing problem. Furthermore, companies can also be incentive to reduce production (brine) inputs without necessarily reducing production output. Future research should assess brine and freshwater's market and non-market value and how underground resource depletion adversely impacts the ecosystem's integrity.

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[30] For 24 years, a Chilean copper mine operated at a loss, accumulating USD $ 575 million in tax credits. The funds that could have been declared as profits were paid to affiliated companies in terms of interest payments to headquarters based in Bermuda (cf. https://www.engineeringnews.co.za/article/chilean-lawmaker-sues-over-coppermine-tax-evasion-2002-09-02/rep_id:4136, consulted in January 2023.)

[31] References prices have been established in the Chilean copper sector. A metric ton of refined copper in Chile is valued by the Chilean Copper Regulator (Cochilco) based on the average value and copper qualities.

With that information available, we can calculate a Pigouvian tax based on the stocks and intrinsic values of brine and freshwater, being less sensitive to lithium market price volatility and transparency.

6. Conclusions

The present study was designed to reveal the obstacles to designing and enforcing environmental taxes in the mining industry. The contribution of this study was to confirm that an environmental tax reform must consider existing and new distortions of the tax system. This research has raised relevant questions about how governments in mineral-rich developing countries can introduce environmental taxes without exacerbating the possible disadvantages of their fiscal regimes.

The industry typically resists the imposition of additional taxes, especially regressive ones. Mineral-dependent governments may also be wary of regressive taxes. Environmental taxes have a regressive component by design because it aims to discourage harmful behavior rather than increasing public revenues. Thereby, it goes against the well-grounded progressivity approach based on revenue maximization. However, a lack of public intervention means the mining industry will continue destroying overlapping ecosystems and contributing to global carbon emissions. Therefore, implementing environmental taxes implies a redefinition of priorities and raises a much-debated question about whether governments should prioritize welfare, in terms of environmental protection, over revenue maximization. Further research must explore how environmental taxes can be an instrument to enhance a more decentralized natural resource governance that better apprehends the needs and citizens' preferences for their natural resource wealth.

Flaws in environmental tax design can reduce its effectiveness. In this study, the Pigouvian tax is similar to an *ad valorem* royalty because it uses revenue from mined ore at market value as the tax base. One problem arising from this assumption is that the Pigouvian tax will vary with the mineral market value, making it sensitive to transfer mispricing and compromising the environmental benefits of the tax. Instead of taxing the mining output, the Pigouvian tax could target the production input directly. For example, taxing the depleted brine input in lithium production can incentivize companies to reduce groundwater extraction without necessarily reducing mineral production. Therefore, a tax more targeted to production inputs than production value will avoid the transfer mispricing problem. Future research should investigate the optimal groundwater brine and mineral recovery rates to produce lithium. These estimations will allow setting control parameters to regulate the impacts of groundwater exploitation. Altogether, measures considering the production methods and inputs of mining operations can increase Pigouvian tax effectiveness.

The choice of tax bases is crucial to determine the simplicity of the tax system and enforcement level. In this study, environmental taxes would increase the portion of revenue calculated from the gross sales tax base. A priori, taxes calculated from gross sales are simpler than taxes on profits, which can slow down the race between government auditing and corporate tax planning. However, assessing the optimal environmental tax rate requires detailed information and a comprehensive record of ecosystem values and estimated damage costs. In addition, environmental taxes require constant monitoring of production and ecological balances, including coordination with environmental institutions. Consequently, environmental taxes add transaction costs and require strengthening enforcement systems.

Environmental tax rates should be high enough to make mitigation measures attractive. In this study, low environmental taxes do not significantly affect profits and do not give companies enough incentives to mitigate damages. In that case, the environmental tax will only guarantee partial compensation for predicted damages. Suppose taxes are difficult to implement or are suspected to be ineffective. In that case, the only way to prevent environmental damage is to reduce mining projects and leave mineral resources in the ground at the expense of less public and private revenue. Nevertheless, suppose governments allow mineral extraction and tax the related environmental impact. In that case, investing and increasing mineral production has additional tax costs, increasing investors' exposure to lower mineral prices.

In this case study, relatively high carbon and Pigouvian taxes do not prevent a lithium mine like Maricunga from operating. With a hypothetical discount rate of 8% and without transfer mispricing, a project like Maricunga will provide reliable public revenues. However, if the private (hurdle) discount rate is set too high, this will likely lead to the false rejection of projects that will aid social development. Moreover, environmental tax payments will increase government revenues without any environmental mitigation policy. Then, the government's additional *net* tax revenue will be proportional to the reduction in private profits. A further study could assess the best mechanism to administer environmental tax revenues alongside decommissioning funds.

One area to improve in this study is the assumptions on alternative energy sources and mitigation policy costs. The decision to invest in renewable energy is susceptible to those assumptions, including variations in diesel prices, affecting our estimates of project profitability and public revenues. In addition, a financial cash flow analysis does not allow us to infer whether environmental taxes bring second dividends to the economy. Further research must consider the welfare and distribution effects of environmental tax reforms in the mining sector. Despite its exploratory nature, this study offers insight into essential control parameters to account for the environmental damage mining and the fiscal effects of environmental taxes at the project level. The study certainly adds to our understanding of why tax systems can be a tool to account for the hidden costs of resource extraction and reinforce environmental regulation.

Although this research focuses on the lithium mining sector in Chile, the findings may well be related to the importance of global coordination to implement environmental taxes. Two main reasons support this argument. First, if a country enforces environmental taxes, that will increase its tax burden. A high tax burden, well above those applied elsewhere, may encourage profit shifting because mining companies can send profits to low-tax countries. Second, the physical boundaries of the High Andean ecosystems do not correspond to the geopolitical ones. Aboveground ecological landscapes are influenced by underground water systems expanding to neighboring countries. So, what happens to the water balance of a salt pant may affect others in one way or another. Thus, ecosystem taxes can bring benefits not only for Chile but for the High Andean region as well.

Mining is portrayed as an environmentally and socially destructive industry, yet it is the primary source of income in many resource-rich developing countries. The mineral boom fueled by low-carbon technologies offers an opportunity to modernize resource-rich nations, but it must be done with proper accountability of mining footprints. A critical political priority should be planning mineral use with a holistic and long-term perspective and undertaking environmental tax reforms to facilitate social and economic transformations fairly and sustainably.

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Appendix I. Fiscal model assumptions

Table IX. *Current Chilean Mining Fiscal regime*

Fiscal instrument	**Tax rate**	**Tax base**	**Other details**	**Legal source**
Royalty	A uniform tax of 3% on the market value of copper, lithium, and any concessible substance.	Gross sales	This measure was approved (May 2022) in the first instance by the Parliament.	Parliamentary bill to be legally enforced.
Resource Rent Tax - RRT-		Taxable income after deducting capital costs (except interest). CIT is deductible	Since 2006, a specific mining tax has been in force in Chile. This tax is applied to profits obtained by a mining firm based on its annual sales level. The tax rate varied between 0.5% to 1,93% for small mining firms whose annual sales were between 12 000 and 50 000 tons of mineral. For bigger companies whose annual sales exceed the value equivalent to 50,000 metric tons of mineral, the tax rate varies between 5% and 14%, depending on the profit margin. The tax rates and bases apply to all concessional metals and minerals produced in Chile.	Tax code
Corporate Income Tax – CIT-	National rate 10-27%	Taxable profits	27% under the general regime and 10% under regime applicable to small and medium-sized companies until 2022, and 25% for 2023 and following.	Tax Code
Withholding tax	35% 4%-35% 0%/ 15%/ 30%	Dividends Interests Royalties	35% of additional withholding income tax applies to branch profits remitted to the head office, with full or partial credit granted for CIT paid, depending on whether the tax head office is in the tax treaty country.	Tax Code

Data source: https://taxsummaries.pwc.com/chile/corporate/withholding-taxes

Table X. *Price-Variable royalty thresholds and marginal rates*

Lithium threshold price		Marginal rate
0	4 000	6.8%
4 000	5 000	8.0%
5 000	6 000	10.0%
6 000	7 000	17.0%
7 000	10 000	25.0%
10 000		40.0%

Source: Jorrat (2022).

Table XI *Fiscal regime assumptions to calculate the Chilean AERT evolution*

	Tax reform - RRT	Earthquake	Tax reform Higher CTI	Royalty CORFO	COVID-19	**Current (2023)**
Royalty rate: (nominal) price-variable				10.00%*	20.00%**	24.5%***
CIT	17%	20%	27%	27%	10%	27%

* The price-variable royalty was calculated with an estimated nominal lithium price in 2006 (US 6 000 per ton of LCE)

** Calculated with an estimated nominal lithium price in 2018 (US 12 000 per ton of LCE)

*** Calculated with the estimated lithium price for 2021 (US 17 000 per ton of LCE), according to the USGS (2022)

***Table XII** Fiscal regime assumptions for peer group*

Regime name	Argentina	Australia	Bolivia	Brazil	Mexico	Peru
Royalty rate (Flat) Tax base: gross revenues Royalty is CIT and RRT deductible	8%	2.5%	3.4%	3%	7.5%	3%
CIT rate	35%	30%	25%	15%	30%	30%
RRT tax rate			13%			1.93%
Dividend withholding tax	7%	5%	13%	10%	10%	5%
Interest withholding tax	12%	5%	13%	15%	1%	4%
VAT	21.00%	10.00%	13.00%	12.00%	16.00%	18.00%

Source: https://taxsummaries.pwc.com/

***Table XIII** Fiscal regime assumptions for alternative scenarios*

Regime name	Chile Current	New Royalty 3%	Low Env. Taxes	High Env. Taxes
CIT rate	27%	27%	27%	27%
RRT rate	5%	5%	5%	5%
Dividend withholding tax	8%	8%	8%	8%
Interest withholding tax	4%	4%	4%	4%

* The price-variable royalty was calculated with an estimated nominal lithium price in 2021 (US 17 000 per ton of LCE)

***Table XIV** Mine profile*

Summary assumptions	units	
Total production (20 years of operation)	Tons	307 000
Average annual production	Tons	13 348
Production starts	year	4
Production life	year	20
Development costs	$m	627
Replacement capital costs (depreciable)	$m	43
Production to DEV CAPEX	units/$m	490
Mineral Price	$/units	24 000
Operating cost per unit	$/units	3 864
Transport and TC/RC	$/units	-
C1 cash cost minus royalties	$/units	3 864
Total C1 cash costs	$/units	8 589
Discount rate (government)	%	8%
Discount rate (investors)	%	8%
Inflation	%	2 %
Real interest rate	%	5%
Leverage (equity/total assets)	%	50 %

Table V below shows the production ramp-up by type of lithium quality, showing that at full capacity, 90% of the production will be battery-grade lithium carbonate and 10% technical-grade lithium carbonate.

Table XV. *Li2CO3 Production ramp-up*

	2026	*2027*	*2028*	*2036*	*2042*	*2045*
Li2CO3 Battery Grade	4200	12000	14850	13050	14400	14940
Li2CO3 Technical grade	4200	3000	1650	1450	1600	1660
Total production per year	8400	15000	16500	14500	16000	16600

Data source: Minera Salar Blanco S.A., Maricunga Project investors' report, January 2022.

Appendix II. Additional results

Figure 15. *Changes in government revenues in the presence of transfer mispricing (20%) and lower discount rates (6% real)*

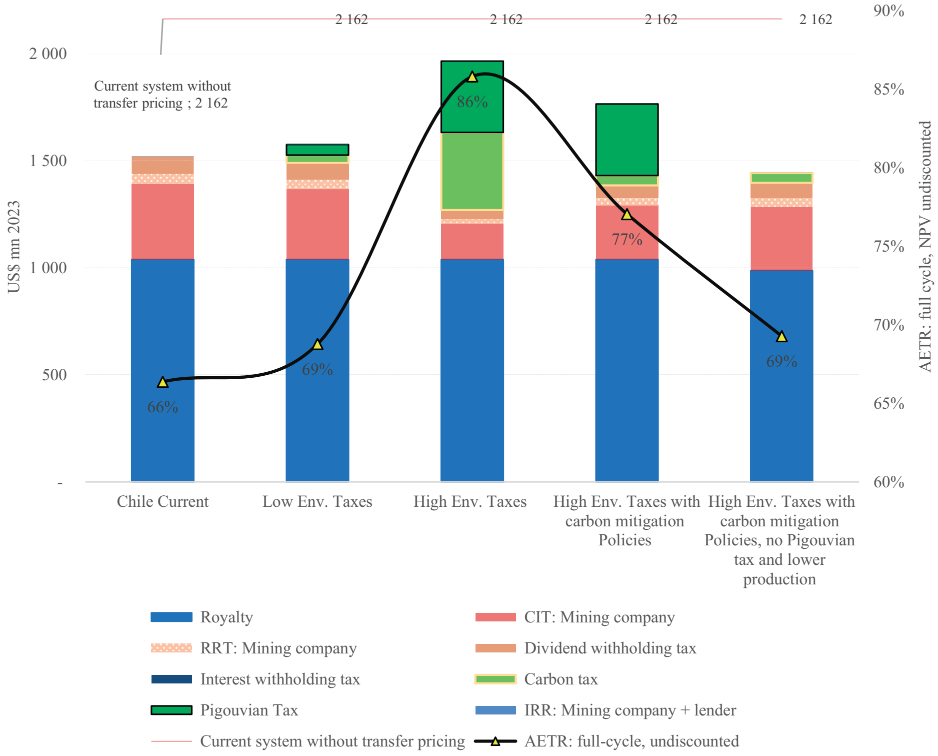
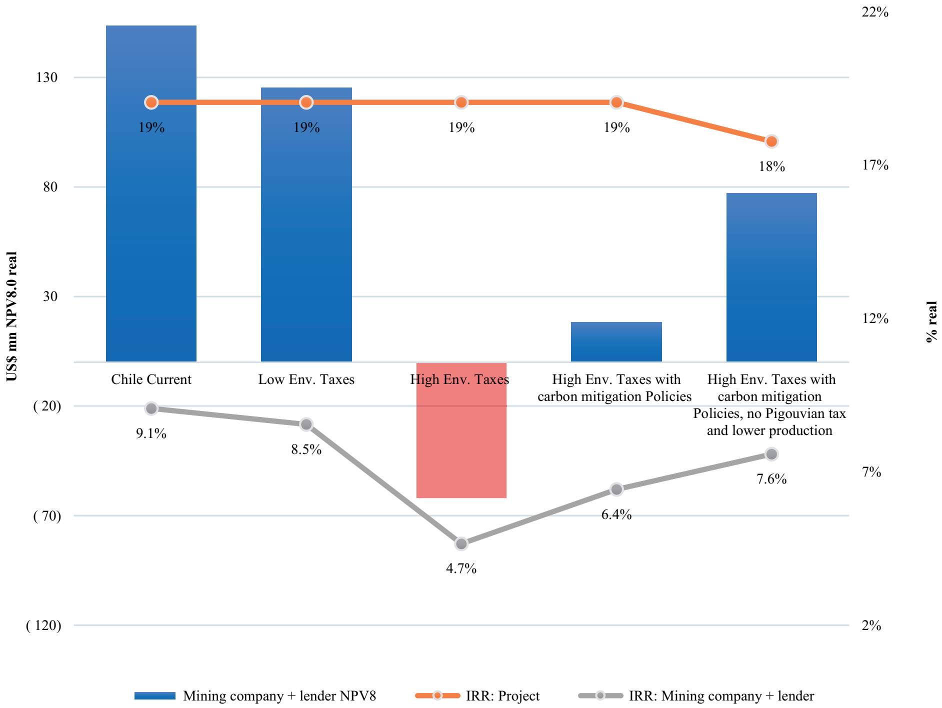


Figure 16. *Changes in Investors' benefits in the presence of 20% transfer mispricing and 6% real discount rate*



Errata List

Abbreviations for different types of corrections:
Cor – correction of language
Cpltf – change of page layout or text format

Page/Line/Footnote	Original text	(Cor) Corrected text
Page 989, Equation (8)	$\dot{L} = y_t - \boldsymbol{\delta} L$	$\dot{L} = y_t - \boldsymbol{\gamma} L$
Page 990, Equation (9), and line 4 in the text	$l_t \leq \boldsymbol{\delta} L$	$l_t \leq \boldsymbol{\gamma} L$
Page 990, line 28	(…) the dynamics of $\dot{\varphi}^c$ depends on the discount and depreciation rates $(r + \boldsymbol{\delta})$	(…) the dynamics of $\dot{\varphi}^c$ depends on the discount and depreciation rates $(r + \boldsymbol{\gamma})$

Diana Roa

Diana Roa was born in Bogotá, Colombia, in 1982. She holds a BSc. Degree in Economics from Externado University of Colombia (2006), a Master of Public Affairs and Policies from SIPA Columbia University NYC and Externado University (2009), and a Master of Industrial Economics and Technology from the Federal University of Rio de Janeiro, UFRJ, Rio de Janeiro, Brazil (2011).

This thesis tackles the sustainable use of minerals in our transition to a low-carbon and digital world. This research is about finding clever ways to make the most of our precious resources at minimal environmental costs. The thesis splits into two parts. The first part takes a deep look at the global mineral market to figure out how we can tackle supply shortages through recycling and how price mechanisms can promote material circularity. The second part explores some of the sustainability trade-offs of mineral development.

By scratching dynamic models and running numerical simulations, Diana's work proves that markets could be better at recognizing the true value of minerals. Still, it might be necessary to provide some incentives to get the most out of scarce minerals and recycle them after use instead of sending them to landfills. The thesis explores the effects of giving subsidies to recyclers while simultaneously dealing with the social costs of used mineral waste. A key finding is that while subsidies are helpful, giving too much money or for too long can create other problems like increased mineral demand and waste and rebound effects.

Diana’s research answers how society can benefit from mineral production while considering the environmental cost -or externalities- of doing it. Despite accurate estimates of the true ecological costs of mining, asymmetric information, and price opacity can undermine environmental tax benefits. Therefore, her work suggests that environmental taxes in the mining sector should target the inputs of mining operations to influence production methods.

Even though this thesis focused mainly on the lithium sector, the research questions, analytical framework, and model simulations can be applied to other mineral industries. The accessibility to these models is an invitation to other students, researchers, and policymakers to replicate these models and apply them across other studies aimed at answering similar or complementary scientific questions.

Associate Professor Knut Einar Rosendahl was Diana’s main supervisor, and Associate Professor Ståle Navrud her co-supervisor.

E-mail: dianarua@icloud.com

School of Economics and Business
Norwegian University of Life Sciences (NMBU)
P.O Box 5003
N-1432 Ås, Norway

Telephone: +47 6496 5700
Telefax: +47 6496 5701
e-mail*: hh@nmbu.no*
http:/www.nmbu.no/hh

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Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no

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