Clean Energy, Material Scarcity and Urban Mining

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The low-carbon economy is a materials economy. Clean energy technologies – essential for the reduction of carbon emissions – require large amounts of critical raw materials. The supply of these critical materials cannot keep up with skyrocketing demand, which may be a roadblock for the current ambitious energy transition plans. In this paper we study two practical approaches that can sustain the clean energy industry’s momentum: (i) Material Reduction, i.e., changes to production technology to reduce the critical materials used; (ii) Urban Mining, i.e., recovering and recycling critical materials from end-of-life clean energy technology products. We show that the effectiveness of these two approaches depends on the levels of material scarcity and systemic leakage in circular infrastructures. A long-term focus on clean energy production favors Urban Mining (Material Reduction) when material scarcity is high (low). Meanwhile, an urban mining strategy is more likely to maintain the profitability of the clean energy industry. Yet, we find that producer incentives to implement these material scarcity mitigation strategies need not align with policy objectives. In turn, subsidizing producers to ease the capital expenditure burden of the urban mining (material reduction) strategy will be necessary when the access to end-of-life products is constrained and material scarcity is high (when material scarcity is moderate).

Key Words: Recycling; Scarcity; Critical Minerals; Closed-Loop Supply Chains; Clean Energy

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1. Introduction

The global energy sector and governments worldwide are rapidly shifting towards clean energy, fueled by the improving economics of clean energy technologies against rising and volatile fossil fuel prices, increasing policy support and “a strong alignment of climate and
energy security goals” (IEA 2023c). Nearly 200 countries pledged to triple their renewable power capacity by 2030 at the COP28 climate conference in Dubai (IEA 2023b), putting pressure on governments to further raise their installation targets.

A low carbon economy, however, is a materials economy. Building clean energy products, such as solar panels, wind turbines, or electric vehicle (EV) batteries, requires significantly more metals and minerals than their fossil-fueled counterparts (Pitron 2020). Wind turbines depend on rare earth elements, batteries require lithium, nickel, and cobalt, and solar panels use indium and silver, among other rare metals and minerals (DOE 2022). Correspondingly, the amount of metals and minerals needed for electricity generation has increased by 50% in the last decade as the share of renewables has risen (IEA 2021). Meeting carbon neutrality goals could lead to a fivefold increase in demand for critical materials for solar PV by 2030. For instance, around 55% of today’s lithium demand is used by clean energy technologies, and this number is expected to grow to 83% by 2030 (IEA 2022a). Yet, the current supply of many critical materials falls short of what is required to expand the clean energy capacity as planned. Supply shortages for many of these minerals in the next decade appear inevitable (IEA 2024), making these energy-critical materials scarce. Rapid solutions to alleviate this scarcity are in general not feasible or guaranteed. For instance, new mines are unlikely in the near term due to long construction lead times that average over 16 years (IEA 2023c), and face opposition due to risks of harm to the environment and communities (Corlin 2023).

The scarcity of critical materials drives up their prices, potentially undermining the economic viability of clean energy adoption. The cost of clean energy products is highly dependent on material prices: years of technological advancements have reduced the overall cost of clean energy products by over 90%, making raw materials a primary component of production costs. For example, raw materials currently account for 50–70% of total battery pack
costs (IEA 2021). In a net-zero emissions scenario, the value of some critical minerals could increase six-fold due to the surge in demand. In 2021, a spike in material prices disrupted the decade-long trend of declining clean energy technology production costs (IEA 2023a).

The geographical concentration of existing critical material supply chains further amplifies the price increases driven by scarcity, and makes them more volatile (IEA 2021). For many critical minerals, a single country accounts for over half of the global production: China extracts over 60% and processes up to 90% of rare earth minerals, where South Africa and the Democratic Republic of the Congo account for 70% of global production of platinum and cobalt, respectively (IEA 2022a). As an illustration, nickel prices rose in 2022 following the Russia-Ukraine war as Russia holds 20% of high-quality nickel supply (Forbes 2022). With rising prices and volatile supplies of raw materials, clean energy producers may face financial constraints, challenging governments to maintain the cost competitiveness of clean energy and reach ambitious installation targets (IMF 2021). In short, material scarcity could hinder the future of clean energy.

In this context, we study two prevalent strategies to address the impact of critical raw material scarcity on the clean energy transition. The first strategy, Material Reduction, comprises incremental efforts for critical material reduction in the design of clean energy products – either by reducing the intensity of critical materials used in production (or improving methods to reduce manufacturing waste), or by replacing them with other, more abundant materials. Material reduction is a prevalent strategy in the clean energy industry, and is proposed in policy circles including the International Energy Agency, World Economic Forum and the European Commission (Pavel et al. 2016, Gielen 2021, World Economic Forum 2024). Some examples include the reduction in the silver content in PV cells (INES 2022) or the cobalt and manganese content in batteries (DOE 2021) through efficiency improvements.
or substitution with other materials. However, these alternatives often entail trade-offs in energy conductivity and manufacturing costs (Petrova 2021, IEA 2022c) – partly substituting the silver in solar panels compromises the solar cell efficiency and the required sophisticated process makes manufacturing more expensive (Chen et al. 2022).

The second strategy, *Urban Mining*, consists of investing in advanced recycling processes and infrastructure that can recover critical materials from end-of-life clean energy products (Gallagher et al. 2019, EC 2022, IEA 2022c). While we use the terms ‘urban mining’ and ‘recycling’ interchangeably in the remainder of the paper, we note that existing recycling approaches for renewable energy technologies (such as PVs and wind turbines) often lack advanced processes required to recover valuable materials from end-of-use clean energy products. For example, from PV panels, one can typically gets bulk materials such as glass shards and aluminium frames\(^1\), but not the critical materials such as silicon and silver. Urban mining is a more refined form of closed-loop supply chain management for recovering value from end-of-use products – demanding investment into a collection ecosystem and advanced recycling processes. The high cost and the infrastructure gap have so far been a barrier against large-scale development for urban mining for renewables. ROSI Solar in France (Beyer 2022) and SolarCycle in the US (Forbes 2023) have begun developing the required processes for urban mining, but the capacities remain very low due to prohibitive capital investments. As of 2022, silicon and silver from crystalline silicon cells (the technology that accounts for 95% of PV panels) were not recovered (Komoto et al. 2022). Photorama is a EU-funded project from 2021 to build a consortium of 13 organizations for large-scale recovery of materials from PV panels, but its pilot line is yet to be built (Photorama 2024). Less than 1% of rare earth

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\(^1\) Around 68% and 15% of the weight of a photovoltaic panel is glass and aluminium, respectively. Their combined weight suffices to cover the targets set by legislation, even the strict European WEEE directive (European Commission 2012).
elements are recycled due to a lack of collection systems and steep costs of building recycling capacity (Scrreen 2023). Li-Cycle was set to build a network of facilities for the recovery of critical materials from lithium-ion batteries, but put a pause on all projects after a few pilot sites due to high infrastructure costs (Radwanski 2023); recycling rates for lithium are around 0.5% (IEA 2021). In turn, analyzing the economic viability of scaling urban mining investments is important for the clean energy transition.

The objective of this paper is to study the respective roles of material reduction and urban mining in maintaining the pace of the energy transition, compare the two strategies from the producer and policy maker perspectives, and provide insights for policy and decision makers. We do so by formulating a stylized analytical model that captures the key features of the issues discussed above. The material reduction strategy we study captures the reduction in raw material consumption with cost and energy generation efficiency trade-offs. The urban mining strategy we study captures the salient features of a circular system with restricted access to end-of-life products and an infrastructure and technology investment cost barriers (Atasu et al. 2021). We explicitly model the effect of a critical material’s scarcity and supply concentration on its price, and endogenize the impact of the clean energy industry’s production decisions on material scarcity. We formulate the producer options that represent material reduction and urban mining strategies, and investigate their respective abilities to maintain the production momentum of clean energy products against a benchmark where the scarcity of critical materials is not addressed. We determine the optimal decisions for clean energy producers and evaluate these from the perspective of a regulator that wants to maintain a profitable clean energy industry and maximize clean energy generation. To the best of our knowledge, our paper is the first to study the material scarcity driven supply and demand imbalances present in the clean energy transition as a strategic operational challenge.
Our results provide several managerial and policy insights, which we relate to practice by calibrating our model with real-life data from the solar panel industry. We find that the material reduction strategy, which appears to have been favoured by producers and policy makers so far, has limited potential to preserve the clean energy transition momentum under high material scarcity. The increased efficiency of material use in production may cause the producer to consume a larger amount of the critical material due to a *scarcity rebound effect* akin to the well-known rebound effect (Alcott 2005). Meanwhile, access to a steady stream of a secondary supply of critical materials through urban mining means that production can profitably continue even when the raw material is extremely scarce. Yet, prohibitive set-up costs for urban mining or insufficient access to end-of-life clean energy products hinder the producer profits and thus the incentives for choosing to invest in urban mining. We also find that investing in both material reduction and urban mining can be counterproductive as reduced material content requires producers to collect and process more end-of-life products to recover the same amount of material.

Furthermore, we investigate the success of different strategies in achieving the policy objectives of maximizing clean energy production and maintaining a profitable clean energy industry. Under the material reduction strategy, we find that the additional reliance on virgin raw materials increases producers’ vulnerability to price volatility. Yet, when the supply of critical materials is not too constrained, this strategy can effectively maximize clean energy production. Conversely, under moderate scarcity, producers need not choose the material reduction strategy due to its associated additional costs. In scenarios of very high scarcity, urban mining proves more effective in achieving policymakers’ targets and is essential for sustaining the clean energy transition’s momentum. Nevertheless, restricted access to end-of-life products and high infrastructure investment costs may deter producers from investing in
urban mining without policy support. When such misalignment between producer and policy objectives occurs, policy interventions that reduce producers’ capital outlay for urban mining and improve infrastructure for material recovery appear necessary. Policy measures that reduce systemic leakage, such as infrastructure support to collect end-of-life products, can help the industry favor urban mining by increasing the returns on urban mining investments.

The rest of this paper is structured as follows. In Section 2, we discuss the relevant literature. Section 3 outlines our model set-up and assumptions. In Section 4, we find the optimal decisions taken by the producer. In Section 5, we compare the effectiveness of each producer strategy in maintaining the momentum of the clean energy transition, and discuss policy implications. Section 6 explores relevant extensions and Section 7 concludes.

2. Literature Review

Our paper contributes to the energy-related stream of the sustainable operations literature (see Agrawal and Yücel 2021 for a review) that looks at the design of policies and business models to support the expansion of the clean energy industry against various operational challenges. Several papers explore business models that align incentives for utility firms, private owners, and regulators to increase the adoption of clean energy products. For example, Sunar and Swaminathan (2021) and Singh and Scheller-Wolf (2022) study tariff structures and business strategies that may make these incentives converge; Agrawal et al. (2022) investigate the incentives for utility companies and their customers under non-ownership business models for solar panels. The most direct way to encourage adoption appears to be subsidies, whose optimal structure has been widely studied (Goodarzi et al. 2015, Alizamir et al. 2016, Ma et al. 2019). Other studies focus on intermittency in renewable energy generation, which can undermine the profits of clean energy producers and hinder clean energy adoption (Hu et al. 2015, Aflaki and Netessine 2017, Kaps et al. 2022). To the best of our knowledge, our
paper is the first to investigate raw material scarcity as an operational challenge that may impede the clean energy transition. We contribute to the literature by addressing the implications of raw material scarcity on the producers of clean energy products, and in relation, on the momentum of clean energy adoption. While the shortage of raw materials appear in the operations literature in the context of inventory allocation under supply chain shortages, scarcity is taken as temporary limitations to material availability for use in production. For instance, Benjaafar et al. (2017) consider an exogenously-specified limit on the amount of an input a firm can use in production, but the raw material faces no scarcity in the market or due to the production decisions. In our paper, the firm does not have an explicit cap for raw material procurement, but rather the material becomes increasingly scarce, and in turn, more expensive as higher quantities are used.

Our work also relates to the environmental economics literature on scarce resources. Hotelling’s seminal work (1931) shows that the price of a nonrenewable asset increases over time as stocks diminish. Building on this work, Krautkraemer (1998) discusses factors that contribute to the stochasticity of the price. Our key assumptions about critical material pricing are based on this literature; specifically, we represent the material price as a random variable whose mean increases as a reflection of material scarcity. We build on these ideas and follow-up work in production economics that highlights the effect of material scarcity on the clean energy transition (e.g., Habib and Wenzel 2014, Gaustad et al. 2018, Fiandra et al. 2022). Nevertheless, our study explores what we see as a unique challenge that material scarcity poses in maintaining the energy transition momentum. Significant demand by the clean energy industry for critical materials implies that production decisions endogenously affect raw material scarcity and vice versa. We capture this cause-and-effect relationship by endogenizing the effect of clean energy industry’s production decisions on material scarcity.
Finally, we relate to the stream of research in closed-loop supply chains on various forms of value recovery (e.g., products, components, or materials). These studies address recycling in the context of extended producer responsibility (EPR) based take-back legislation for e-waste (see Atasu and Van Wassenhove 2012 for an overview), recycling strategies (Esenduran et al. 2020), mechanism design for recycling decisions (Cui and Sošić 2019), recycling as a supply alternative for competing manufacturers (Raz and Souza 2018) and the design of recycling supply chains (Nagurney and Toyasaki 2005, Demeester et al. 2013). Circular economy solutions are also proposed in other papers studying end-of-use and end-of-life planning of clean energy products, such as closed-loop supply chain design for portable batteries (Schultmann et al. 2003), reverse supply network design for end-of-life wind turbine blades (Rentizelas et al. 2022), and the link between technology adoption and end-of-life waste from residential solar panel installations (Duran et al. 2022). We complement these studies by proposing urban mining as a circular economy approach of value recovery as a solution to critical raw material scarcity in the clean energy industry.

3. Model

We consider the decisions of a profit-maximizing producer in a single-period model representing the lifecycle of a clean energy technology product, which requires a scarce raw material. The production decisions impact the scarce material price and availability. We assume that the producer is a price-taker on the clean energy product demand side for simplicity. A series of extensions capturing other salient features of competitive clean energy markets — e.g., an oligopolistic market on the supply side (see §6.1), or endogenous pricing or price stochasticity on the demand side (see Appendices I.1 and I.2) — show that this assumption is without loss of generality.
3.1. The supply of the critical material

We assume that the critical raw material is sold at a unit price of \( s(q, A) \) for \( q \) units of supply, where \( A \) represents the base level price for the virgin raw material absent producer demand, i.e., \( s(0, A) = A \). In our formulation, \( A \) is a non-negative random variable with a probability distribution function \( f_A \), a cumulative distribution function \( F_A \), and a known mean denoted by \( \mu \). Hard commodities used in clean energy products (e.g., silver, cobalt, etc) are sold on commodity markets, and prices show stochasticity due to multiple unobservable factors such as geopolitical unrest, ease of mining, market speculation, legislation, and supply chain disruptions (Krautkraemer 1998). In effect, the mean price \( \mu \) reflects the price expectation and the scarcity of the material as perceived in the market.

In addition to the stochasticity, the demand for the critical material from the clean energy industry has a non-negligible effect on commodity market prices as it represents a large and growing fraction of the total demand. This effect materializes as a positive relationship between the demand for the material and its traded price, as explored in the literature (e.g., Issler et al. 2014, Zhao et al. 2015). In other words, \( \partial s(q, A)/\partial q > 0 \), and securing increasing amounts of the scarce material comes at an increasing cost. For simplicity, and following earlier work on commodity sourcing (Inderfurth et al. 2018), we represent the stochasticity and the quantity limitations with a linear price function, i.e., with \( b > 0 \), \( s(q, A) = A + bq \).

Commodities are often traded through index-based or index-linked price contracts, meaning that the producer chooses the purchase quantity of the raw material, \( q \), ahead of time, but the price paid for the commodity depends on the evolution of market prices (Bolandifar and Chen 2020). As seen in the literature (Kouvelis et al. 2018, Zhang et al. 2014), these types of contracts are common in sourcing environments with high price volatility, such as commodity
markets. Accordingly, the producer must secure the critical material for production before observing the base price $A$, as depicted in Figure 1.

![Figure 1 Sequence of events for the producer’s purchase of the critical raw material.](image)

### 3.2. Product characteristics

Using $q$ units of the material (e.g., silver, cobalt or neodymium) in production yields $y = y(q)$ units of the clean energy product (e.g., PV panels, batteries or wind turbines). The production yield $y(\cdot)$ depends on the material intensity of the product’s design. The energy generation capability of the clean energy product, in return, is given by $e = e(y)$ megawatt-hours (MWh), depending on its energy conversion efficiency. The product is sold in a competitive marketplace at a price of $p$ per MWh of energy generation, which represents the profit margin net of any production costs besides the cost of purchasing the critical material. Thus, the producer’s revenues are proportional to $e(y(q))$, as opposed to the number of products $y(q)$, as products with higher generation capacity have a higher price point.

### 3.3. Formulation of the producer’s problem

Recall that our goal is to study and compare the role of two strategies, material reduction and urban mining, in maintaining the pace of the energy transition. Accordingly, we next describe the producer’s problem under four scenarios. In the benchmark scenario (§3.3.1),

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2 We confirmed with a former trader at Glencore (interview with Adam Langevin, November 22, 2022), one of the largest commodity trading companies, that index-linked contracts are the industry standard for energy-critical metals. Examples of contracts between Glencore and its Canadian clients are shown on the SEDAR database (SEDAR 2018).

3 We use the MWh (measure for energy) as a metric because it accounts for the actual energy produced over the lifetime of the product, as opposed to MW (measure of power) which only measures the potential for energy generation.
the producer employs no specific investment to reduce the use of scarce material, or to recover critical materials from end-of-life clean energy products to mitigate the impact of critical material scarcity on production volumes. We then describe the producer’s problem conditional on investing in a single strategy, namely material reduction (§3.3.2) or urban mining (§3.3.3), to maintain production under critical material scarcity. Finally, we model a combined scenario (§3.3.4) where the producer invests in both material reduction and urban mining together. In what follows, we let subscript \( i \in \{B, M, U, C\} \) represent the benchmark, material reduction, urban mining and combined strategies, respectively, with \( q_i \) representing the quantity of virgin critical material purchased, \( y_i \) representing the production quantity, and \( e_i \) representing the generation capability of the final product under each scenario. Table 1 provides an overview of the decision variables and the parameters used in our models, while Figure 2 plots the flow of materials under each of the strategies described.

### 3.3.1. The producer’s problem in the benchmark

In the benchmark model, the producer employs no particular strategy to compensate for the scarcity of the critical material beyond the status quo, and chooses \( q_B \) to maximize his expected profit \( \mathbb{E}_A [\pi_B (q_B | A)] \). For ease of analysis, and without loss of generality, we assume that the costs are scaled in a way that \( e_B = y_B = q_B \) in the baseline scenario, i.e., at the status quo, one unit of virgin raw material produces one unit of the clean energy product with generation capacity rated at one megawatt-hour. Then, the producer’s profit is given by \( \pi_B (q_B | A) = q_B p - s(q_B, A)q_B \), where the first term is the producer’s revenue, and the second term is his production cost. The producer’s problem of choosing virgin material purchase quantity \( q_B \) is thus:

\[
\max_{q_B \geq 0} \mathbb{E}_A [q_B p - (A + bq_B)q_B].
\]
3.3.2. The producer’s problem for the material reduction strategy

With a material reduction strategy, the producer redesigns the clean energy product to reduce its dependency on the scarce material, either by substituting some of the critical material with another, more abundant one, or by improving the efficiency of its use in production (IEA 2021). For example, producers have historically improved the efficiency of silver use in solar panels and can substitute some of it with other conductive metals (CRU Consulting 2018). Likewise, EV manufacturers are racing to reduce the use of cobalt in batteries by using other materials such as nickel, manganese or iron phosphate (IEA 2021, Li et al. 2020).

We represent the level of material reduction in the new design by the parameter \( \beta \). Upon investment, \( y_M(q, \beta) \) clean energy products can be produced from \( q \) units of virgin material with \( y_M(q, 0) = q \) and \( \partial y_M(q, \beta) / \partial \beta \geq 0 \). We let the improvement in production yield be \( y_M(q, \beta) = (1 + \beta)q \); that is, the material reduction strategy allows the producer to manufacture \( \beta \) additional products from a unit of the critical material. The producer incurs a convex R&D cost of \( \Phi(\beta) \) to develop the new design, with \( \Phi(0) = 0 \) and \( \lim_{\beta \to \infty} \frac{\Phi(\beta)}{\beta} \to \infty \).

This investment cost relates to \( \beta \) as it reflects incremental efforts incurred in improving the material efficiency in the product design. Indeed, material efficiency improvements in most clean energy products exhibit diminishing returns, which can be reflected by a convex function. For instance, the amount of silver used in a solar panel is estimated to reduce by 20% every time cumulative production doubles (Goldschmidt et al. 2021). We set \( \Phi(\beta) = \phi \beta^2 \) for ease of exposition (akin to, e.g., Bhaskaran and Krishnan 2009 and Rahmani et al. 2021).

Reducing the concentration of the critical material comes with a trade-off, usually in the form of lower energy generation yield and/or higher manufacturing costs (IEA 2022c). We assume that the new design introduces an additional processing cost \( c \) per unit of production (see Appendix C.2 for an extension with convex additional processing costs). Silver, for
instance, is easier to use in screen printing than copper, which implies that introducing more copper in solar panels increases manufacturing costs (S&P Global 2020). If material reduction is due to material substitution, the producer also has to pay $c_m$ per unit to purchase the substitute (non-scarce) raw material. For ease of exposition, we set $c_m = 0$ without loss of generality (see Appendix C.1 for a generalization with $c_m > 0$).

Finally, $y$ units of products with the new design can produce $e_M(y, \beta)$ units of energy, where $e_M(y, 0) = y$ and $\partial e_M(y, \beta)/\partial \beta \leq 0$. In particular, we set $e_M(y_M(q, \beta), \beta) = \frac{1+(1-\gamma)\beta}{1+\beta}y_M(q, \beta) = q + (1-\gamma)\beta q$. That is, while $\beta$ extra products can be built with a unit of the critical material, the additional energy generated is $(1-\gamma)\beta$, with $\gamma \in [0, 1]$ capturing the loss in energy conversion.\(^4\) Note that the total energy yield $e$ per unit of the critical material $q$ under the new design is still superior to the benchmark for $\beta > 0$. The energy yield $e$ per product $y$, however, reduces to $1 - \frac{\beta\gamma}{1+\beta}$ for the entire production volume upon adopting the material reduction strategy, which shrinks with $\beta$ at faster rates for a higher value of $\gamma$. For instance, reducing the use of lithium by 42% in lithium-ion batteries leads to a 22% decrease in specific energy (Ballinger et al. 2019). Likewise, partial substitution of silver by copper in photovoltaic panel cells compromises conversion efficiency.

Given that design changes are decided before production, $\beta$ is chosen before $q_M$.\(^5\) With these assumptions, the producer’s problem is written as:

$$\max_{\beta \geq 0} -\phi\beta^2 + \max_{q_M \geq 0} \mathbb{E}_A [\pi_M(q_M|A, \beta)],$$

\(^4\)Our model isolates the R&D for critical material reduction to derive insights most relevant to the practical issues of material scarcity. Producers can also spend R&D effort to improve the energy conversion efficiency of their products alongside material reduction, which would introduce additional convex costs of improvement. Our results are robust to such improvement with $\gamma < 0$, which changes the willingness to invest in material reduction.

\(^5\)Note that the optimal $\beta$ could also be chosen from a discrete set of values including 0. This does not change our insights, and our continuous set-up mimics a learning curve of technology developments more closely.
where \( \pi_M(q_M|A, \beta) = \left(1 + (1 - \gamma)\beta\right) q_M p - (A + bq_M) q_M - (1 + \beta) q_M c 1_{\beta > 0}. \)

### 3.3.3. The producer’s problem for the urban mining strategy

Under an urban mining strategy, the producer invests in advanced and dedicated recycling processes that allow the recovery of the scarce critical material from the end-of-life clean energy products (§6.2 discusses an extension with a strategic, third-party recycler).

We assume the processing costs of recycling display diseconomies of scale (Huang et al. 2019) given that the cleanest, most easily dismantled end-of-life products are cherry-picked first, while higher volumes require processing deteriorated or contaminated products at higher costs. Thus, recovering \( r \) units of the critical raw material through recycling \( r \) clean energy products involves convex costs \( C_r(r) \), where \( C_r(0) = 0 \) and \( \lim_{r \to \infty} C_r(r) \Rightarrow 0 \); specifically, \( C_r(r) = c_r r^2 \). Our model is robust to the scenario where the producer bears the costs of collection in addition to processing. Collection costs also display diseconomies of scale (Atasu et al. 2013), and one could revise the definition of the parameter \( c_r \) to include the reverse-logistics operations. Setting up the infrastructure for urban mining requires a significant capital investment. Accordingly, the producer incurs an initial investment cost \( \alpha(r) \) (with \( \alpha(0) = 0 \) and \( \alpha(\cdot) \) weakly increasing in \( r \)) for the urban mining technology, which we model as \( \alpha(r) = \alpha 1_{r > 0} \). This additional fixed cost is introduced as developing urban mining requires creating a new process along with an ecosystem: the producer may need to set-up a collection infrastructure and invest in advanced recycling technology.

The virgin material purchased, \( q_U \) and the recycled material \( r \) processed can both be used in production\(^7\), adding to \( y_U = y_U(q_U, r) = q_U + r \) units of clean energy product, and

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\(^6\) Appendix G presents an extension where recycling costs are convex in the recycling rate \( \frac{r}{q_M} \) instead.

\(^7\) Metals generally do not face downcycling or quality degradation issues during recycling, and can be recycled without any loss in performance (EuRIC 2020). Quality degradation issues during recycling, if any, however, would amount to greater effective systemic leakage and recycling costs, lowering the profits in the Urban Mining strategy.
generating $e_U(y_U) = y_U$ MWh of clean energy. In circular systems, the amount of material that can be recycled $r$ is limited by the production volume $y_U$: there might be a loss of material to other markets, low collection rates due to dumping, exporting or an immature collection ecosystem, and limited processing due to products being too contaminated or damaged to be recycled. We model this dependency between the production and recycling volumes by the parameter $\kappa \in (0, 1]$, where $r \leq (1 - \kappa)y_U$ (equivalently, $r \leq \frac{1-\kappa}{\kappa} q_U$). That is, $\kappa$ represents an exogenous systemic leakage over the production lifecycle of the clean technology as depicted in Figure 2. Given that a non-zero quantity of virgin material is required for the products produced prior to urban mining, $\kappa > 0$, and no critical material can be recovered ($r = 0$) when $\kappa = 1$. Hence, the producer’s problem under the urban mining strategy is written as:

$$\max_{q_U \geq 0, r \geq 0} \mathbb{E}_A[\pi_U(q_U, r|A)] \quad \text{subject to} \quad r \leq (1 - \kappa)y_U,$$

where $\pi_U(q_U, r|A) = (q_U + r)p - (A + bq_U)q_U - c_r r^2 - \alpha I_{r>0}$. (4)

We note that this urban mining formulation is a static and aggregate representation of closed-loop system flows over the lifecycle of the technology, which allows for tractability in what follows. We address the critical material supply and demand balance in such a setting with the help of the parameter $\kappa$, for which a complete aggregate characterization is provided in Appendix D. We note, however, that this formulation does not capture temporal effects that can be present in clean energy adoption and decommissioning processes, the dynamics of which are highlighted in §6.3 and discussed in detail in Appendix E.

3.3.4. The producer’s problem for the combined strategy With a combined strategy, the producer can jointly invest in both material reduction and urban mining. The producer first chooses the level of material reduction, $\beta_C$ and incurs an associated material reduction
Table 1 Summary of notation.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>( q )</td>
<td>Virgin material purchase quantity under strategy ( i )</td>
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<tr>
<td>( \beta )</td>
<td>Level of product redesign under the Material Reduction strategy</td>
</tr>
<tr>
<td>( r )</td>
<td>Recycled material quantity under the Urban Mining strategy</td>
</tr>
<tr>
<td>( p )</td>
<td>Revenue per unit of MWh produced</td>
</tr>
<tr>
<td>( A )</td>
<td>Random commodity market base price of virgin material</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Scarcity level, or expected commodity market price of virgin material</td>
</tr>
<tr>
<td>( b )</td>
<td>Effect of virgin material demand on the commodity market price</td>
</tr>
<tr>
<td>( \phi )</td>
<td>R&amp;D investment cost associated with a unit of material reduction</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Loss of efficiency associated with material reduction</td>
</tr>
<tr>
<td>( c )</td>
<td>Additional processing cost associated with material reduction</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Initial set-up costs of urban mining</td>
</tr>
<tr>
<td>( c_r )</td>
<td>Marginal processing cost of urban mining</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>Systemic leakage of end-of-life products</td>
</tr>
</tbody>
</table>

R&D cost of \( \Phi(\beta_C) \). Subsequently, the producer decides on the virgin and recycled material quantities, \( q_C \) and \( r_C \), and incurs the fixed costs to develop urban mining, \( \alpha(r_C) \) if \( r_C > 0 \).

Material reduction incurs the same trade-offs in production costs and energy conversion efficiency as in §3.3.2. The resulting product yield is \( y_C = y_C(q_C, r_C, \beta_C) = (1 + \beta_C)(q_C + r_C) \) and the energy yield is \( e_C(y_C, \beta_C) = \frac{(1 + (1 - \gamma) \beta_C)}{(1 + \beta_C)} y_C = (1 + (1 - \gamma) \beta_C)(q_C + r_C) \).

The reduced density of the critical material implies more clean energy products need to be recycled to recover the same amount of material. A portion of the recycling processing costs (e.g., chemical processes to purify metals) scale with material recovered, while others (e.g., reverse logistics costs like collection and transportation, or disassembly costs) scale with the number of products processed (US EPA 2023). Accordingly, we model the recycling costs in the combined strategy as \( C_{r,C}(r_C, \beta - C|j) = c_r(1 + \beta_C)^j r_C^2 \). With \( j = 0 \), recycling costs are driven entirely by the amount of material recovered \( r_C \); \( j = 2 \) means recycling costs are driven by the amount of clean energy products recycled \( y_C \); \( j \in (0,2) \) represents anything in between. Then, the producer solves:

\[
\begin{align*}
\max_{\beta_C \geq 0} \quad & -\phi \beta_C^2 + \max_{r_C \geq 0, q_C \geq 0} \mathbb{E}_A \left[ (1 + (1 - \gamma) \beta_C)(q_C + r_C) p - (A + b q_C) q_C \right. \\
& - (1 + \beta_C)(q_C + r_C) c I_{\beta_C > 0} - \alpha I_{r_C > 0} - c_r(1 + \beta_C)^j r_C^2 \\
\end{align*}
\] (5)
subject to \( r_C \leq (1 - \kappa)(q_C + r_C) \).

**Figure 2** The flow of materials under each producer strategy.

**Benchmark strategy**
- Virgin supply
- \( q_v \) units of virgin material
- \( q_v \) products
- \( q_v \) MWh
- Unrecovered material

**Material Reduction Strategy**
- Virgin supply
- \( q_m \) units of virgin material
- \( (1 + \beta)q_m \) products
- \( (1 + (1 - \gamma)\beta)q_m \) MWh
- Unrecovered material

**Urban Mining Strategy**
- Virgin supply
- \( q_v \) units of virgin material
- \( q_v + r \) products
- \( q_v + r \) MWh
- End-of-life products
- Unrecovered material

**Combined Strategy**
- Virgin supply
- \( q_v \) units of virgin material
- \( (1 + \beta)(q_v + r) \) products
- \( (1 + (1 - \gamma)\beta)(q_v + r) \) MWh
- End-of-life products
- Unrecovered material

**Material Recovery**
- \( r \) units of recycled material

**Reverse Logistics/collection**
- Systemic Leakage

**Note.** There is no material recovery from end-of-life clean energy products in the benchmark and material reduction strategies. With urban mining, materials can be recovered from the share of products not subject to systemic leakage.

### 3.4. Numerical calibration

To relate our results to practice, we calibrate our model using real-life data based on the solar panel industry and its use of silver. Further details regarding the scarcity of silver and the details of all parameter values and assumptions are presented in Appendix H.

We compare the results of our conclusions for two different geographies where producers have a high or low access to end-of-life solar panels, due to low or high systemic leakage \( \kappa \), respectively. For example, solar panels fall under the WEEE directive in the European Union, which enforces high target collection rates of 80% or more (European Commission 2012); we thus an optimistic low systemic leakage as \( \kappa_l = 0.20 \). Meanwhile, less than 10% of the end-of-life solar panels are collected in the US (Crownhart 2021); according to which we set a pessimistic high systemic leakage as \( \kappa_h = 0.9 \).
4. Producer’s Strategic Investment Decisions

In this section we characterize the optimal decisions for the producer under each of the benchmark, material reduction, urban mining, and combined scenarios. The proofs for all propositions are relegated to Appendix A.

4.1. Benchmark strategy

Under the benchmark strategy, the producer’s only decision is the virgin material purchase quantity which will maximize his expected profits given in Equation (1). The optimal order quantity for the producer, denoted by \( q^*_B \) is given as

\[
q^*_B = \left( \frac{p - \mu}{2b} \right)^+.
\]

In this simple optimization problem, the producer does not enter the market whenever \( \mu \), the expected base level price of the raw material, is greater than \( p \), the margin from selling the product. Furthermore, the production quantity \( y_B = q^*_B \) decreases when demand from the clean energy industry strongly impacts the raw material market (i.e., when \( b \) is high). That is, high levels of scarcity, be it related to \( \mu \) or \( b \), discourage production, and there exists a scarcity threshold beyond which the production slows down or stops. Hence, scarcity intuitively undermines the profitability of the clean energy industry and hinders the momentum of the clean energy transition. In what follows, we demonstrate how the three strategies we evaluate help overcome this limitation.

4.2. Investing in material reduction

Under the material reduction strategy, the producer chooses the level of material reduction, \( \beta \) and the virgin material purchase quantity, \( q_M \), to maximize the profit function given in Equation (2). The optimal decision vector \((q^*_M, \beta^*)\) is described in Proposition 1. Moving forward, we restrict our attention to the case where \( \phi > \phi = \frac{(1-\gamma)(p-c)^2}{4b} \), i.e., the product redesign cost for material reduction is not unrealistically cheap. In the absence of this assumption,
the producer would remove all of the critical material from the clean energy products when, in reality, there is a technical limit to these design changes.\(^8\)

**Proposition 1.** There exists a scarcity threshold, \(\mu_a(\phi) \in [0, p - c]\), with \(\frac{\partial \mu_a(\phi)}{\partial \phi} \leq 0\), such that when (i) efficiency loss from material reduction is small, i.e., \(\gamma \leq \frac{p - c}{p}\), and (ii) material scarcity is lower than the threshold, i.e., \(\mu < \mu_a(\phi)\), the producer’s problem has a unique solution given by \((q^*_M, \beta^*) = \left(\frac{2\phi(p - \mu - c)}{4b\phi - ((1 - \gamma)p - c)^2}, \frac{(p - \mu - c)((1 - \gamma)p - c)}{4b\phi - ((1 - \gamma)p - c)^2}\right)\). Otherwise, \((q^*_M, \beta^*) = (q^*_B, 0)\).

Proposition 1 shows that the producer prefers a material reduction strategy to the benchmark under two conditions: low loss of energy efficiency when reducing the material content and low scarcity level (in relation to investment costs). The first condition provides a natural bound for the acceptable efficiency loss in the new design, \(\gamma \leq \frac{p - c}{p}\), beyond which the added processing costs are not worth incurring. The second condition implies that a material reduction strategy is preferred only when the material is abundant enough and its price is below a bounded threshold \(\mu_a(\phi) \leq p - c\). Furthermore, as the investment becomes costlier (\(\phi\) increases), the producer engages in material reduction for increasingly lower values of the scarcity level \(\mu \in [0, p - c]\). These results may seem counterintuitive. One would expect the production volumes to be less dependent on the scarcity of the critical material after redesigning the product to have lower amounts of the material. After all, industry experts advocate for the material reduction strategy to fight critical material scarcity, expecting it to be effective under high levels of scarcity. Yet, we reach the opposite conclusion: Material reduction is more effective under low levels of scarcity. Moreover, investing in material reduction reduces the range of values of scarcity \(\mu\) for which production takes place to \(0 \leq \mu < p - c\).

---

\(^8\) A natural limitation to material reduction can also be implemented by imposing a technical boundary on how much critical material can be removed from the product design, i.e., there exists an upper bound \(\beta\) (meaning that \(\beta \in [0, \beta]\)). Such a modelling change would lead to another boundary solution, but does not change our insights.
(from 0 \leq \mu < p in the benchmark strategy) because of the higher production costs. That is, engaging in material reduction can be less effective than engaging in no strategy at all in ensuring continued production of clean energy products. This significant result can be linked to a scarcity rebound effect, as discussed below.

**Proposition 2.** With the material reduction strategy, the producer ends up consuming more virgin critical material than in the benchmark case, i.e., \( q^*_M > q^*_B \) when \( \beta^* > 0 \).

Proposition 2 can be tied to Jevons’ paradox (Jevons 1865) which states that whenever technological progress (or a public policy) increases the efficiency of the use of a resource, that resource will be used more intensively than before. In our case, the producer invests in material reduction when \( \gamma \) is small enough to lead to an overall efficiency increase. The efficiency increase drives the producer to produce more, offsetting the benefits of using less critical material per product and leading to greater consumption of virgin material. As a result, the production is more vulnerable to scarcity and supply shocks, rendering the material reduction strategy ineffective in high scarcity conditions. This phenomenon, which we refer to as the *scarcity rebound effect*, can have significant implications for the producer in terms of ex-post profitability, and for the policy maker in terms of maintaining clean energy adoption targets, which we discuss in detail in §5.

4.3. Investing in urban mining

Under the urban mining strategy, the producer simultaneously chooses how much critical material to recycle, \( r^* \), and how much virgin critical material to purchase, \( q^*_U \). The optimal decision vector \((q^*_U, r^*)\) chosen by the producer depends on the urban mining investment cost \( \alpha \), the scarcity level \( \mu \), and systemic leakage of end-of-life products \( \kappa \), as described below.

**Proposition 3.** There exists an investment cost threshold, \( \hat{\alpha}(\mu, \kappa) \), and two scarcity thresholds, \( m_a(\kappa) \) and \( m_b(\kappa) \), with \( m_a(\kappa) < 1 < m_b(\kappa) \), such that the producer optimally chooses one of the following three approaches:
a. A unique interior solution \((q^*_U, r^*) = \left( \frac{p - \mu}{2b}, \frac{p}{2c}\right)\) is chosen whenever the scarcity of the critical material is low, i.e., \(\mu < m_a(\kappa)p\), and the investment cost is lower than the threshold which is constant in this region, i.e., \(\alpha < \hat{\alpha}(\mu, \kappa) = \hat{\alpha}\).

b. A boundary solution \((q^*_U, r^*) = \left( \frac{\kappa(p - \kappa \mu)}{2bc^2 + 2er^2(1 - \kappa)^2}, \frac{(1 - \kappa)(p - \kappa \mu)}{2bc^2 + 2er^2(1 - \kappa)^2}\right)\) is chosen if the scarcity of the critical material is moderate, i.e., \(m_a(\kappa)p \leq \mu < m_b(\kappa)p\) and the investment cost is lower than the threshold, i.e., \(\alpha < \hat{\alpha}(\mu, \kappa)\).

c. No urban mining investment is made, and the benchmark strategy \((q^*_U, r^*) = (q^*_B, 0)\) is optimal if either the scarcity or the investment costs are too high, i.e., \(\mu \geq m_b(\kappa)p\) or \(\alpha \geq \hat{\alpha}(\mu, \kappa)\).

Figure 3 illustrates the three outcomes described in Proposition 3 for two regions with different systemic leakage rates. The producer invests in urban mining in the striped regions (interior and boundary solutions, resp.), whereas we fall back to the benchmark strategy in the unshaded region (no urban mining). The solid line in Figure 3 represents the threshold \(\hat{\alpha}(\mu, \kappa)\) above which the investment cost \(\alpha\) for developing urban mining is too large to be a profitable venture for the producer. The investment cost threshold is constant \((\hat{\alpha}(\kappa, \mu) = \hat{\alpha})\) and at its highest for the interior solution, i.e., when the recycling volume is not constrained by systemic leakage. Once the producer hits the systemic leakage constraint in (3) and chooses a boundary solution, the investment threshold begins to tighten as the scarcity level increases, i.e., \(\frac{\partial \hat{\alpha}(\mu, \kappa)}{\partial \mu} < 0\). As scarcity increases, the profit margins shrink, making the producer less willing to invest in urban mining altogether.

Interestingly, the relationship between the scarcity and the investment cost threshold is non-linear and it is concave decreasing for \(\mu \leq p\), but convex for \(\mu > p\). The solid line in Figure 4 (which plots the solutions described in Proposition 3 based on the systemic leakage) mimics this relationship. For \(\mu > p\) (high scarcity), the benchmark strategy is not profitable.
Figure 3  **Optimal solutions in the urban mining strategy based on scarcity and investment cost.**

Note. The solid line represents the investment cost threshold $\hat{\alpha}(\mu, \kappa)$ as a function of $\mu$ for a given $\kappa$. The two panels compare $\kappa_I = 0.20$ and $\kappa_h = 0.9$. Our parameter space is $p = 1.615$, $b = c_r = 0.0000003$.

Urban mining is the only feasible strategy that can yield a profit. In such a region, reducing the systemic leakage $\kappa$ would prompt the producer to invest in urban mining by lowering the investment cost threshold for urban mining adoption as $\frac{\partial \hat{\alpha}(\mu, \kappa)}{\partial \kappa} \leq 0$. Intuitively, better access to and recovery of end-of-life products allows a higher recycling yield from the same virgin material, hence pay-off the initial investment costs. Reducing systemic leakage is thus a lever that could be used by policy makers to foster urban mining, as discussed in §5.

Figure 4  **Optimal solutions in the urban mining strategy based on scarcity and systemic leakage.**

Note. The solid line depicts the values of systemic leakage $\kappa$ that makes urban mining viable for various values of $\mu$. With dashed lines $\kappa < m^{-1}_u(\frac{\alpha}{p})$ implies the optimal solution falls in the interior, and $\kappa > m^{-1}_u(\frac{\alpha}{p})$ implies there would be no investment even with $\alpha = 0$. The horizontal dotted lines show the calibrated values $\kappa_h = 0.9$ and $\kappa_I = 0.2$. Our parameter space is $p = 1.615$, $c_r = 0.0000003$, $\alpha = 10^5$, $b = 0.5c_r$ in the left plot, and $b = 2c_r$ in the right plot.
A particular advantage of urban mining is that production takes place for a wider range of scarcity \((\mu \in [0, m_b(\kappa)p])\) under this strategy than under the benchmark \((\mu \in [0, p])\). However, \(m_b(\kappa)p\) – the scarcity threshold beyond which the production stops altogether – decreases with systemic leakage, i.e., \(\frac{\partial m_b(\kappa)}{\partial \kappa} < 0\). Thus, while a producer can maintain production under a wider range of scarcity values with urban mining than in the benchmark strategy, high levels of systemic leakage undermine said advantage of urban mining.

In fact, based on the systemic leakage, we can distinguish between two regimes. For low systemic leakage, i.e., \(\kappa < \frac{c_r}{c_r + b}\), the producer operates in what we call a Low Leakage Regime, and there exists a range of scarcity levels (i.e., \(\mu < m_a(\kappa)p\)) for which the interior solution described in Proposition 3 is possible. In this interior solution, the producer is not constrained by the availability of end-of-life products, and can freely diversify between primary (virgin) and secondary (recycled) supply depending on the relative costs of sourcing. As the scarcity of virgin material worsens and \(\mu\) approaches \(m_a(\kappa)p\), the producer sources a greater share of inputs from urban mining. For even higher scarcity levels with \(\mu \geq m_a(\kappa)p\), the producer ends up in the boundary solution described in Proposition 3 even with low systemic leakage and recycles all available end-of-life products. Essentially, the sourcing cost increase due to scarcity outweighs the scale diseconomies of urban mining. Figure 5 shows the share of the material used in production that is sourced from recycling, which is by definition bounded above by \(1 - \kappa\), limiting recycling volumes under high scarcity levels.

As systemic leakage increases, the region for the interior solution shrinks, i.e., \(\frac{\partial m_a(\kappa)}{\partial \kappa} \leq 0\). Thus, the producer needs to maintain a higher input of virgin material to avoid being constrained by the availability of end-of-life products. Once the systemic leakage becomes sufficiently high, i.e., \(\kappa \geq \frac{c_r}{c_r + b}\), the producer operates in what we call a High Leakage Regime and always ends up in a boundary solution, constrained by the availability of end-of-life
products. In a high leakage regime, \( m_a(\kappa) \leq 0 \) and the interior solution is never possible, so even in the absence of scarcity (i.e., if the material was free), the producer would still not have access to enough end-of-life products to meet the desired recycling volume. In a boundary solution, the producer continues to recycle but (i) recycles less volume than ideal due to the limited supply of end-of-life products, and (ii) purchases more virgin material than is optimal. As a consequence, we find evidence of over-purchasing in the form of a leakage-related rebound effect even under urban mining, as shown in Proposition 4.

**Proposition 4.** Given a scarcity level \( \mu \), the consumption of virgin material is higher in the urban mining strategy than the benchmark strategy, i.e., \( q^*_U > q^*_B \), when \( \kappa > \frac{c_r(p-\mu)}{bp+c_r(p-\mu)} \).

The above result shows that the inability to reclaim end-of-life products can lead to higher consumption of scarce material and drive a scarcity rebound effect even under urban mining. However, contrary to the material reduction strategy, the rebound effect only becomes a concern for high levels of systemic leakage and could be avoided by enhancing the degree of circularity – i.e., reducing the systemic leakage. In fact, the next result highlights an unexpected positive impact of the rebound effect on total clean energy generation for moderate levels of systemic leakage.
Proposition 5. There exists two thresholds $\tilde{\kappa}$ and $\hat{\kappa}$ with $\hat{\kappa} \in [\tilde{\kappa}, 1)$ such that the total clean energy generation under urban mining $e_U^*(q^*_U, r^*) = q^*_U + r^*$ is constant for $\kappa \in (0, \hat{\kappa}]$ (where an interior solution exists), increases in $\kappa \in (\tilde{\kappa}, \hat{\kappa}]$ and decreases in $\kappa \in (\tilde{\kappa}, 1]$.

Proposition 5 (illustrated in Figure 6) shows that systemic leakage does not affect clean energy generation provided that scarcity levels let the producer choose an interior solution. Conversely, when high systemic leakage or high scarcity levels push the producer towards a boundary solution, the producer’s ability to recycle becomes constrained. In anticipation, the producer purchases more virgin material than optimal so as to still recycle abundantly, creating the scarcity rebound effect. Surprisingly, the scarcity rebound effect can lead to a higher clean energy generation under the constrained boundary solution compared to the interior solution. Above a certain threshold $\tilde{\kappa}$, the high loss from leakage pushes the producer to reduce production levels, hence clean energy generation decreases. Note that for $\kappa = 1$, the producer is not able to recover any material through recycling, and the optimal solution reduces to the benchmark strategy.

Figure 6 Total clean energy generation as a function of systemic leakage.

Note. The thresholds $\tilde{\kappa}$ and $\hat{\kappa}$ are those defined by Proposition 5, which we compare to $\kappa_l = 0.20$ and $\kappa_h = 0.9$. $\kappa$ values that correspond to interior and boundary solutions for urban mining are marked below the horizontal axis. Here, $p = 1.615$, $c_r = 0.0000003$, $\mu = 1$, $\alpha = 10^6$, $b = 0.5c_r$ in the left plot, and $b = 2c_r$ in the right plot.
4.4. Investing jointly in both strategies

Recycling costs in the combined strategy are given by $c_r(1 + \beta_C)^j r_C^2$, as presented in §3.3.4. That is, the costs can scale either with the amount of material recovered $r_C$ (low values of $j$) or the number of clean energy products processed (high values of $j$). Accordingly, investing in both strategies together has a synergistic effect (i.e., higher revenues due to higher product yield per unit of recycled material) and an opposite effect (i.e., the increased urban mining costs due to the lower critical material density). Depending on which effect dominates, urban mining and material reduction can be complements or substitutes. Proposition 6 describes the conditions for complementarity where a combined strategy brings higher expected profits than if the strategies were applied separately.

**Proposition 6.** A combined strategy maximizes the producer’s expected profit only when:

(i) recycling is not constrained (i.e., the producer chooses an Interior Solution) and $j < 1$, or

(ii) recycling is constrained (i.e., the producer chooses a Boundary Solution) and $\gamma < \gamma_{\max}(j)$,

where the threshold $\gamma_{\max}(j)$ is decreasing in $j$.

The conditions provided in Proposition 6 are intuitive: material reduction should cause a limited energy efficiency loss and have a synergistic effect on the processing costs for urban mining for a combined strategy to be viable. The first condition in Proposition 6(i) suggests that a combined strategy is suitable for economically viable urban mining when the recycling processing costs scale with material recovery ($j = 0$). If the recycling costs are linked to closed-loop logistics ($j = 2$) and scale with the number of products processed, the presence of material reduction undermines the economic benefits associated with urban mining. The second condition (Proposition 6(ii)), on the other hand, suggests that when the benefits from urban mining are already limited by the availability of end-of-life products, the efficiency loss from material reduction needs to be substantially smaller for a combined
strategy to be viable. Combined with the fact that executing both strategies in parallel requires a substantially larger capital outlay, we believe that these observations provide a compelling explanation as to why the combined strategy is not prevalent in practice.

Indeed, we generally observe either only urban mining, or more prevalently, only material reduction being adopted for a given critical material in a given industry. For instance, the recovery rates for rare earth elements from wind turbines, lithium from batteries or for silver from PV panels, were below 0.5% as of 2022 (IEA 2021, ROSI Solar 2023a), whereas significant efforts have been made in the direction of material reduction (INES 2022). In contrast, around 29-41% of nickel is recycled, but modern batteries have 21% more, rather than less, nickel than older models (Knehr et al. 2022). In turn, in what follows we focus our attention on a comparison between urban mining and material reduction strategies in isolation, which simplifies the analysis substantially.

4.5. Producer’s choice between urban mining and material reduction

The producer is interested in choosing the investment strategy that maximizes his expected profits. Proposition 7 describes the producer’s optimal strategic choice to mitigate the critical material scarcity challenge.

**Proposition 7.** There exists an investment cost threshold \( \tilde{\alpha}(\mu, \kappa) \leq \hat{\alpha}(\mu, \kappa) \) such that a producer maximizing expected profits will choose:

a. A material reduction investment if \( \alpha \geq \tilde{\alpha}(\mu, \kappa) \) and \( 0 \leq \mu < \mu_a(\phi) \).

b. An urban mining investment if \( \alpha < \tilde{\alpha}(\mu, \kappa) \) and \( 0 \leq \mu < m_b(\kappa)p \).

c. No investment (benchmark strategy), otherwise.

Figure 7 illustrates the three outcomes described in Proposition 7, where the solid lines represent the thresholds beyond which one strategy is preferred to the other. Material reduction results in the greatest expected profits provided that the scarcity \( \mu \) is low enough,
and the investment costs associated with urban mining are high. Given any scarcity level \( \mu \) and systemic leakage \( \kappa \), the producer will expect more profits from the urban mining strategy when the investment costs are limited, i.e. \( \alpha < \tilde{\alpha}(\mu, \kappa) \). Interestingly, this threshold has a non-monotonous relationship with the scarcity level. Intuitively, for very low values of scarcity, the material reduction strategy achieves high profits because of the greater margins associated with investment in a \( \beta^* > 0 \); therefore, the urban mining strategy is only favoured if its required investment costs are very low. As scarcity increases, the producer increasingly favors urban mining and \( \tilde{\alpha}(\mu, \kappa) \) increases as long as recycling quantities are not constrained by systemic leakage. Once high scarcity levels push the producer towards a boundary solution, margins shrink due to systemic leakage and \( \tilde{\alpha}(\mu, \kappa) \) decreases with \( \mu \) again, making the producer less willing to invest in urban mining altogether. The right plot in Figure 7 illustrates an analogous relationship between the thresholds on the systemic leakage \( \kappa \) for urban mining investment and the scarcity level.

![Figure 7](image-url)  
**Figure 7** Optimal producer strategy by scarcity level, investment cost (left) and systemic leakage (right).

*Note.* The solid lines represent the thresholds for \( \alpha, \kappa \) and \( \mu \) for indifference between strategies, resp. Our parameter space is \( p = 1.615, c_r = 0.0000003, b = c_r, c = 0.2 \) and \( \phi = 2.68M \). There is no production in benchmark to the right of the dashed vertical line where \( \mu > p \).
Our results so far establish that the costs of investment into advanced strategies ($\alpha$, $\phi$) and the systemic leakage in circularity infrastructures ($\kappa$) all moderate the producer’s optimal strategy and the clean energy transition challenges posed by critical material scarcity. Producers will only opt for material reduction under low levels of material scarcity, and urban mining is the only strategy that can feasibly keep production under high scarcity levels.

Yet, the producer’s choices may not align with the clean energy transition goals if, e.g., investment costs are too high. The implications of producer choices on the momentum of the clean energy transition are discussed further and drive our policy recommendations in §5.

5. Policy Objectives and Interventions

In this section, we introduce two policy objectives that support the clean energy transition, specifically in the form of maximizing clean energy generation and maintaining a profitable clean energy product industry as per our focus so far. We then discuss policy interventions that would help align the producer’s preferred strategy with these policy objectives.

5.1. Maximizing clean energy generation

Given the ambitious goals to shift towards clean energy for climate change mitigation, the policymaker would like the producer to choose the strategy that maximizes the clean energy generated. In Proposition 8 below, we compare the clean energy generated under each strategy, i.e., $e_i^*$ for $i \in \{B, M, U\}$:

**Proposition 8.** There exists a scarcity threshold $\hat{\mu} \leq p - c$ such that the highest clean energy generation is achieved under urban mining (i.e., $e_U^* > e_M^* > e_B^*$) when $\mu > \hat{\mu}$ and under material reduction (i.e., $e_M^* > e_U^* > e_B^*$) when $\mu \leq \hat{\mu}$.

Proposition 8 shows that, aligned with our results in §4, the trade-off between material reduction and urban mining from a clean energy maximization perspective is also moderated by the level of material scarcity. If material scarcity is low, material reduction provides
the highest clean energy generation and, as shown in Proposition 1, higher profits than the benchmark strategy. This observation could provide a compelling explanation as to the prevalence of material reduction in current policy and producer strategies. Current actions, however, need not reflect possible stark price increases under ambitious clean energy targets. If the price of the critical raw material increases further, our results suggest that a producer that has invested in material reduction could reduce their generation of clean energy. When scarcity and its impact on commodity markets is higher, investing in urban mining to secure a secondary supply of materials could be essential to continuing the momentum in favor of clean energy. While the producer’s preferred strategy should ideally align with this policy objective, the following corollary to Propositions 7 and 8 suggests that a policy maker looking to maximize clean energy generation may be in favor of urban mining (material reduction), but not find the producer on its side.

**Corollary 1.** An Urban Mining Misalignment exists for \( \mu > \hat{\mu} \) and \( \alpha > \tilde{\alpha}(\mu, \kappa) \) where urban mining maximizes clean energy generation but the producer chooses another strategy. A Material Reduction Misalignment exists for \( \mu < \hat{\mu} \) and \( \alpha < \tilde{\alpha}(\mu, \kappa) \) where material reduction results in the highest clean energy generation but the producer chooses another strategy.

Corollary 1 (illustrated in Figure 8) characterizes the areas where the incentives of a producer and a policy maker do not naturally align. The producer and the policy maker objectives overlap for the white (unshaded) regions of the parameter space in Figure 8, and the shaded regions show the incentive misalignment areas (details on our numerical calibration can be found in Appendix H). Note that Corollary 1 is written with respect to the investment cost \( \alpha \) for compactness. Figure 9 presents more interesting insights relating to systemic leakage \( \kappa \), whose formal presentation is tedious due to the non-monotonic behavior of \( e^*_U \) with respect to \( \kappa \) discussed in Proposition 5 and observed in Figure 6.
Figure 8  Alignment of producer and energy generation policymaker goals by scarcity level and investment cost.

Note. The dotted lines separate the regions where the producer’s choice and the policy objectives differ. In the dotted (striped) area, the producer chooses a strategy other than urban mining (material reduction) despite it generating more clean energy. Our parameter space is \( \kappa_l = 0.2, \kappa_h = 0.9, p = 1.615, c_r = 0.000003, b = c_r, c = 0.2 \) and \( \phi = 2.68M \).

Figure 9  Alignment of producer decisions with energy generation goals by scarcity level and systemic leakage.

Note. In the striped (dotted) area, the producer chooses a strategy other than urban mining (material reduction) despite it generating more clean energy. Our parameter space is \( \alpha = 1.5e6, p = 1.615, c_r = 0.000003, b = c_r, c = 0.2 \) and \( \phi = 2.68M \).

In particular, a Material Reduction Misalignment exists (striped areas in Figures 8 and 9) when scarcity is low or moderate, material reduction requires a high investment cost, and the cost of urban mining investment \( \alpha \) is low, particularly when systemic leakage \( \kappa \) is limited. In this case, the policy maker may be interested in nudging the producer toward material reduction, for instance by subsidizing its investment cost (i.e., \( \phi \)). Yet, this scenario is only relevant if material scarcity is not a constraint in the foreseeable future, while multiple
indicators point to the industry hitting critical material scarcity under the ambitious energy transition goals.

Seen from this point of view, we believe that a more relevant misalignment would be that of Urban Mining, which exists under high material scarcity (dotted areas in Figures 8 and 9), large investment costs of urban mining (i.e., \( \alpha \)), and/or high systemic leakage (i.e., \( \kappa \)). As such, while subsidies can help overcome the investment cost hurdle, reducing systemic leakage \( \kappa \) is a key component of the clean energy transition, as supported by Proposition 9.

**Proposition 9.** The investment threshold where urban mining is chosen other strategies decreases when systemic leakage increases, i.e., \( \frac{\partial \hat{\alpha}(\mu, \kappa)}{\partial \kappa} \leq 0 \).

Proposition 9 unveils a necessity for forward-looking policy makers wishing to promote clean energy installations. As an alternative to subsidizing investments required for urban mining, a policy maker could instead facilitate improved circularity through reduction of systemic leakage \( \kappa \) when the parameter space falls into an Urban Mining Misalignment. In such a region, reducing the systemic leakage \( \kappa \) would prompt the producer to invest in urban mining, because it would lower the investment cost threshold for urban mining adoption as \( \frac{\partial \hat{\alpha}(\mu, \kappa)}{\partial \kappa} \leq 0 \). Systemic leakage can be reduced by attaining higher return of end-of-life clean energy products through legislation against landfilling and non-return of products, investments in infrastructure, enforcement against illegal exports or consumer/corporate education at scale. Consequently, urban mining would be more profitable as the producer would have access to a larger share of end-of-life products, thereby recovering more critical materials. As a result, the producer would be willing to invest in urban mining even at a higher investment cost, and increase clean energy generation.

Alternatively, policymakers could move away from the Urban Mining Misalignment by subsidizing the price of the scarce material to producers. While subsidizing commodities is
not uncommon (e.g., in agriculture), and reducing the baseline price of the critical material would boost clean energy generation under all strategies, Corollary 2 shows that policy makers should be wary of an additional unintended consequence on virgin material consumption:

**Corollary 2.** *Subsidizing the raw material costs – reducing \( \mu \) – under Material Reduction (Urban Mining) leads to a stronger (weaker) scarcity rebound effect and virgin material consumption. Equivalently, \( \frac{\partial}{\partial \mu} (q^*_M(\mu) - q^*_B(\mu)) \leq 0 \) and \( \frac{\partial}{\partial \mu} (q^*_U(\mu) - q^*_B(\mu)) \geq 0 \).*

Corollary 2 indicates that subsidies to raw material prices may incentivize producers towards investing more in material reduction (i.e., choosing a greater \( \beta^* \)). However, it also exacerbates the scarcity rebound effect, and the producer consumes more than what he would under a benchmark strategy, even accounting for subsidies. As a result, the exposure of producers to negative profits might increase, and so will the eventual environmental implications of virgin material consumption, as observed before for steel and aluminium (S&P Global 2022). Under the urban mining strategy, subsidies to raw material prices allow for better hedging between virgin and recycled material in the supply mix, reducing the need to over consume. Thus, subsidies to raw material prices may particularly be effective when targeted towards firms planning to invest or having already invested in urban mining.

### 5.2. Business Continuity

To maintain the momentum of the clean energy transition, policy makers need to ensure that the volatility in material prices does not stop the production of clean energy products. Profitability in clean technology industries is critical for their survival, yet has been volatile in the past few years, leading to bankruptcies which could slow the pace of installations (IEA 2022b). One third of solar PV production capacity is under risk of bankruptcy (IEA 2022c), and the wind industry is facing similar pressure (Millard 2023). Aligned with this, the policymaker would like the producer to choose a strategy that minimizes the probability
of ex-post losses that could drive them to bankruptcy, even if expected profits are positive. In other words, the policymaker would like to maximize the probability of business continuity for the producer, or equivalently, minimize the probability of the producer having negative ex-post profits.

Hereafter, we assume the two advanced strategies are viable with respect to their investment costs $\phi$ and $\alpha$ in the relevant scarcity ranges except where noted, and define $\Delta = \{\mu | q_B^*(\mu) > 0, q_M^*(\mu) > 0, \beta(\mu)^* > 0, r(\mu)^* > 0\}$ as the range of scarcity levels where all strategies are feasible. Let $\rho_i$ be the probability of negative ex-post profits for the producer conditional on choosing strategy $i$. Specifically, $\rho_B = P(\Pi_B(q_B^*(\mu)) < 0 | \mu \in \Delta)$, $\rho_M = P(\Pi_M(q_M^*(\mu), \beta^*) < 0 | \mu \in \Delta)$ and $\rho_U = P(\Pi_U(q_U^*(\mu), r^*) < 0 | \mu \in \Delta)$ where $\Pi_i(\cdot)$ represents the ex-post profits of the producer under strategy $i$. Proposition 10 compares $\rho_i$ for $i \in \{B, M, U\}$.

**Proposition 10.** Material reduction always increases the probability of negative profits for the producer and $\rho_M > \rho_B$ for $\mu \in \Delta$. With urban mining, the probability of negative profits decreases except when both material scarcity and the investment costs are high. That is, there exists a threshold $\bar{\alpha}(\mu, \kappa)$ such that $\rho_U < \rho_B$ if $\mu \in [0, m_a(\kappa)\rho] \subseteq \Delta$ or $\alpha < \bar{\alpha}(\mu, \kappa)$. Otherwise, $\rho_U \geq \rho_B$.

Propositions 2 and 10 together imply that the material reduction strategy increases the producer’s exposure to scarcity-driven raw material price increases and price volatility due to the rebound effect in the consumption of virgin material. The higher total demand for the critical raw material in the material reduction strategy increases the probability of losses for the producer. With urban mining, the producer hedges sourcing between virgin material from the commodity market and recycled material from end-of-life products. Hence, production is partly shielded from scarcity and price volatility, even more so when the systemic leakage and the investment cost are low. As long as investment into urban mining is not extremely
costly, the urban mining strategy results in the lowest probability of negative ex-post profits, which implies that a policy maker that would like to minimize potential bankruptcy risks should in general favor urban mining over material reduction. Yet, the following corollary to Propositions 7 and 8 suggests that the producer’s preferred strategy does not always align with this policy objective.

**Corollary 3.** An Urban Mining Misalignment exists for \( \tilde{\alpha}(\mu, \kappa) < \alpha < \bar{\alpha}(\mu, \kappa) \) where urban mining minimizes the probability of ex-post negative profits but the producer chooses another strategy. A Benchmark Misalignment exists for \( \alpha > \bar{\alpha}(\mu, \kappa) \) and either \( \mu < \mu_a(\phi) \) or \( \alpha < \tilde{\alpha}(\mu, \kappa) \) where the benchmark strategy results in the lowest probability of ex-post negative profits but the producer chooses another strategy.

Figure 10 characterizes the areas described in Corollary 3 where the incentives of a producer and a policymaker wishing to maintain business continuity do not naturally align. The producer and the policy maker objectives overlap for the white (unshaded) regions of the parameter space in Figure 10, and the dotted (checked) regions show the Urban Mining (Benchmark) incentive misalignment areas. Note that there are no Material Reduction misalignment areas, because this strategy is always dominated in terms of probability of business continuity.

For low scarcity values, participation in urban mining is enough to guarantee that urban mining dominates the benchmark in terms of business continuity, because \( \bar{\alpha}(\mu, \kappa) > \tilde{\alpha}(\mu, \kappa) \). However, if scarcity is high, \( \tilde{\alpha}(\mu, \kappa) < \bar{\alpha}(\mu, \kappa) \) would mean that for some values of \( \alpha \) the producer chooses urban mining despite that strategy being worse in terms of probability of business continuity.

Our comparison of the strategies in this section provides nuanced consequences of subsidizing urban mining investment costs or systemic leakage reductions. While trying to maximize
clean energy generation, a policymaker may provide subsidies to urban mining investment costs to nudge the producer toward urban mining. However, unless the provided subsidies are sufficiently large, the producer (and thus, the continuation of the clean energy installations) may end up more vulnerable to volatility in the price of the scarce material. In such cases, combining the subsidies to the investment costs with other measures, e.g. a reduction in the systemic leakage through better collection infrastructure, or material price subsidies, would work best to preserve the momentum of the clean energy transition.

6. Extensions

Before closing, we briefly discuss three extensions that capture additional market features observable in our context.

6.1. Multiple competing producers

We present a setting where \( N \) symmetric producers compete for the supply of the critical material, akin to a reverse-Cournot setting in Appendix B. Our key results and insights (e.g., rebound effects in material reduction, and the structural results regarding the producer’s and the policymaker’s preferred strategies) remain robust to this extension. Primarily, we find that equilibrium outcomes for all producers combined (the virgin material used, the
production volume, and energy production) scale with the number of producers in the market. That is, a higher competition intensity on the supply side results in a more aggressive extraction of the virgin material which exacerbates the scarcity issue. In turn, less investment is made into material reduction per producer due to reduced marginal returns. As a result, as competition intensifies, the misalignment region for the material reduction strategy shrinks. On the other hand, as number of players increase, amplified scarcity concerns may make the case for urban mining stronger from a policy perspective at times of high scarcity. The misalignment in urban mining may then grow with competition, unless the competing producers can share the costs of investment for the recycling and recovery infrastructure.

6.2. Third-party recycler

Our vertically integrated set-up where the producer undertakes urban mining represents relevant current industry practice (White House 2022, EIU 2023), e.g., Tesla recycles their batteries in-house in their Nevada Gigafactory (Tesla 2021). Likewise, direct partnerships between recyclers and manufacturers are common for solar panels (ROSI Solar 2023b) and wind turbines (Vestas 2023). However, it is possible for urban mining to be performed by a third-party recycler. In this case, we find (see Appendix F) that the benefits of urban mining continue to hold, albeit weaker than in the vertically integrated setting due to double marginalization, and extra material leakage as the recycler may sell critical materials to other markets or industries.

6.3. Temporal effects in supply-demand imbalance

Our main problem formulation represents a static and aggregate representation of the system material flows (virgin material and recycled material) over the lifecycle of the technology. However, this formulation does not capture the temporal effects arising from the lag between the clean energy product installations and their decommissioning, especially if the demand for clean energy products grows or shrinks during the lifespan of the technology. To investigate
the implications of an industry growth phase, we study a two-period extension to our main model where the temporal constraints are captured by two additional parameters: the market growth in period 2 (in relation to period 1), and a dynamic systemic leakage parameter, reflecting higher recovery of end-of-life products installed in earlier periods. The details of this analysis are relegated to Appendix E. While our key results continue to hold in this dynamic formulation, we find that material reduction is preferred in cases of high market shrinkage or high market growth. Intuitively, urban mining provides lower revenues if the market shrinks by the time used products can be recovered, so the producer is less keen on paying for high investment costs. Likewise, in case of high market growth, material reduction becomes more profitable because its material reduction investments pay off over a larger volume whereas urban mining is constrained by end-of-life products installed earlier. These observations suggest that the presence of temporal effects in the form of reverse flow supply and dynamic demand mismatches can limit the benefits of urban mining and favor early investments into material reduction, an observation akin to the systemic leakage limitations identified in Section 5.

7. Conclusions

Accelerated global efforts to reduce carbon emissions have resulted in a rapid shift towards clean energy technologies whose production requires large amounts of critical metals and minerals. The projected supply for these critical materials falls behind the expected surge in demand from the clean energy industry as governments ambitiously commit to decarbonize their energy sectors within the next two decades. Ramping up the primary supply of critical materials to meet soaring demand in a meaningful time frame, however, is challenging. As a result, the inadequate supply of critical materials can diminish the cost-competitiveness of clean energy products and delay or hinder the momentum of the clean energy transition.
Motivated by this challenge, we analyze two prevalent approaches that can preserve that momentum in the decade ahead by alleviating the strained supply of critical materials: material reduction and urban mining. Material reduction appears to have been favored more by producers and policy makers so far, but our results suggest that it can leave producers more vulnerable to scarcity-driven price increases and volatility, and can cause an undesirable rebound effect. Furthermore, the material reduction strategy can maintain the momentum in clean energy generation only when the supply of critical materials is not too constrained, that is, when material scarcity is low. In contrast, our results suggest that an urban mining strategy will be in a better position to maintain the profitability of the clean energy industry and lead to superior clean energy generation when critical material scarcity is high. Thus, urban mining appears essential to maintain the momentum of the clean energy transition under critical material scarcity.

Despite the advantages of urban mining, a number of roadblocks may keep the clean energy industry from investing in this circular strategy in a timely manner without policy support. In the presence of these roadblocks, the producers may not direct enough capital towards reclaiming critical materials as the industry favors a material reduction strategy early on when scarcity levels are still low. First, as opposed to technology improvement efforts in material reduction, urban mining may require large investment in and further development of dedicated recycling solutions along with a collection ecosystem for end-of-life products. Second, systemic leakage in circularity infrastructures can be a limiting factor on the volume of material recovery and recycling profits. Policymakers could reduce systemic leakage to encourage urban mining by enforcing legislation against landfiling, minimum material recovery requirements, ecosystem development, stimulating user participation, encouraging timely recycling and overall providing a better infrastructure for collection of end-of-use products.
References


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Online Appendix for Clean Energy, Material Scarcity and Urban Mining

A. Proofs

**Proof of Proposition 1**  Let \( f_M(q_M, \beta) \) be the objective function of the producer’s problem for material reduction given in Equation (2). We first find the optimal virgin material purchase quantity \( q_M^*(\beta) \) as a function of the investment level \( \beta \). \( f_M(q_M, \beta) \) is strictly concave in \( q_M \) as \( b > 0 \), so the first-order condition \( \frac{\partial f_M}{\partial q_M} = 0 \) is sufficient to identify \( q_M^*(\beta) = \left( \frac{\rho (1+\beta(1-\gamma) - \mu) - (1+\beta) c}{2b} \right)^+ \). Observe that for \( q_M^*(0) = q_B^* \).

We next find the optimal investment level \( \beta^* \) by maximizing \( f_M(q_M^*(\beta), \beta) \). We have \( \frac{\partial^2 f_M(q_M^*(\beta), \beta)}{\partial \beta^2} < 0 \) for \( \phi > \phi = \frac{(1-\gamma)(p-c)^2}{4b} \), and setting \( \frac{\partial f_M(q_M^*(\beta), \beta)}{\partial q_M} = 0 \) gives us the unique maximizer for the unconstrained problem as \( \beta_M^* = \left( \frac{(p-c)(1-\gamma) - \rho}{4b(s^2 + (1-\gamma)p-c)^2} \right)^+ \). Since \( \beta \geq 0 \), either \( \beta^*_M = 0 \) or \( \beta^*_M = \beta_M^* > 0 \). We have \( \beta^*_M > 0 \) if and only if \( p-c > \mu \). Furthermore, for \( p-c > \mu \), \( q_M^*(0) = q_B^* \) implies that \( \beta^*_M = 0 \) when \( E_A[\pi_B(q_B^*|A)] \geq f_M(q_M^*(\beta)^*_M, \beta_M^*) \).

In other words, for \( \beta^*_M > 0 \), the producer also needs to have higher profits under material reduction then the benchmark case. Setting \( E_A[\pi_B(q_B^*|A)] < f_M(q_M^*(\beta)^*_M, \beta_M^*) \) leads to the threshold \( \phi < \phi_a(\mu) = \frac{(1-\gamma)(p-c)^2(p-\mu)^2}{4bc(2p-2\mu-c)^2} \), i.e., the second condition of the proposition. For \( \beta^*_M > 0 \), we have \( q_M^*(\beta)^*_M = \frac{2\phi (p-c)(1-\gamma) - \rho}{4b(2p-2\mu-c)} \). Finally, \( q_M^*(\beta)^*_M > 0 \) implies \( (1-\gamma) p - c > 0 \), leading to the first condition of the proposition, i.e., \( \gamma \leq \frac{c-p}{p} \). \( \square \)

**Proof of Proposition 2**  Following Proposition 1, we have \( q_M^* = q_B^* = \left( \frac{p-c}{2b} \right)^+ \) when \( \beta^*_M = 0 \) and \( q_M^* = \frac{2\phi (p-c)(1-\gamma) - \rho}{4b(2p-2\mu-c)} \) when \( \beta^*_M > 0 \). As shown in the proof of Proposition 1, \( \beta^*_M > 0 \) if and only if \( p-c > \mu \) and \( \phi < \frac{(1-\gamma)(p-c)^2(p-\mu)^2}{4b(2p-2\mu-c)^2} \). Observe that \( p-c > \mu \) implies \( 2p - 2\mu - c > p - \mu \), or equivalently, \( \frac{\rho}{2} < \frac{\rho}{2} \frac{p-c}{2b} < 1 \). Then, \( \beta^*_M > 0 \) implies \( \phi < \frac{(1-\gamma)(p-c)^2(p-\mu)^2}{4b(2p-2\mu-c)} \). We have \( \phi < \frac{(1-\gamma)(p-c)^2(p-\mu)^2}{4b(2p-2\mu-c)} \) if and only if \( \frac{2\phi (p-c)(1-\gamma) - \rho}{4b(2p-2\mu-c)} > \frac{p-c}{2b} \), i.e., \( q_M^* > q_B^* \) for \( \beta^*_M > 0 \). \( \square \)

**Proof of Proposition 3**  Let \( L_U(q_U, r, \lambda) \) be the Lagrangian function of the producer’s problem for urban mining given in Equation (3), where:

\[
L_U(q_U, r, \lambda) = (q_U + r)p - \mu q_U - b q_U^2 - c r^2 - \alpha \mathbb{1}_{r > 0} - \lambda \left( r - \frac{1-\kappa}{\kappa} q_U \right).
\]

First, observe that for \( r^* = 0 \), the producer’s problem reduces to the benchmark scenario, in which case \( q_M^* = q_B^* \). Furthermore, \( (q_M^*, r^*) = (0, r) \) for any \( r > 0 \) is not a feasible solution.

The Hessian of \( L_U \) is negative definite, so the KKT conditions are sufficient for optimality. For \( \lambda = 0 \), setting \( \frac{\partial L_U}{\partial q_U} = 0 \) and \( \frac{\partial L_U}{\partial r} = 0 \) characterizes the interior solution at \( (q_M^*, r^*) = \left( \frac{p-c}{2b}, \frac{p-c}{2b} \right) \). At the interior solution, the constraint holds with a strict inequality, i.e., \( r^* < \frac{1-\kappa}{\kappa} q_U^* \) for \( \mu < \left( 1 - \frac{b}{1+\kappa c} \right) p := m_u(\kappa)p \), where \( m_u(\kappa) < 1 \). For \( \lambda > 0 \), the complementary slackness leads to \( r = \frac{1-\kappa}{\kappa} q_U \). Solving \( \frac{\partial L_U}{\partial q_U} = 0 \) and \( \frac{\partial L_U}{\partial r} = 0 \) for \( \lambda \) gives the boundary solution at \( (q_M^*, r^*) = \left( \frac{p-c}{2b}, \frac{p-c}{2b}, \frac{p-c}{2b}, \frac{p-c}{2b} \right) \). For \( r^* > 0 \), \( q_M^* > 0 \) implies \( \mu < \frac{\kappa}{\kappa} := m_u(\kappa)p \) where \( m_u(\kappa) > 1 \). Finally, the producer invests in urban mining with \( r^* > 0 \) if and only if \( E_A[\pi_U(q_U^*, r^*|A)] > E_A[\pi_B(q_B^*|A)] \) which is equivalent to \( \alpha < \alpha(\mu, \kappa) \) where

\[
\hat{\alpha}(\mu, \kappa) = \begin{cases} 
\frac{\mu^2}{4c} & \text{if } \mu < m_u(\kappa)p \\
\left( \frac{1}{1+\kappa} \right) \beta(p-c)(1-\gamma) - (1+\kappa) \rho c \left( \frac{p-c}{4b} \right)^2 & \text{if } \mu \leq m_u(\kappa)p
\end{cases}
\]

if \( \mu < m_u(\kappa)p \)
Proof of Proposition 4  The condition \( \kappa < \frac{c_r(p-\mu)}{b_p+c_r(p-\mu)} \) holds if and only if \( \mu < m_a(\kappa)p \) or \( \mu > m_b(\kappa)p \). If \( \mu < m_a(\kappa)p \), the producer chooses the interior solution (a) in Proposition 3 and \( q_U^* = q_a^* = \frac{p-\mu}{2b} \). If \( \mu > m_a(\kappa)p \), the producer chooses the solution (c) in Proposition 3, and \( q_U^* = q_B^* = 0 \). For \( \kappa > \frac{c_r(p-\mu)}{b_p+c_r(p-\mu)} \), the producer chooses the boundary solution (b) in Proposition 3 and \( \kappa > \frac{c_r(p-\mu)}{b_p+c_r(p-\mu)} \) implies \( q_U^* = \kappa \frac{p-\mu}{2b} = \frac{p-\mu}{2b} = q_B^* \).  

Proof of Proposition 5  Following Proposition 3, the total clean energy generation under urban mining, subject to investment, can be written as a function of \( \kappa \) as:

\[
e_U^*(\kappa) = q_U^*(\kappa) + r^*(\kappa) = \begin{cases} \frac{\kappa p}{2b} + \frac{p}{2c_r} & \text{if } \kappa \in (0, \max(0, m_a^{-1}(\frac{\mu}{p}))] \\ \frac{p-\mu}{2b} + \frac{p-\mu}{2b} \kappa \frac{p-\mu}{2b} & \text{if } \kappa \in \left[\max(0, m_a^{-1}(\frac{\mu}{p})), \min(1, m_b^{-1}(\frac{\mu}{p}))\right] \\ 0 & \text{if } \kappa \in \left(\min(1, m_b^{-1}(\frac{\mu}{p})), 1\right] \end{cases},
\]

where:

- \( m_a(\kappa) = \frac{(1-\kappa)c_r-c_kb}{(1-\kappa)c_r} \leq 1 \) is a bijection for \( \kappa \in (0,1] \) and thus \( m_a^{-1}(\frac{\mu}{p}) = \frac{\mu}{p} \frac{1}{1 + \frac{\mu}{p}(1-\frac{\mu}{p})} \);
- \( m_b(\kappa) = \frac{1}{\frac{\mu}{p}} \geq 1 \) is a bijection for \( \kappa \in (0,1] \) and thus \( m_b^{-1}(\frac{\mu}{p}) = \frac{\mu}{p} \).

Letting \( \tilde{\kappa} := \max(0, m_a^{-1}(\frac{\mu}{p})) \), \( e_U^*(\kappa) \) does not depend on \( \kappa \) and hence, is constant in \( (0, \tilde{\kappa}) \). For \( \kappa \in (\tilde{\kappa}, \min(1, m_b^{-1}(\frac{\mu}{p}))) \), \( \frac{\partial^2 e_U^*(\kappa)}{\partial \kappa^2} = \frac{\mu(b+c_r)\kappa^2 - 2p(b+c_r)\kappa + c_r(2p-\mu)}{(2b+c_r)(1-\kappa)^2} \) has only one root at \( \bar{\kappa} = \frac{p-\mu}{2b} - \sqrt{\frac{p^2+c_r(p-\mu)^2+c_r^2(p-\mu)^2-2c_r(p-\mu)}{2b+c_r}} \), which is a maximum because \( \frac{\partial^2 e_U^*(\kappa)}{\partial \kappa^2} \leq 0 \), \( e_U^*(\bar{\kappa}) = \frac{\mu(p-\mu)}{2b+c_r} \), and \( e_U^*(\bar{\kappa}) > \max(0, \min(1, m_b^{-1}(\frac{\mu}{p})) \). Consequently, \( e_U^*(\kappa) \) is increasing for \( \kappa \in (\tilde{\kappa}, \bar{\kappa}) \) and decreasing for \( \kappa \in (\bar{\kappa}, 1] \). Lastly, with some algebra, we have \( \tilde{\kappa} = \frac{c_r(p-\mu)}{\mu (p+\mu)(p-\mu)} \frac{p-\mu}{p} \frac{1}{p} \frac{\mu}{p} \frac{1}{p} < \tilde{\kappa} = \frac{\kappa p}{2b+\kappa c_r(p-\mu)} \frac{p-\mu}{2b+\kappa c_r(p-\mu)} \frac{p-\mu}{2b+\kappa c_r(p-\mu)} \frac{p-\mu}{2b+\kappa c_r(p-\mu)} \).

Hence, the optimal total clean energy generation under the urban mining strategy is constant in \( (0, \tilde{\kappa}) \), increasing in \( (\tilde{\kappa}, \bar{\kappa}) \) and decreasing in \( (\bar{\kappa}, 1] \).

Proof of Proposition 6  We first show the producer’s expected profit under the combined strategy has strictly increasing differences in \( (\beta_C, r_C) \). A differentiable function \( g(x, y) \) has strictly increasing differences (SID) in two variables \( (x, y) \) if and only if \( \frac{\partial^2 g}{\partial x \partial y} > 0 \). Let \( \pi_C(q_C, r_C) = (1+\gamma)\beta_C(q_C+r_C)p-\gamma(1+\mu)\beta_C(1+\beta)\gamma(\gamma+1)(\gamma+2)\frac{h}{(1+\beta)\gamma((1+\beta)\gamma+1)} \). We take \( g(x, y) = E_A[\pi_C(q_C, r_C)|A] \) and \( (x, y) = (r_C, \beta_C) \). In the interior, we have \( \frac{\partial^2 E_A[\pi_C(q_C, r_C, \beta_C)|A]}{\partial \beta_C \partial \beta_C} = (1-\gamma)p - 2c_rj(1-\beta_C)^{-1}r_C \). Note that this expression is positive if and only if \( r_C < \frac{(1-\gamma)p}{2(1-\beta_C)}(1-\beta_C) \). Yet, by using the FOC, we have that the producer wants to choose \( r_C^*(\beta_C) = \frac{(1+\gamma)r_Cq_C(1+\beta_C)^{\gamma+1}}{2c_r(1+\beta)^{\gamma+1}} \). The inequality \( r_C^*(\beta_C) = \frac{(1+\gamma)r_Cq_C(1+\beta_C)^{\gamma+1}}{2c_r(1+\beta)^{\gamma+1}} < \frac{(1-\gamma)p-c}{2c_rj(1-\beta_C)^{-1}} \) is verified whenever \((1-\gamma)p-c)(\beta_C j - \beta_C - 1) + (p-c)j < 0 \). This inequality can only be true for \( j < \frac{(1-\gamma)p-c}{2c_rj(1-\beta_C)^{-1}} \). In the boundary, we have \( \frac{\partial^2 E_A[\pi_C(q_C, r_C, \beta_C)|A]}{\partial \beta_C \partial \beta_C} = (1-\gamma)p - \frac{1}{1-\kappa} - 2c_rj(1-\beta_C)^{-1}r_C \). Again, this expression is positive whenever \( r_C < \frac{(1-\gamma)p-c}{2(1-\beta_C)^{-1}} \). Yet, by using the FOC, we have \( r_C^*(\beta_C) = \frac{(1+\gamma)r_Cq_C(1+\beta_C)^{\gamma+1}}{2c_r(1+\beta)^{\gamma+1}} \). Let us define \( \gamma_{max}(j) = \frac{(1+\gamma)r_Cq_C(1+\beta_C)^{\gamma+1}}{2c_r(1+\beta)^{\gamma+1}} < \frac{(1-\gamma)p-c}{2(1-\beta_C)^{-1}} \). The inequality \( r_C^*(\beta_C) = \frac{(1+\gamma)r_Cq_C(1+\beta_C)^{\gamma+1}}{2c_r(1+\beta)^{\gamma+1}} < \frac{(1-\gamma)p-c}{2(1-\beta_C)^{-1}} \) is verified whenever \( \gamma < \gamma_{max}(j) \). Lastly, we need to prove that \( \gamma_{max}(j) \) is decreasing in \( j \). Let us define the function \( h(j) = \frac{1}{(1-\gamma)p-c} - \frac{1}{\gamma_{max}(j)} \). Note that the sign of \( h'(j) \) is the same as the sign of \( \gamma_{max}'(j) \). Since \( h(j) = -\frac{1}{(1-\gamma)p-c} - \frac{1}{\gamma_{max}(j)} \) is decreasing in \( j \) because it is the sum of three terms which are all decreasing or constant in \( j \). Thus, \( \gamma_{max}(j) \) is decreasing in \( j \).
Proof of Proposition 7 Let \( \hat{\alpha}(\mu, \kappa) \) represent the participation threshold of the urban mining strategy and be defined as:

\[
\hat{\alpha}(\mu, \kappa) = \begin{cases} 
\frac{(p-\mu)^2 + \frac{\mu^2}{4c_r} - \frac{\phi(p-\mu-c)^2}{4b(\mu-(1-\gamma)c)^2}}{2b(\mu-(1-\gamma)c)^2} & \text{if } \mu < \min(\mu_a(\phi), \mu_a(\kappa))p \\
\frac{2(\mu-(1-\gamma)c)^2}{4b(\mu-(1-\gamma)c)^2} & \text{if } \min(\mu_a(\phi), \mu_a(\kappa))p \leq \mu < \mu_a(\phi) \\
\hat{\alpha}(\mu, \kappa) & \text{if } \mu \geq \mu_a(\phi) 
\end{cases}
\]

where \( \mu_a(\phi) \) and \( \mu_a(\kappa)p \) are defined in the proofs of Propositions 1 and 3. First, observe that \( \hat{\alpha}(\mu, \kappa) \leq \hat{\alpha}(\mu, \kappa) \) for \( \mu \geq \mu_a(\phi) \) by definition, and the relationship holds for \( \mu < \mu_a(\phi) \) as \( \mu < \mu_a(\phi) \) implies \( E_A[\pi_B(q_B^*|A)] < E_A[\pi_B(q_{B,M}^*, \beta^*|A)] \). Also note that by Proposition 1, \( \gamma \leq \frac{p-\epsilon}{q} \) is required for a material reduction strategy, and otherwise, the producer’s only choice is between urban mining and benchmark as characterized in Proposition 3.

For solution (a) for \( \gamma \leq \frac{p-\epsilon}{q} \) by Proposition 1, a material reduction strategy is preferred to benchmark for \( \mu < \mu_a(\phi) \). The condition on \( \alpha \) follows by setting \( E[\Pi_M(q_{B,M}^*, \beta^*)] > E[\Pi_U(q_{U,M}^*, r^*)] \) and rearranging terms. There are two different thresholds if \( \mu_a(\phi) < \mu_a(\kappa)p \) as the boundary solution for urban mining emerges for \( \mu_a(\phi) \leq \mu < \mu_a(\kappa)p \). Solution (b) follows similarly for \( \mu < \mu_a(\phi) \). For \( \mu \geq \mu_a(\phi) \), the producer never chooses material reduction over the benchmark by Proposition 1, and for \( \mu < \mu_a(\kappa)p \), the producer prefers urban mining to benchmark as long as \( \alpha < \hat{\alpha}(\mu, \kappa) = \hat{\alpha}(\mu, \kappa) \) by Proposition 3. \( \square \)

Proof of Proposition 8 First, we show that \( e^*_U > e^*_B \) and \( e^*_M > e^*_B \) for any value of \( \mu \). If \( \mu < \mu_a(\kappa)p \), then \( e^*_U = \frac{\mu - \kappa \mu}{2b} + \frac{\mu}{2c_r} > \frac{\mu - \kappa \mu}{2b} = e^*_B \), and if \( \mu \geq \mu_a(\kappa)p \), then \( e^*_U = \frac{\mu - \kappa \mu}{2b} + \frac{2(\mu-(1-\gamma)c)^2}{2b(\mu-(1-\gamma)c)^2} \geq \frac{\mu - \kappa \mu}{2b} + \frac{2(\mu-(1-\gamma)c)^2}{2b(\mu-(1-\gamma)c)^2} > e^*_B \). Meanwhile, since \( \beta^* > 0 \), we have \( q_{B,M} > q_B^* \) by Proposition 2 and \( e^*_M = (1 + (1-\gamma)^2)q_{B,M} > q_{B,M}^* > q_B^* = e^*_B \).

Next, we show that there exists a scarcity threshold \( \hat{\mu} \in [p-c, p) \) that makes \( e^*_U > e^*_M \) whenever \( \mu > \hat{\mu} \) and \( e^*_U < e^*_M \) otherwise. Observe that for \( \mu \in [p-c, \mu_a(\kappa)p] \), \( e^*_M = e^*_B < e^*_U \). Thus, if \( \hat{\mu} \) exists, it must be that \( \hat{\mu} \in [0, p-c] \). Let \( f(\mu) := e^*_U(\mu) - e^*_M(\mu) \). Assume without loss of generality that \( \mu_a(\kappa)p < p-c \).

**Case A:** \( \mu \in [\mu_a(\kappa)p, p-c) \). Then, by Propositions 1 and 3:

\[
f(\mu) = \frac{p-\kappa \mu}{2b} + \frac{2\phi(p-\mu-c)(4b \phi - ((1-\gamma)p-c)((1-\gamma)\mu-\gamma c))}{(4b \phi - ((1-\gamma)p-c)\mu-\gamma c)^2}.
\]

Since \( f(\cdot) \) is a strictly concave, quadratic function with \( f(p-c) = e^*_U(p-c) > 0 \), \( f(\cdot) \) has exactly one root in \( [p-c, \infty) \) and at most one root in \( [\mu_a(\kappa)p, p-c) \). If \( f(\mu_a(\kappa)p) < 0 \), there is exactly one root in \( [\mu_a(\kappa)p, p-c) \), which we denote \( \hat{\mu} \) and the proof is complete, because \( f(\mu) > 0 \) and \( e^*_U(\mu) > e^*_M(\mu) \) for \( \mu \in (\hat{\mu}, p-c) \) and \( e^*_U(\mu) < e^*_M(\mu) \) for \( \mu \in [0, \hat{\mu}] \). If \( f(\mu_a(\kappa)p) > 0 \), then \( e^*_U(\mu) > e^*_M(\mu) \) for \( \mu \in [\mu_a(\kappa)p, p-c) \) and if \( \hat{\mu} \) exists, then \( \hat{\mu} < \mu_a(\kappa)p \).

**Case B: **\( \mu \in [0, \mu_a(\kappa)p) \). Then, by Propositions 1 and 3:

\[
f(\mu) = \frac{p-\mu}{2b} + \frac{2\phi(p-\mu-c)(4b \phi - ((1-\gamma)p-c)((1-\gamma)\mu-\gamma c))}{(4b \phi - ((1-\gamma)p-c)\mu-\gamma c)^2}.
\]

Since \( f(\cdot) \) is a strictly concave, quadratic function with \( f(\mu_a(\kappa)p) > 0 \), \( f(\cdot) \) has exactly one root in \( [0, \mu_a(\kappa)p) \), which we denote \( \hat{\mu} \) and the proof is complete as \( \hat{\mu} < \mu_a(\kappa)p < p-c \). Note that it could be that \( \hat{\mu} < 0 \), in which case \( f(\mu) > 0 \) for all \( \mu > 0 \) and the urban mining strategy always results in greater energy generation than the material reduction strategy.

Finally, if \( \mu_a(\kappa)p > p-c \), the proof follows similarly as in Cases A and B for the intervals \( \mu \in [p-c, \mu_a(\kappa)p] \) and \( \mu \in [0, p-c) \). \( \square \)
Proof of Corollary 1 Proposition 8 shows that $e_U^* > \max(e_M^*, e_B^*)$ for $\mu > \hat{\mu}$ and $e_M^* > \max(e_U^*, e_B^*)$ for $\mu \leq \hat{\mu}$. Meanwhile, as shown in the proof of Proposition 7, we know that if $\alpha \leq \hat{\alpha}(\mu, \kappa)$, then $E_A[\pi_U(q_U^*, r^*[A]) > \max(E_A[\pi_M(q_M^*, \beta^*[A]), E_A[\pi_B(q_B^*[A])])$ and the producer selects urban mining. \hfill \Box

Proof of Proposition 9 Following the Proof of Proposition 1, the participation threshold of the urban mining strategy can be written as:

$$
\bar{\alpha}(\mu, \kappa) = \begin{cases} 
\frac{(p-\mu)^2}{2(\mu-\kappa)} + \frac{\alpha^2}{4(\mu-\kappa)^2} - \frac{\phi(p-\mu-c)^2}{4\phi_0(4(\mu-\kappa)^2) - \phi(p-\mu-c)^2} & \text{if } \mu \leq \min(\mu_\alpha(\phi), m_\alpha(\kappa)p) \\
\frac{2\kappa^2(1-\gamma)^2}{(\mu-\kappa)^2} & \text{if } \min(\mu_\alpha(\phi), m_\alpha(\kappa)p) \leq \mu < \mu_\alpha(\phi) \\
\bar{\alpha}(\mu, \kappa) & \text{if } \mu \geq \mu_\alpha(\phi)
\end{cases}
$$

where $\mu_\alpha(\phi)$ and $m_\alpha(\kappa)p$ are defined in the proofs of Propositions 1 and 3.

Assume that $\min(\mu_\alpha(\phi), m_\alpha(\kappa)p) = m_\alpha(\kappa)p$. Then, $\bar{\alpha}(\mu, \kappa)$ does not depend on $\kappa$ and hence is constant in $[0, m_\alpha(\kappa)p)$ . For $\mu \in [m_\alpha(\kappa)p, \mu_\alpha(\phi))$, we find $\frac{\partial}{\partial \mu} \bar{\alpha}(\mu, \kappa) = \frac{(p-\mu)^2}{4(\mu-\kappa)^2} - \frac{\phi(p-\mu-c)^2}{4\phi_0(4(\mu-\kappa)^2) - \phi(p-\mu-c)^2} \leq 0$ and only if $\mu \geq m_\alpha(\kappa)p$. Finally, for $\mu \geq \mu_\alpha(\phi)$ we consider $\bar{\alpha}(\mu, \kappa)$ as given in the proof of Proposition 3, and we can show that, after some calculus, $\mu \geq m_\alpha(\kappa)p$ implies $\frac{\partial \bar{\alpha}(\kappa, \kappa)}{\partial \kappa} \leq 0$ and hence $\bar{\alpha}(\mu, \kappa)$ is decreasing in $\kappa$. Otherwise, if $\min(\mu_\alpha(\phi), m_\alpha(\kappa)p) = \mu_\alpha(\phi)$, $\bar{\alpha}(\mu, \kappa)$ does not depend on $\kappa$ and hence is constant in $[0, \mu_\alpha(\phi))$. For $\mu \geq \mu_\alpha(\phi)$, $\bar{\alpha}(\mu, \kappa)$ is decreasing in $\kappa$ because $\bar{\alpha}(\mu, \kappa)$ is decreasing in $\kappa$. \hfill \Box

Proof of Corollary 2 Following Proposition 1, we can write:

$$
q_M^*(\mu) - q_B^*(\mu) = \begin{cases} 
0 & \text{if } \mu < \mu_\alpha(\phi) \\
\frac{2\kappa^2(1-\gamma)^2}{(\mu-\kappa)^2} & \text{otherwise}
\end{cases}
$$

If $\mu < \mu_\alpha(\phi)$, then $\frac{\partial}{\partial \mu} (q_M^*(\mu) - q_B^*(\mu)) = 0$. Otherwise, $\frac{\partial}{\partial \mu} (q_M^*(\mu) - q_B^*(\mu)) = \frac{1}{2\kappa^2} - \frac{1}{2b+2c, (1-\gamma)^2} > 0$.

Following Proposition 3, we can write:

$$
q_U^*(\mu) - q_B^*(\mu) = \begin{cases} 
\frac{\kappa(\mu-\kappa)^2}{2b(\mu-\kappa)^2} - \frac{\mu^2 - \kappa^2}{2b} & \text{if } \alpha \leq \bar{\alpha}(\mu, \kappa) \text{ and } \mu \in [m_\alpha(\kappa)p, m_\alpha(\kappa)p] \\
0 & \text{otherwise}
\end{cases}
$$

If $\alpha \leq \bar{\alpha}(\mu, \kappa)$ and $\mu \in [m_\alpha(\kappa)p, m_\alpha(\kappa)p]$, then $\frac{\partial}{\partial \mu} (q_U^*(\mu) - q_B^*(\mu)) = \frac{1}{2\kappa^2} - \frac{1}{2b+2c, (1-\gamma)^2} > 0$. Otherwise, $\frac{\partial}{\partial \mu} (q_U^*(\mu) - q_B^*(\mu)) = 0$. \hfill \Box

Proof of Proposition 10 For $F_A$ describing the cumulative distribution function of $A$, and $\Pi_i(\cdot)$ representing the ex-post profits of the producer under strategy $i$, we have $\rho_B = P(\Pi_B(q_B^*) > 0|q_B^* > 0) = P\left(\frac{(p-A)^2-(A-\mu)^2}{4b} \leq 0\right) = P\left(\frac{(p-A)^2-(A-\mu)^2}{4b} \leq 0\right) = P\left(A > \frac{p+\mu}{2}\right) = 1 - F_A\left(\frac{p+\mu}{2}\right)$. Similarly, $\rho_M = P(\Pi_M(q_M^*, \beta^*) < 0|q_M^* > 0, \beta^* > 0) = P\left(\frac{(p-\alpha)(p-\mu+c+2A)}{4b\phi_0(p-\mu+c+2A)^2} \leq 0\right) = P\left(A > \frac{p+\mu+c}{2}\right) = 1 - F_A\left(\frac{p+\mu+c}{2}\right)$ for $\phi > \frac{(p-\alpha)(p-\mu+c+2A)}{4b\phi_0(p-\mu+c+2A)^2}$. As $F_A$ is a distribution and $c > 0$, we have $F_A\left(\frac{p+\mu+c}{2}\right) < F_A\left(\frac{p+\mu}{2}\right)$ and thus $\rho_B < \rho_M$.

Let $m_\alpha(\kappa) = \frac{(1-\kappa)c_{\alpha \kappa} + \kappa c_\mu}{1-\kappa}$. For $\mu < m_\alpha(\kappa)p$, we have $\rho_U = P(\Pi_U(q_U^*, r^*) < 0|q_U^* > 0, r^* > 0, \mu < m_\alpha(\kappa)p) = P\left(\frac{p^2-\alpha - (\alpha+p)^2-(A-\mu)^2}{4b} \leq 0\right) = P\left(A > \frac{p+\mu}{2} + 2b\frac{p^2-\alpha}{4c} \geq \alpha\right) = 1 - F_A\left(\frac{p+\mu}{2} + 2b\frac{p^2-\alpha}{4c}\right)$.

Since $F_A\left(\frac{p+\mu}{2} + 2b\frac{p^2-\alpha}{4c}\right) > F_A\left(\frac{p+\mu}{2}\right)$, we have $\rho_U < \rho_B$ for $\mu \in [0, m_\alpha(\kappa)p]$.

For $\mu \geq m_\alpha(\kappa)p$, we have $\rho_U = P(\Pi_U(q_U^*, r^*) < 0|q_U^* > 0, r^* > 0, \mu \geq m_\alpha(\kappa)p) = P\left(\frac{p^2+\phi^2-2\alpha(\mu-p)}{4b(1-\kappa)^2} \leq 0\right) = P\left(A > \frac{p+\mu}{2} - \frac{4a(b^2+c+1-\kappa)^2}{2\phi_0(p-\mu)}\right) = 1 - F_A\left(\frac{p+\mu}{2} - \frac{4a(b^2+c+1-\kappa)^2}{2\phi_0(p-\mu)}\right)$. Then, $\rho_U < \rho_B$ if $F_A\left(\frac{p+\mu}{2} - \frac{4a(b^2+c+1-\kappa)^2}{2\phi_0(p-\mu)}\right) > 0$. \hfill \Box
which happens whenever both $\alpha < \tilde{\alpha}(\mu, \kappa)$ and $\alpha < \bar{\alpha}(\mu, \kappa) := \frac{p(1-\kappa) \mu (p-\kappa \mu)}{4e \gamma(1-\kappa^2) + 4 \rho \kappa}$. Note that for $\mu \in [m_a(\kappa)p, p]$, we have $\bar{\alpha}(\mu, \kappa) \leq \tilde{\alpha}(\mu, \kappa)$. Thus, $\rho_U < \rho_B$ when $\alpha < \bar{\alpha}(\mu, \kappa)$ and $\rho_U > \rho_B$ when $\bar{\alpha}(\mu, \kappa) < \alpha < \tilde{\alpha}(\mu, \kappa)$, for $\mu \in [m_a(\kappa)p, p]$.

Proof of Corollary 3 Proposition 10 shows that $\rho_B < \rho_M$ always, whereas $\rho_U < \rho_B$ for when $\mu \in [0, m_a(\kappa)p]$ if $\alpha < \tilde{\alpha}(\mu, \kappa)$ and when $\mu \in [m_a(\kappa)p, p]$ if $\alpha < \bar{\alpha}(\mu, \kappa)$. Otherwise, $\rho_U > \rho_B$ otherwise. Meanwhile, as shown in the proof of Proposition 7, we know that if $\alpha \leq \bar{\alpha}(\mu, \kappa)$, then $E_A[\pi_M(a^*_M, b^*_M|A)] > \max(E_A[\pi_M(q^*_M, \beta^*_M|A)], E_A[\pi_B(q^*_B|A)])$ and the producer selects urban mining whereas the producer selects benchmark when $\alpha > \tilde{\alpha}(\mu, \kappa)$ and $\mu > m_a(\phi)$. This allows us to fully characterize the incentive compatibility areas.

B. Producer Competition

We consider an extension of our model with $N$ symmetric, price-taking producers competing for the critical material. All other details and assumptions are identical in setting to our original model. The equilibrium outcomes in the $N$-player setting mimic the optimal solutions of a single producer, albeit scaled by a factor of $\frac{2N}{N+1}$. Our key propositions, structural results and insights continue to hold with some adjustments on the optimality conditions and parameter ranges for this scaling factor. For brevity, only proof sketches are provided for the results in this section and full proofs are available from the authors upon request.

Benchmark strategy. In the benchmark setting, each producer $i \in \{1, \ldots, N\}$ solves the following program, given the decisions $q^*_B$ of all other producers $\ell \in \{1, \ldots, i-1, i+1, \ldots, N\}$:

$$\max_{q^*_i} \mathbb{E}_A \left[ q^*_B p - (A + b \sum_{\ell=1}^{N} q^*_\ell)q^*_B \right].$$

(A.1)

The objective function is concave and continuously differentiable, and the first-order conditions characterize the best response of producer $i$ (given other producers’ decisions $q^*_B$):

$$p - \mu - b \sum_{\ell=1}^{N} q^*_\ell = bq^*_i, \quad \forall i.$$ 

It is straightforward to identify a symmetric equilibrium. Letting $q^*_B = q^B$ for all $i = 1, \ldots, N$, we find the optimal benchmark solution for the producers to be $q^B = \frac{p - \mu}{\rho (N+1)p}$. The range of production under the benchmark strategy remains unchanged at $\mu < p$.

Material reduction. Under the material reduction strategy, each producer $i \in \{1, \ldots, N\}$ solves (given the decisions $q^*_B$ of all other producers $\ell \in \{1, \ldots, i-1, i+1, \ldots, N\}$):

$$\max_{q^*_i \geq 0} -\phi(\beta^i)^2 + \max_{q^*_M \geq 0} \mathbb{E}_A \left[ (1 + (1-\gamma)\beta^i)q^*_Mp - (A + b \sum_{\ell=1}^{N} q^*_\ell)q^*_M - (1 + \beta^i)q^*_M c \mathbf{1}_{\beta^i > 0} \right].$$

Solving for the second-stage first, we find the symmetric optimal strategy (characterized by the first-order conditions) for any producer $i$ to be: $q^*_i(\beta^i) = \left( \frac{p(1+\beta^i(1-\gamma)-\mu)-(1+\beta^i)c}{(N+1)p} \right)^{\frac{1}{2}}$. Observe that $q^*_i(0) = q^B$. Substituting $q^*_M(\beta^i)$ in, we find the unique maximizer as $\beta^i = \left( \frac{(1-\gamma)p-c}{(N+1)p} \right)^{\frac{1}{2}}$ as long as the concavity condition holds, i.e., $\phi > \frac{(1-\gamma)p-c}{(N+1)p}$. Then, the optimal virgin material purchase decision for each producer can be written as $q^*_i = q^M = \frac{(N+1)p \mu - \mu \phi}{(N+1)^2 \rho - (1-\gamma)p}. \phi$. The formal proof follows that of Proposition 1. The efficiency loss threshold for entry remains the same at $\gamma \leq \frac{\rho}{p}$ as in the single producer setting. The production
takes place when \( \mu \) is lower than a bounded threshold \( \mu_{a,N}(\phi) \leq p - c \) that depends on the number of producers, and while lengthy, can be derived in closed form by setting the profits under material reduction to be higher than in the benchmark for each producer. We find that the threshold \( \mu_{a,N}(\phi) \in [0, p - c] \) decreases with the number of producers \( N \) or the investment cost \( \phi \). Figure EC.1 plots the optimal material reduction investment \( \beta^i \) and the virgin material procurement \( q^M \) for each producer, along with the resulting total clean energy generation \( e^N_M(\beta^i, q^M) = N(1 + (1 - \gamma)\beta^i)q^M \) for \( N = 1, N = 2 \) and \( N = 5 \).

\[ \mu_{a,N}(\phi) \in [0, p - c] \]

Figure EC.1 Producer decisions in material reduction with competition.

Note. Optimal material reduction investment \( \beta^i \), virgin material procurement \( q^M \), and total clean energy generation \( e^N_M(\beta^i, q^M) \) as a function of scarcity level \( \mu \), for \( N = 1, N = 2 \) and \( N = 5 \). Our parameter space is \( p = 1.615, b = 0.0000003, c = 0.01, \gamma = 0.065, \) and \( \phi = 3.74M \).

Essentially, higher competition results in a more aggressive extraction of the virgin material, scaling up the need for materials and amplifying scarcity concerns. As a result, as number of players increase, less investment is made into material reduction per producer. Notably, we find that material reduction suffers from the Jevons’ paradox as stated in Proposition 2 for any number of producers, i.e., \( q^N > q^B \) if any material reduction investment is made.

**Urban mining.** In the urban mining strategy, we first let each producer invest in their own recycling plant and process their own product returns. In this case, each producer \( i \in \{1, ..., N\} \) solves the following program, given the decisions of all other producers \( i' \in \{1, ..., i - 1, i + 1, ..., N\} \):

\[
\max_{q_U^i, r^i, r^i} \mathbb{E}_A \left[ (q_U^i + r^i) p - (A + b \sum_{j=1}^{N} q_U^j)q_U^i - c_i (r^i)^2 - \alpha \mathbbm{1}_{r^i > 0} \right]
\]

s. t. \( r^i \leq (1 - \kappa)(r^i + q_U^i) \).

The symmetric optimal strategy for any producer is given by (following the steps outlined in the proof of Proposition 3):

(Interior): \( (q_U^i, r^i) = \left( \frac{p - \mu}{(N+1)b} + \frac{p - \mu}{2c}, \frac{\kappa(p - \mu)(1 - \kappa)}{(N+1)b(1 - \kappa)^2} \right) \) if \( \mu < m_{a,N}(\kappa)p \).

(Boundary): \( (q_U^i, r^i) = \left( \frac{\kappa(p - \mu)(1 - \kappa)}{(N+1)b(1 - \kappa)^2}, \frac{N(1 - \kappa)(p - \mu)}{(N+1)b(1 - \kappa)^2} \right) \) if \( m_{a,N}(\kappa)p \leq \mu < m_b(\kappa)p \).

Here, \( m_{a,N}(\kappa) = \left( 1 - \frac{\kappa}{1 - \kappa} \right) \frac{N+1}{2c} < m_a(\kappa) \) so as more players enter, the region for an interior equilibrium shrinks and is only possible for increasingly lower scarcity values. The upper bound on scarcity for a boundary
solution, interestingly, remains at \( m_i(\kappa)p = p/\kappa \) as in the single producer case, which implies that the region for a boundary solution grows larger as more players enter. The investment cost threshold on \( \alpha \) for entry remains the same for an interior equilibrium, but depends on the number of players for a boundary solution, and can be derived by setting the profits under urban mining to be higher than in the benchmark for each producer, i.e., \( E_A[\pi_U(q^*_i, r^i|A)] > E_A[\pi_B(q^*_j|A)] \). We plot the equilibrium virgin material purchase \( q^*_i \) and the optimal recycling quantity \( r^i \) for each producer, along with the resulting total clean energy generation \( e^N_U \) for \( N = 1, N = 2 \) and \( N = 5 \).

**Figure EC.2 Producer decisions in urban mining with competition.**

![Image](image.png)

*Note.* Optimal recycled material \( r^i \), optimal virgin material procurement \( q^*_i \), and resulting clean energy generation \( e^N_U \) as a function of scarcity level \( \mu \), for \( N = 1, N = 2 \) and \( N = 5 \). Our parameter space is \( p = 1.615, b = c_r = 0.0000003, \alpha = 0, \) and \( \kappa = 0.2 \).

**Producer’s optimal strategy and policymaker objectives** In Figure EC.3, letters \{B, M, U\} label the regions where the optimal strategy selection of a producer is the benchmark, material reduction or urban mining, respectively. We observe that competition discourages urban mining strategy. The shading in Figure EC.3 highlights the regions where the producer incentives are not aligned with the policy objectives. In the dashed regions, the policymaker prefers material reduction strategy, and in the dotted regions, the policymaker prefers the urban mining strategy. As competition intensifies, the misalignment region for the material reduction strategy shrinks, while the misalignment in urban mining grows.

Finally, we find that profitability comparisons as stated in Proposition 10 continue to hold in the competitive setting. Specifically, material reduction always increases the probability of negative profits for a producer. With urban mining, the probability of negative profits will reduce for a producer unless the fixed cost of investment is very high.

**Urban mining with shared investment costs** In an urban mining strategy, competing producers have the possibility of sharing the investment costs for the recycling and recovery infrastructure. In the most extreme scenario with full cooperation, each producer covers \( \alpha/N \) portion of the fixed cost. With shared investment costs, the equilibrium decisions \( (q^*_i, r^i) \) remain unchanged for all producers \( i \in \{1, \ldots, N\} \) but urban mining becomes much more attractive - the investment cost threshold required for entry scale up by
Figure EC.3  Producer strategies and their alignment with policymaker goals with competition.

**Note.** Here, $p = 1.615$, $b = c_r = 0.0000003$, $\kappa = 0.2$, $c = 0.01$, $\gamma = 0.065$, and $\phi = 3.74M$. $\alpha$ values go up to $25M$ and $\mu$ values go up to $2p$. Panels show results for $N = 1$, $N = 5$ and $N = 20$, resp. Letters B, M, U represent the benchmark, material reduction and urban mining strategies for the producer, resp.

a factor of $N$ for both the interior and the boundary solutions. Figure EC.4 shows the regions where the optimal strategy selection of a producer is the benchmark, material reduction or urban mining, respectively, for different number of producers. When investment costs can be shared, competition encourages urban mining. As number of producers increase, urban mining becomes more and more attractive and after a certain point, material reduction ceases to be a viable strategy for the producers.

Figure EC.4  Producer strategies and their alignment with policymaker goals with competition (shared costs).

**Note.** Here, $p = 1.615$, $b = c_r = 0.0000003$, $\kappa = 0.2$, $c = 0.01$, $\gamma = 0.065$, and $\phi = 3.74M$. $\alpha$ values go up to $25M$ and $\mu$ values go up to $2p$. Panels show results for $N = 1$, $N = 5$ and $N = 20$, resp. Letters B, M, U represent the benchmark, material reduction and urban mining strategies for the producer, resp.

C. Cost trade-offs in material reduction strategy

We consider two cost trade-offs associated with production under the material reduction strategy, which lets $\beta$ additional products to be produced with the same amount of critical raw material in comparison to the
benchmark setting. Our specifications for these cost trade-offs are motivated by practice. For instance, the use of silver in solar panels can be reduced by (1) partially substituting the lines of silver by another metal, such as copper or nickel (Han et al. 2022, Grübel et al. 2022, Chen et al. 2023) or (2) employing a more sophisticated printing method FlexTrail which can reduce around 60% of the silver compared to traditional screen printing (Schube et al. 2022).

The first-trade-off considers the additional procurement cost for the substitute, non-scarce raw material, and is represented by the parameter $c_m$. Accordingly, these additional material purchase costs scale with the amount of material reduction $\beta$, leading to total additional material purchase costs of $c_m\beta q_M$. In our main analysis, we set $c_m = 0$ for simplicity of the exposition, and without loss of generality. Such a scenario would arise if substitution is driven by efficiency improvements without the need for additional materials, or if the substitute material is abundant and has a negligible price. In subsection C.1 below, we present the general version of our model with $c_m > 0$, and show that our results are robust to this generalization. In particular, setting $c_m > 0$ is equivalent to our simplified setting with a slightly higher efficiency loss parameter $\gamma$.

The second trade-off focuses solely on the change in processing costs associated with the new product design, lack of any material price considerations, and is represented by the parameter $c$. Our original analysis assumes a constant increase of $c > 0$ in processing costs associated with the new product design after material reduction, which does not scale with $\beta$. Yet, one could argue that higher levels of material reduction would result in increasingly higher additional costs of processing. Subsection C.2 below presents an extension where the additional processing costs $c$ also increase in the amount of material reduction and shows that our key results are robust to this specification. The presence of increasing marginal processing costs dampens down the optimal investment and production quantities of the producer. However, all of our key insights continue to hold directionally, and in particular, our key result regarding the scarcity rebound effect (or Jevons’ paradox) is maintained.

### C.1. Costs of purchasing a substitute material

Under a general setting with $c_m > 0$, the producer’s profit can be written as (note that concavity in the original problem ($c_M = 0$) implies concavity in the generalized version):

$$
\max_{\beta \geq 0} -\phi \beta^2 + \max_{q_M \geq 0} E_A [\pi_M^{\text{mat}}(q_M|A, \beta, c_m)],
$$

where

$$
\pi_M^{\text{mat}}(q_M|A, \beta, c_m) = (1 + (1 - \gamma)\beta) q_M p - (A + b q_M) q_M - (1 + \beta) q_M c \mathbb{1}_{\beta > 0} - c_m \beta q_M.
$$

Observe that $\pi_M^{\text{mat}}(q_M|A, \beta, c_m) = \pi_M(q_M|A, \beta) - c_m \beta q_M$, where $\pi_M(q_M|A, \beta, \gamma = \gamma_0)$ is the producer’s profit function in the original model (where we denote the efficiency trade-off associated with material reduction by $\gamma_0$). Then, $\pi_M^{\text{mat}}(q_M|A, \beta, c_m) = \pi_M(q_M|A, \beta, \gamma = \hat{\gamma})$ if one sets $\hat{\gamma} := \gamma_0 + \frac{c_m}{p}$. In other words, considering the substitute material costs to be non-zero is equivalent to setting $c_m = 0$ with an additional loss in efficiency, as $\hat{\gamma} > \gamma_0$ for positive values of $c_m$. As a result, the generalized setting with $c_m > 0$ preserves all of our main results and insights. We observe the following minor differences, primarily due to the reduced profit margin of the producer since each additional unit of substitute material has a marginal cost of $c$ and provides a marginal benefit of $(1 - \gamma)p = (1 - \gamma_0)p - c_m$. 

[Note: The text is truncated due to the limitations of the model, and further details are omitted for the sake of brevity.]
• **Producer entry conditions:** The producer does not invest in material reduction when \( \gamma_0 \geq \frac{\mu - c_m - c_m}{\beta} \), as opposed to \( \gamma_0 \geq \frac{\mu - c_m}{\beta} \) in our original formulation as presented in Proposition 1. In turn, the scarcity threshold below which the producer chooses Material Reduction over Benchmark decreases as \( \gamma \) increases, i.e., \( \frac{\partial \gamma}{\partial \gamma} < 0 \). Thus, for \( \hat{\gamma} > \gamma_0 \), the region for which the producer chooses Material Reduction over Benchmark shrinks compared to the region in the original problem. Similarly, when \( c_m > 0 \), one gets a larger range where urban mining is chosen over material reduction since \( \frac{\partial \hat{\gamma}(\mu, \kappa)}{\partial \gamma} \leq 0 \) and \( \hat{\gamma} > \gamma_0 \), where \( \hat{\alpha}(\mu, \kappa) \) is the investment cost that makes the producer indifferent between investing in Urban Mining or not, i.e.,
\[ E[\Pi_U(q^*_U, r^*)] = \max(E[\Pi_M(q^*_M, \beta^*)], E[\Pi_B(q^*_B)]) \]

• **Investment and production decisions:** The optimal investment level into material reduction \( \beta^* \) and the optimal virgin material purchase \( q^*_M \) are both smaller under \( c_m > 0 \), as both quantities are decreasing in \( \gamma \). Yet, subject to participation, the results related to Jevon’s paradox continues to hold, as that result does not depend on the value of \( \gamma \).

• **Policymaker insights:** The threshold \( \hat{\mu} \) (over which urban mining would result in a greater degree of installations than material reduction as presented in Proposition 8) is lower with \( c_m > 0 \), as \( \frac{\partial \hat{\mu}}{\partial \gamma} \leq 0 \) and \( \hat{\gamma} > \gamma_0 \). Consequently, the scarcity threshold under which the material reduction strategy results in greater energy generation than urban mining shrinks since \( e^*_U(\hat{\mu}) = c^*_M(\hat{\mu}) \). Thus, setting \( c_m > 0 \) has an ambiguous effect on the incentive misalignment areas defined in Proposition 1, because it increases the parameter range in which urban mining is chosen over material reduction but decreases the parameter range in which urban mining results in greater energy generation than material reduction.

### C.2. Convexity of additional processing costs

In our original formulation, the additional processing costs associated with material reduction are linear in the amount of installations made by the producer and are given by \((1 + \beta)q M 1_{\beta > 0}\). Assume that the marginal additional processing costs from material reduction increase with \( \beta \) instead and are given by \((1 + \beta)(c_1 + \beta)q M 1_{\beta > 0}\) for a parameter \( c_1 > 0 \). Then, the producer’s problem found in Equation (2) becomes:

\[
\max_{\beta \geq 0} -\phi(\beta_{conv})^2 + \max_{q_{conv}, M \geq 0} E_A \left[ \pi_{conv}^{conv}(q_{conv}, M | A, \beta_{conv}) \right],
\]

where \( \pi_{conv}^{conv}(q_{conv}, M | A, \beta_{conv}) = (1 + (1 - \gamma)\beta_{conv})q M P - (A + b q_{conv}, M)q_{conv}, M \)

\[= R \text{Revenue from product sales} - (1 + \beta_{conv})q_{conv}, M (c + c_1 \beta_{conv}) 1_{\beta_{conv} > 0} \text{Additional processing costs} \]

Proposition A1 characterizes the solution to the producer’s problem given in Equation A.2. In particular, the generalization to convex increasing additional processing costs makes the material reduction strategy a less favoured option for the producer. That is, with lower installations and profits at the optimum, material reduction is the optimal strategy for a smaller range of parameters.

**Proposition A1.** There exists a scarcity threshold \( \mu_4(\phi) \) so that when (i) efficiency loss from material reduction is small, i.e., \( \gamma \leq \frac{\mu - c_m - c_1}{\beta} \), and (ii) material scarcity is lower than the threshold, i.e., \( \mu <
\(\mu(\phi)\), the producer’s problem has a unique solution \((q_{\text{conv,M}^*, \beta_{\text{conv}}}^*)\) that is bounded above by \((\zeta_{\text{conv}}^*, \beta_{\text{conv}}^*) = \left(\frac{1}{\mu} \left(p - \mu - c + \frac{(1-\gamma)(p-c-e \cdot \phi)}{2e_1}\right), \frac{1-\gamma}{2e_1}\right)\). Otherwise, \(\beta_{\text{conv}}^* = 0\), and no investment is made into material reduction.

**Proof of Proposition A1.** We first show that the problem given in Equation A.2 is concave. Let \(f_{\text{conv}}\) be the objective function of the producer’s problem given in Equation A.2 and let \(H_{\text{conv}}(q_{\text{conv,M}^*, \beta_{\text{conv}}}^*)\) be its Hessian:

\[
H_{\text{conv}}(q_{\text{conv,M}^*, \beta_{\text{conv}}}^*) = \begin{pmatrix}
\frac{\partial^2 f_{\text{conv}}}{\partial q_{\text{conv,M}^*, \beta_{\text{conv}}}^*} & \frac{\partial^2 f_{\text{conv}}}{\partial q_{\text{conv,M}^*, \beta_{\text{conv}}}^*} \\
\frac{\partial^2 f_{\text{conv}}}{\partial q_{\text{conv,M}^*, \beta_{\text{conv}}}^*} & \frac{\partial^2 f_{\text{conv}}}{\partial q_{\text{conv,M}^*, \beta_{\text{conv}}}^*}
\end{pmatrix} = \begin{pmatrix}
-2b & (1-\gamma)p - c - c_1 - 2c_1 \beta_{\text{conv}}^* \\
2\beta_{\text{conv}}^* & 2b
\end{pmatrix}.
\]

As \(b > 0\), \(f_{\text{conv}}(q_{\text{conv,M}^*, \beta_{\text{conv}}}^*)\) is strictly concave if \(2b(2q_{\text{conv,M}^*}c_1 + 2\phi) > [(1-\gamma)p - c - c_1 - 2c_1 \beta_{\text{conv}}^*]^2\).

This is true for any \(q_{\text{conv,M}^*} \geq 0\) and any \(\beta_{\text{conv}}^* > 0\) as long as the original problem is concave, i.e., as long as \(\phi > \phi\), because by assumption \(c_1 > 0\). Then, the first-order condition is sufficient to identify \(q_{\text{conv,M}^*}^*(\beta_{\text{conv}}^*) = \frac{(1-\gamma)(p-c-e \cdot \phi)(1-\gamma)p - c - c_1 - 2c_1 \beta_{\text{conv}}^*)}{(1+(1-\gamma)\beta_{\text{conv}}^*)p-\mu-(1+\beta_{\text{conv}}^*)(c+c_1 \beta_{\text{conv}}^*)}\).

We next find the optimal investment level \(\beta_{\text{conv}}^*\) by maximizing \(f_{\text{conv}}(q_{\text{conv,M}^*, \beta_{\text{conv}}}^*)\). Setting \(\frac{df_{\text{conv}}(q_{\text{conv,M}^*, \beta_{\text{conv}}}^*)}{d\beta_{\text{conv}}^*} = -2\phi \beta_{\text{conv}}^* + ((1-\gamma)p - c - c_1 - 2c_1 \beta_{\text{conv}}^*) = 0\) gives us the unique maximizer for the unconstrained problem \(\beta_{\text{conv}, u}^*\). Let us define \(f(X) = -2\phi X + ((1-\gamma)p - c - c_1 - c_1 X)(1+(1-\gamma)X)p-\mu-(1+\beta_{\text{conv}}^*)(c+c_1 \beta_{\text{conv}}^*)\), which is a third degree polynomial whose limits \(\lim_{x \to \infty} f(x) = -\infty\) and \(\lim_{x \to -\infty} f(x) = \infty\). The function \(f(x)\) has at most 3 roots, which would be the possible values of \(\beta_{\text{conv}, u}^*\). Since \(f(0) > 0\), \(f(x)\) has at least one positive root. Since \(f\left((-\sqrt{(1-\gamma)p-c-e \cdot \phi})^2+4c(p-\mu)-(1-\gamma)p-c-e \cdot \phi\right) < 0\), \(f(x)\) has at least 2 negative roots. Thus, \(f(x)\) has exactly one positive root. Furthermore, since \(f\left((-\sqrt{(1-\gamma)p-c-e \cdot \phi})^2+4c(p-\mu)-(1-\gamma)p-c-e \cdot \phi\right) < 0\), \(f(x)\) can guarantee that \(\beta_{\text{conv}, u}^* < \frac{(1-\gamma)p-c-e \cdot \phi}{2e_1} = \overline{\beta}_{\text{conv}}\). Since \(q_{\text{conv,M}^*}^*(\beta_{\text{conv}}^*)\) is maximized at \(\overline{\beta}_{\text{conv}}\), we can further define \(\overline{\zeta}_{\text{conv}} = q_{\text{conv,M}^*}^*(\overline{\beta}_{\text{conv}})\).

**COROLLARY EC.1.** The optimal levels of material reduction and the optimal procurement of virgin material with convex costs are lower than the optimal levels of material reduction and the optimal procurement of virgin material with linear costs, i.e., \(\beta_{\text{conv}}^* \leq \beta^*\) and \(q_{\text{conv,M}^*}^* \leq q_{M}^*\).

**Proof of Corollary EC.1.** Let \(\beta_{\text{conv}}(c_1)\) be the maximizer of \(f_{\text{conv}}(q_{\text{conv,M}^*}^*(\beta_{\text{conv}})), \beta_{\text{conv}}\), and let \(\beta^*\) be the optimal \(\beta\) in the original problem. Note that \(\beta_{\text{conv}}(0) = \beta^*\) and that \(f_{\text{conv}}(q_{\text{conv,M}^*}, \beta)\) has strictly decreasing differences in \((\beta, c_1)\). Thus, \(c_1 > 0\) implies \(\beta_{u, \text{conv}, c_1}(c_1) < \beta_u^*\). It follows that \(\beta_{\text{conv}}^* \leq \beta^*\). With a similar argument, we can conclude that \(q_{\text{conv,M}^*}^* \leq q_{M}^*\).

Proposition A1 and its corollary above imply that assuming convex increasing additional processing costs results in the material reduction strategy being a less favoured option for the producer. Indeed, with lower installations and profits at the optimum, Material Reduction is the optimal strategy for a smaller range of parameters. Yet, assuming a \(c_1 > 0\) does not change the structure of our insights compared to the case where \(c_1 = 0\). In particular, Proposition A2 below shows that Jevon’s paradox introduced in Proposition 2 continues to hold. All of our other key results are robust to the convex processing cost assumption, albeit with a smaller range of parameters for which the material reduction strategy is optimal. The detailed proofs for these follow in a similar fashion, and are available from the authors upon request.
PROPOSITION A2. Jevon’s paradox continues to hold for convex processing costs associated with the material reduction strategy: Subject to the producer choosing the material reduction strategy, the total virgin consumption of the scarce material is greater than in the benchmark strategy, i.e., $q_{\text{conv},M}^* > q_{B}^*$.

Proof of Proposition A2. Assume that $\beta_{\text{conv}}^* > 0$, which implies that $E_A[\pi_B(q_{B}^*)] < f_{\text{conv}}(q_{\text{conv},M}^*, \beta_{\text{u,conv}}^*)$, which implies the following condition holds:

$\left( (1 - \gamma)\beta_{\text{conv}}p - (1 + \beta_{\text{conv}})(c + c_1\beta_{\text{conv}}) \right) \left( \frac{p - \mu}{2b} + \frac{(1 - \gamma)\beta_{\text{conv}}p - (1 + \beta_{\text{conv}})(c + c_1\beta_{\text{conv}})}{4b} \right) \geq \phi b_{\text{conv}}^2 > 0$

For the above condition to hold, it must be that the expression $\left( (1 - \gamma)\beta_{\text{conv}}p - (1 + \beta_{\text{conv}})(c + c_1\beta_{\text{conv}}) \right)$ and $\left( \frac{p - \mu}{2b} + \frac{(1 - \gamma)\beta_{\text{conv}}p - (1 + \beta_{\text{conv}})(c + c_1\beta_{\text{conv}})}{4b} \right)$ have the same sign. Yet, since $q_{\text{conv},M}(\beta_{\text{conv}}) = \left( \frac{p - \mu}{2b} + \frac{(1 - \gamma)\beta_{\text{conv}}p - (1 + \beta_{\text{conv}})(c + c_1\beta_{\text{conv}})}{4b} \right)$, we know that $\left( \frac{p - \mu}{2b} + \frac{(1 - \gamma)\beta_{\text{conv}}p - (1 + \beta_{\text{conv}})(c + c_1\beta_{\text{conv}})}{4b} \right) > 0$. This implies that $\frac{p - \mu}{2b} + \frac{(1 - \gamma)\beta_{\text{conv}}p - (1 + \beta_{\text{conv}})(c + c_1\beta_{\text{conv}})}{2b} > \frac{p - \mu}{2b}$, i.e., $q_{\text{conv},M}^* > q_{B}^*$.

Observe that $\pi_{\text{conv}}^M(q_{\text{conv},M}|A, \beta_{\text{conv}}) = \pi_M(q_{\text{conv},M}|A, \beta_{\text{conv}}) - c_1(1 + \beta_{\text{conv}})q_{\text{conv},M}\beta_{\text{conv}}$, where $\pi_M(q_{\text{M}}|A, \beta, \ldots)$ is the producer’s profit function in the original model (where the processing costs are linear in the material reduction level). Thus, under the assumption $c_1 > 0$, $q_{\text{conv},M} \geq 0$ and $\beta_{\text{conv}} \geq 0$, the introduction of convex costs in the material reduction strategy result lower incentives for the producer to choose material reduction over the other strategies compared to the case where $c_1 = 0$. Furthermore, it results in a worse performance in terms of clean energy installations and probability of ex-post negative profits.

Following a similar rationale than in Appendix C.1, this results in (1) a weakly higher threshold $\hat{\alpha}(\mu, \kappa)$ for the investment cost $\alpha$ below which the producer chooses urban mining over material reduction or benchmark, and (2) a strictly lower threshold $\hat{\mu}$ for the scarcity $\mu$ over which choosing urban mining results in greater clean energy generation. Thus, setting $c_m > 0$ has an ambiguous effect on the incentive misalignment areas defined in Proposition 1, because it increases the parameter range in which urban mining is chosen over material reduction but decreases the parameter range in which urban mining results in greater energy generation than material reduction.

D. Characterization of the systemic leakage

Consider a finite lifecycle of a clean energy technology spanning $T$ periods with $T > 1$. At each period $t \in [1, T]$, $q_t$ units of virgin material and $r_t$ units of recycled material is used in the production of new clean energy products which then reach their end-of-life at the end of period $t$. We assume that no products exist before $t = 1$, and the technology is no longer in the market after $t = T$, i.e., the last production cycle happens at $t = T$. Furthermore, let $h_t \in [0, 1]$ represent the systemic leakage at period $t$, where $h_t = 0$ indicates a perfectly circular system where all critical material can be recovered from the end-of-life products, and $h_t = 1$ means no material can be recovered.

In period $t = 1$, all production happens with $q_1$ units of virgin material as there is no recycled material ($r_1 = 0$). At the end of $t = 1$, period 1 products reach their end-of-life and the $q_1$ units of virgin material in them are available for recycling. However, only a fraction $(1 - h_1)q_1$ of the materials in these products can
be recovered due to systemic leakage, while $h_1q_1$ are lost. Therefore, the recycled material that can be used in production at $t = 2$ is limited to $r_2 \leq (1 - h_1)q_1$. During $t = 2$, $q_2$ units of virgin material and $r_2$ units of recycled material are used in production. At the end of $t = 2$, period 2 products reach their end-of-life, and systemic leakage allows for the recovery of at most $(1 - h_2)(q_2 + r_2)$ units of the critical material in them. Thus, the amount of recycled material that can be used in production in period 3 is constrained by $r_3 \leq (1 - h_2)(q_2 + r_2)$, and so on for all subsequent periods.

In other words, for all $t \in [2, T]$, $q_t$ units of virgin material and $r_t$ units of recycled material can be used in production subject to $r_t \leq (1 - h_{t-1})(q_{t-1} + r_{t-1})$, and the maximum recoverable critical material at the end of each period $t$ is $(1 - h_t)(q_t + r_t)$, which limits $r_{t+1}$, the recycled material available for use in the next period. We define the total virgin and the total recycled material used in the lifecycle horizon as $q$ and $r$, respectively, where

$$q \overset{\text{def}}{=} \sum_{t=1}^T q_t, \quad \text{and} \quad r \overset{\text{def}}{=} \sum_{t=2}^T r_t \leq (1 - h_1)q_1 + \sum_{t=2}^{T-1} (1 - h_t)(q_t + r_t).$$

Let us further assume that material inputs are uniformly spread through the lifecycle, i.e., $q_t = \frac{1}{T} q$ for all $t \in [1, T]$ and $r_t = \frac{1}{T-1} r$ for all $t \in [2, T]$. Then, with some re-arrangement:

$$r \leq (T - 1) \frac{T - 1 - \sum_{t=1}^{T-1} h_t}{T(T - 1) + 1 - Th_1 + \sum_{t=1}^{T-1} h_t} (q + r).$$

Now, define $\kappa$ as the total systemic leakage over $[0, T]$:

$$\kappa \overset{\text{def}}{=} 1 - (T - 1) \frac{T - 1 - \sum_{t=1}^{T-1} h_t}{T(T - 1) + 1 - Th_1 + \sum_{t=1}^{T-1} h_t} = \frac{T (1 - h_1 + \sum_{t=1}^{T-1} h_t)}{T(T - 1) + 1 - Th_1 + \sum_{t=1}^{T-1} h_t},$$

which implies $r \leq (1 - \kappa)(q + r)$ as used in our model set-up. Note that even if there is no systemic leakage throughout the lifecycle, i.e., $h_t = 0$ for all $t$, the circularity of the system is imperfect due to the initial need for virgin material in the first period, which makes $\kappa > 0$. Likewise, full systemic leakage with $h_t = 1$ for all $t$ implies the total systemic leakage $\kappa = 1$.

Whenever $T$ is finite, the total systemic leakage in $\kappa$ depends on the number of periods $T$ because the products installed in the last period cannot be recovered, and on the initial leakage $h_1$ because no recycling can happen in the first period. Let us assume that the systemic leakage in each period $h_t$ has a long-term average $h$, that is, $\lim_{T \to \infty} \frac{1}{T-1} \sum_{t=1}^{T-1} h_t \to h$. Then, in a steady-state scenario when $T \to \infty$, the total systemic leakage tends to the average systemic leakage of each period, i.e., $\kappa \to h$. Our single-period setting can thus represent both finite and infinite-horizon settings; in the infinite-horizon setting, this formulation is robust to the timing when the clean energy products were installed.

E. Temporal effects in supply-demand imbalance

Clean energy products can only be recycled when they are decommissioned, which happens some time after their installation. Furthermore, during this time lag, the clean energy product’s lifecycle might evolve, meaning that the demand for the clean energy product might increase or shrink by the time that the material from previously installed products can be recycled. In this extension, we investigate the effect of a temporal lag in the presence of product lifecycle effects.
We limit our analysis to the simplest non-trivial set-up with 2 periods, and model the decision-making of a strategic and forward-looking producer. Our notation for the producer’s decisions mimics the single-period setting: For each period $t$, $q_t$ represents the amount of virgin raw material used in the production of the clean energy products in period $t$, $r_t$ represents the amount of recycled raw material assuming the producer invests in urban mining, and $\beta_t$ represents the level of producer’s investment in material reduction. We exclude the simultaneous undertaking of the material reduction and urban mining, where the complementarity of the two strategies follow similarly to the combined strategy analysis in §4.4.

We assume that the price of the scarce raw material $s_t(.)$ depends on the quantities of the virgin raw material purchased in the past, as well as on a random base price, just like in the single-period model. We allow the random base price $A_t$ to be different at each period, although with the same expected value, i.e., $E[A_t] = \mu$. The price of the commodity in period $t$ can then be written as $s_t(A_t, q_1, ..., q_t) = A_t + b \sum_{i=1}^{t} q_i$.

As discussed, the producer’s recycling decisions are constrained by previous virgin material installations. While clean energy products often have long lifetimes, there are several reasons in practice for the products to be retired much earlier: (1) production scrap generated during the manufacturing process — in the case of REE-base magnets, 30% of magnet alloys end up in scraps during manufacture (Screen 2023); (2) early replacement of products by consumers due to financial incentives (Duran et al. 2022a); and (3) product failures due to early malfunction (IRENA 2018). Because of the long product lifespans, the producer can recover more products installed in the first period than products installed in the second period where only early retirement products (e.g. production scrap, early deteriorated or early replacement) can be recycled.

We thus consider two systemic leakage parameters: (1) a base systemic leakage $\kappa$, akin to the systemic leakage used in our single-period model, covering the limits to recycling due to loss of material to other markets, low collection rates due to dumping, exporting or an immature collection ecosystem, etc., and (2) a dynamics-related systemic leakage $\kappa_2$, covering the limits to recycling due to the temporal lag between installations and decommissioning. We thus assume that the producer can recover in period 2 up to $1 - \kappa$ of the material in the installations made in period 1, but only $1 - \kappa - \kappa_2$ of the material in the installations made in period 2. This results in the following systemic leakage constraint: $r_2 \leq (1 - \kappa)q_1 + (1 - \kappa\kappa_2)(q_2 + r_2)$.

As discussed, the demand for the clean energy product might evolve throughout the lifecycle, and be different in each period. We introduce the parameter $\Delta$ to represent the demand for the product that falls under period 2 (versus period 1), capturing the relative size of the two periods to account for either market expansion or market shrinking. We assume a demand function in period $i$ of $p_i(e_i) = p(1 - \nu e_i)$, and again assume that the relative size of the clean energy market to the total energy market is small, so that the producer is a price-taker and $\nu \approx 0$. This means that the price of energy in P1 and P2 will be $p$ and $\Delta p$, respectively. Note that our Appendix I.2 extends our single-period analysis to the case where the producer has some pricing power (and thus $\nu > 0$).

In what follows, we construct the two-period model progressively by first investigating the Benchmark strategy in both periods (see §E.1). Next, we consider the case where the producer can additionally choose to invest in Material Reduction in the first period, the second period, or in both (see §E.2). Finally, we allow the producer to choose Urban Mining in the second period (see §E.3). In each setting, the producer
is strategic and maximizes the sum of the expected profits in both periods, without any discount factor. We compare the equilibrium outcomes between the three scenarios in §E.4 and plot the respective incentive misalignment zones with regards to the policy objective of maximizing clean energy generation.

### E.1. Benchmark strategy

Let us define \( \pi_1,B(q_1,B) \) and \( \pi_2,B(q_2,B|q_1,B) \) as the profits from producing an installing the clean energy technology product in each of the two periods of the product’s lifecycle.

\[
\pi_1,B(q_1,B) = E_{A_1}[pq_1,B - s_1(A_1,q_1,B)q_1,B]
\]

\[
\pi_2,B(q_2,B|q_1,B) = \max_{q_2,B \geq 0} E_{A_2}[\Delta pq_2,B - s_2(A_2,q_1,B + q_2,B)q_2,B]
\]

The strategic producer chooses each period’s production quantities to maximize the total profits over the whole product lifecycle: \( \pi_1,B(q_1,B) + \pi_2,B(q_2,B|q_1,B) \}. This results in 4 different equilibria as characterized below, which are shown in Figure EC.5.

\[
q^*_1,B = \begin{cases} \frac{\mu - \mu_p}{2\Delta} & \text{if } \Delta < \frac{1}{2} + \frac{\mu}{2p} \text{ and } p > \mu \\ \frac{\mu + \mu_p}{2\Delta} & \text{if } \frac{1}{2} + \frac{\mu}{2p} < \Delta < 2 - \frac{\mu}{p} \\ 0 & \text{otherwise} \end{cases}
\]

\[
q^*_2,B = \begin{cases} 0 & \text{if } \Delta < \frac{1}{2} + \frac{\mu}{2p} \text{ and } p > \mu \\ \frac{\Delta \mu - \mu_p}{2\Delta} & \text{if } \frac{1}{2} + \frac{\mu}{2p} < \Delta < 2 - \frac{\mu}{p} \\ \frac{\Delta \mu - \mu_p}{2\Delta} & \text{if } \Delta > \max\left(\frac{\mu}{p}, 2 - \frac{\mu}{p}\right) \end{cases}
\]

The producer chooses to produce when the mean market-price \( \mu \) for the material is small enough to result in expected profits, as in the single-period setting. However, depending on whether the industry is in a growth or shrink phase, the producer may decide to produce everything in the first period (shrinking industry with small \( \Delta \)), produce everything in the second period (growing industry with large \( \Delta \)), or produce in both.

Indeed, even if \( \mu \) is small enough (i.e., it is profitable to install in the first period), if the market is growing it might be optimal for the producer to delay all installations to period 2, so that the inexpensive commodity is saved for later. If \( \mu \) is small and \( \Delta \) is moderate, the producer installs some positive quantity in both periods. Finally, if \( \Delta \) is small, the producer installs everything in the first period because it is not worth it to wait. We plot the optimal installations as a function of the scarcity \( \mu \) for several values of \( \Delta \) (representing market shrinkage, stationary market, and market expansion) in Figure EC.6. The total installations invariably fall as the scarcity increases, but the share of installations in period 2 increases with \( \Delta \).

### E.2. Material Reduction

Next, we analyze the case where Material Reduction is also a feasible strategy in any period, and the producer can invest in \( \beta_t \) for \( t \in 1,2 \). For tractability, we analyze the most favorable case for Material Reduction, i.e., when there is no trade-off on efficiency nor any additional processing costs from Material Reduction. Thus, we set \( \gamma = 0 \) and \( c = 0 \). This also allows us to identify the cases where, despite having adopted assumptions in favor of Material Reduction, Urban Mining still dominates in the long term. We define \( \pi_M(q_1,M, \beta_1, q_2,M, \beta_2) \)
as the profits from producing an installing the clean energy technology product in each of the two periods of the product’s lifecycle under material reduction:

\[
\pi_M(q_{1,M}, \beta_1, q_{2,M}, \beta_2) = E_{A_1, A_2}[(1 + \beta_1)pq_{1,M} + (1 + \beta_1 + \beta_2)\Delta pq_{2,M} - s_1(A_1, q_{1,M})q_{1,M} - s_2(A_2, q_{1,M} + q_{2,M})q_{2,M} - \phi(\beta_1 + \beta_2)^2]
\]

Note that the profit function is concave in \((q_{1,M}, q_{2,M})\) for any positive value of \(\beta_1\) and \(\beta_2\). Thus, we can obtain the maximum values of the virgin material procurement quantities through the first order condition, as a function of \(\beta_1\) and \(\beta_2\). We find that the optimal investments are \(\beta_1^* > 0\) and \(\beta_2^* = 0\). Thus, the producer always chooses to invest in Material Reduction in the first period, and does not invest further in the second period. Intuitively, since R&D costs are the same regardless of the period of investment, it makes sense for the producer to invest as soon as possible so as to reap the benefits of material reduction in both periods.
Given a concave problem, the 4 possible equilibria when the producer is allowed to invest in material reduction are shown in Figure EC.7 and are characterized as (with $\beta^*_2 = 0$):

\[ q^*_1 = \begin{cases} 
\frac{(\Delta - 1)\Delta p^2 - 2b\phi(\mu + (\Delta - 2)\mu)}{4b\phi - 2(\Delta - 1)\Delta + 1)p^2} & \text{if } \mu < C_1 \text{ and } \mu < C_2 \\
0 & \text{if } \mu > C_1 \\
\frac{2\phi(p - \mu)}{4\phi - p^2} & \text{if } \mu < C_1 \text{ and } \mu > C_2 
\end{cases} \]

\[ q^*_2 = \begin{cases} 
\frac{2b\phi(\mu - 2\Delta p + p + (\Delta - 1)\mu)}{6b\phi - 2(\Delta - 1)\Delta + 1)p^2} & \text{if } \mu < C_1 \text{ and } \mu < C_2 \\
\frac{2b\phi(\mu - 2\Delta p - p)}{2(\Delta - 1)\Delta + 1)p^2} & \text{if } \mu > C_1 \text{ and } \mu < C_2 \\
0 & \text{otherwise} 
\end{cases} \]

\[ \beta^*_1 = \begin{cases} 
\frac{p(-\Delta \mu - \mu + 2\Delta_2 p - 2\Delta p + 2p)}{2(3b\phi - \Delta^2 p^2 + 3\Delta p^2 - p^2)} & \text{if } \mu < C_1 \text{ and } \mu < C_2 \\
\frac{2p(\mu - 2\Delta p - p)}{4b\phi - 3\Delta p^2 + \Delta^2 p^2} & \text{if } \mu > C_1 \text{ and } \mu < C_2 \\
\frac{p(\mu - 2\Delta p - p)}{4b\phi - p^2} & \text{if } \mu < C_1 \text{ and } \mu > C_2 \\
0 & \text{otherwise} 
\end{cases} \]

where $C_1 := \frac{4b\phi - 2b\Delta \phi}{2b\phi - 3\Delta p^2 + \Delta^2 p^2}$ and $C_2 := \frac{4b\phi - 2b\Delta \phi}{2b\phi + \Delta^2 p^2 - p^2}$ are two constants. We find that Jevon’s paradox is verified in all cases (proofs are available from the authors).

Figure EC.7 Producer decisions in material reduction with temporal effects.

Note. $p = 1.615$, $b = 0.0000003$, $c = 0$, $\gamma = 0$, and $\phi = 15.7M$.

E.3. Urban Mining

Let us define $\pi_{1,B}(q_{1,U})$ and $\pi_{2,U}(q_{2,U}, r_{2,U} | q_{1,U})$ as the profits from producing an installing the clean energy technology product in each of the two periods of the product’s lifecycle, with the possibility of investing in Urban Mining in Period 2.

\[ \pi_{1,B}(q_{1,U}) = E_A[pq_{1,U} - s_1(A_1, q_{1,U})q_{1,U}] \]
\[
\pi_{2,u}(q_{2,u}, r_{2,u} | q_{1,b}) = E_{A_2}[\Delta p(q_{2,u} + r_{2,u}) - s_2(A_2, q_{1,b} + q_{2,b})q_{2,b} - c_rr_2^2 - \alpha_1 1_{r_2 > 0}]
\]

Note that if the producer chooses \( r_2 = 0 \), we fall back to the Benchmark case studied above.

The producer chooses each period’s quantities as to maximize the sum of the profits over the whole lifecycle (i.e., \( \pi_{1,b}(q_{1}) + \pi_{2,u}(q_{2}, r_{2} | q_{1}) \)) subject to \( r_2 \leq \frac{1 - \kappa - \kappa_2}{\kappa + \kappa_2} q_1 + \frac{1 - \kappa - \kappa_2}{\kappa + \kappa_2} q_2 \). This results in 2 regimes of equilibria depending on the magnitude of the effective systemic leakage in the second period (\( \kappa + \kappa_2 \)). Whenever this leakage is low, the producer has 7 possible equilibria, and when this leakage is high, the producer has 5 possible equilibria, which are all reproduced in Figure EC.8. The explicit description of each of the regions results in very crowded notation and is available from the authors upon request. The resulting equilibria have a similar structure, albeit more complicated, to the single-period results, as shown in Figure EC.8.

**Figure EC.8** Producer decisions in urban mining with temporal effects.

- **Urban Mining Equilibria (low \( \kappa + \kappa_2 \) regime)**
  - \( q_{1,b} = 0 \)
  - \( q_{2,b} > 0 \)
  - \( q_{2,b} > \)
  - \( q_{2,b} > \)
  - \( q_{2,b} = 0 \)
  - \( q_{2,b} = 0 \)

- **Urban Mining Equilibria (high \( \kappa + \kappa_2 \) regime)**
  - \( q_{1,b} > 0 \)
  - \( q_{2,b} > 0 \)
  - \( q_{1,b} = 0 \)
  - \( q_{2,b} = 0 \)
  - \( q_{1,b} = 0 \)
  - \( q_{2,b} = 0 \)

*Note.* Two regimes of equilibria arise depending on the sign of \( C(\kappa, \kappa_2, c_r / b) = 2(c_r / b)(1 - \kappa - \kappa_2)\kappa_2 - (\kappa + \kappa_2)^2 \), which is positive (negative) for low (high) values of \( \kappa + \kappa_2 \). Our parameter space is \( p = 1.615, b = c_r = 0.0000003, \alpha = 2.5M, \kappa = 0.2, \kappa_2 = 0.2 \) in the left plot and \( \kappa_2 = 0.6 \) in the right plot.

Intuitively, the producer chooses an interior solution for low values of scarcity (gray with red border area in Figure EC.8), in particular when the total systemic leakage is small (i.e., we are in the low leakage regime), and a boundary solution for higher values of scarcity. These boundaries evolve with the market growth parameter. If the industry is shrinking (i.e. \( \Delta << 1 \)), the producer installs more in the first period than in the second period, and does not have that many incentives to recycle in the second period. Thus, the producer is not constrained by the available end-of-life products, and falls more often in the interior solution. For intermediate values of the market growth parameter (i.e. \( \Delta \approx 1 \)), the producer balances its virgin procurement purchases in both periods; however, this makes the recycling activity more constrained, because the systemic leakage from installations in the second period is larger and thus there is less available material. If the industry grows (i.e. \( \Delta >> 1 \)), the producer has more incentives to generate clean energy in the second period, either by recycling or by purchasing virgin material. Here, two things might happen: if the systemic leakage is low enough, it is best for the producer to heavily install only in the second period, and
then recycle all clean energy products coming from early replacement. However, if the systemic leakage is too high, the producer is better-off keeping some installations in the first period to benefit from the recycling revenues in the second period, because they will suffer from a lower systemic leakage. Intuitively, this means that when the products have a long lifespan (i.e., $\kappa_2$ is large), and there is a large market expansion in the second period (i.e., $\Delta >> 1$), the producer will never find itself in the interior solution, and will always want to recycle as many products as possible.

We plot the optimal virgin and recycling material quantities as a function of the scarcity $\mu$ for several values of the market growth parameter (representing market shrinkage, stationary market, and market expansion) in Figure EC.9. Surprisingly, in the low leakage regime, we find that the amount of virgin material procurement in the first period can increase with scarcity for $\Delta >> 1$ (see green line in plot on the right of the low leakage regime part of Figure EC.9). There, recycling is the most attractive because of the high scarcity and high market potential. Thus, the producer increases the amount of installations in the first period to benefit from the reduced systemic leakage and be able to recycle more in the second period. Other than this phenomenon, the total virgin material purchases ($q_{1,U}^* + q_{2,U}^*$), the virgin material purchases in the second period ($q_{2,U}^*$), and the recycling ($r_2^*$) are all decreasing in the scarcity level $\mu$.

**Figure EC.9** Material procurement decisions of the producer in urban mining with temporal effects.

![Graph showing material procurement decisions](image)

Note. $p = 1.615$, $b = c_r = 0.0000003$, $\alpha = 2.5M$, $\kappa = 0.2$, $\kappa_2 = 0.2$ in the low leakage regime and $\kappa_2 = 0.6$ in the high leakage regime.

### E.4. Optimal strategy

We study now the optimal producer strategy amongst an investment in Material Reduction, an investment in Urban Mining, or no investment (Benchmark). Our numerical results are plot in Figure EC.10, which
shows that Urban Mining is the preferred strategy for intermediate values of \( \Delta \), whereas the producer is most likely to choose Material Reduction when \( \Delta \ll 1 \) or when \( \Delta \gg 1 \).

Intuitively, when the market is shrinking in the second period (i.e., when \( \Delta \ll 1 \)), there is very little potential to sell the products made out of recycled material. Since recycling only happens in the second period, the producer will thus avoid investing in Urban Mining altogether if the revenues from recycling are not enough to cover the fixed costs \( \alpha \). In comparison, the Material Reduction strategy can still make sense even if \( \Delta \ll 1 \) because the benefits from investing in \( \beta_1 \) are reaped early in the first period, so it might still make sense for the producer to invest in \( \beta_1 > 0 \) even if the market shrinks later on.

On the other extreme, when the market is growing in the second period (i.e., when \( \Delta \gg 1 \)), we find that greater margins result in more advantage to the Material Reduction strategy, because a greater market growth results in both higher investments in \( \beta_1^* \) and higher virgin procurement \( q_{1,M}^* \) and \( q_{2,M}^* \). Due to this double effect, the profits in the material reduction strategy grow faster as \( \Delta \) increases compared to the urban mining strategy.

Finally, we study numerically the alignment between the policymaker objective of maximizing clean energy generation and the producer’s optimal choices. We plot the incentive compatibility areas for various levels of market growth \( \Delta \) and systemic leakage \( \kappa_2 \) in Figures EC.11 and EC.12. The structure of the results in this 2-period model is very similar to the one-shot problem, save the non-monotonicity of the results with \( \Delta \). For very low values of \( \Delta \) (see upper left plot in Figures EC.11 and EC.12), urban mining is mostly not chosen as it is not worth it for the producer to invest in \( \alpha \) because of the low potential revenues to be obtained in the second period. In those cases, material reduction dominates urban mining both in terms of profit and installations for low values of scarcity, whereas for intermediate values of scarcity urban mining would have been better. When scarcity is very large, there is no clean energy generated under any strategy. For intermediate values of \( \Delta \) (upper right plot in Figures EC.11 and EC.12), the incentives to recycle grow.
and overall urban mining achieves a greater amount of clean energy generation because the incentive to recycle increases both the installations in period 1 and the recycling in period 2. Finally, for higher values of $\Delta$ (bottom plots in Figures EC.11 and EC.12), we reach the same incentive compatibility areas as in our original problem, albeit with a higher systemic leakage because we now account for both the base systemic leakage and the dynamics-related systemic leakage. Thus, for $\Delta > 1$, an expanded definition of the systemic leakage in the single-period model would allow us to capture these temporal dynamics effects.

Our results underline the importance of subsidizing the large capital investments needed for urban mining only when producers can expect a significant amount of recyclable end-of-life products whenever there is still demand for them, and their product lifecycle is not over. If the policymaker anticipates a shrinking demand, early technology investments like material reduction can be more effective because they do not suffer from this temporal lag between the investment and the reaping of its fruits.

Figure EC.11 Producer strategies and their alignment with policymaker goals with temporal effects.

Note. The preferred strategy for the producer is delimited by solid lines. Dotted (stripped) areas denote the ranges where the clean energy installations would be greater under the Urban Mining (Material Reduction) strategy, but the producer chooses otherwise. Our parameter space is $p = 1.615$, $b = c_r = 0.0000003$, $\kappa = \kappa_1 = 0.2$, $\kappa_2 = 0.2$, $c = 0$, $\gamma = 0$, and $\phi = 15.7M$. 
Note. The preferred strategy for the producer is delimited by solid lines. Dotted (stripped) areas denote the ranges where the clean energy installations would be greater under the Urban Mining (Material Reduction) strategy, but the producer chooses otherwise. Our parameter space is $p = 1.615$, $b = c_r = 0.0000003$, $\kappa = \kappa_1 = 0.2$, $\kappa_2 = 0.2$, $c = 0$, $\gamma = 0$, and $\phi = 15.7M$.

F. Modelling of an independent recycler

We model the case of a disaggregated supply chain with a producer and an independent recycler. The independent recycler may choose to enter the business of urban mining by incurring both the initial investment costs and the marginal recycling costs, and get revenues from selling the recycled raw material to the commodity market. Akin to the integrated setting, the producer gets revenues from the clean energy products at a margin $p$ per MWh of energy generated, and incurs the cost of purchasing the virgin raw material from the commodity market. In this case, the producer does not have the option to invest in urban mining itself.

We assume that the recycled material is a perfect substitute to the virgin material in the commodity market. Let $y_D$ be the total amount of material purchased from the commodity market by the producer. Contrary to our main model, where the producer chose how much of virgin material and recycled material to use in production, in this case the producer is unable to distinguish the virgin from the recycled material and purchases both from the commodity market at the same price. The recycler chooses the quantity of material to get from waste, $r_D$, subject to the systemic leakage constraint $r_D \leq (1 - \kappa)y_D$, which depends on the producer’s choice $y_D$. Given these choices, the price of material on the commodity market is given as
As a function of the recycler’s chosen recycling quantity \( y \), let \( \pi^P_R(y) = (A + b(y_D - r_D))y_D - \alpha r_D^2 \) be the objective function of the producer’s problem in the independent recycler case given in Equation A.3, and let \( \pi^R_P(y_D) = \max_{y_D \geq 0} \mathbb{E}_A [\pi^P_R(y_D) | A] \),

\[
\pi^R_P(y_D | A) = \underbrace{py_D}_{\text{Revenue from product sales}} - \underbrace{(A + b(y_D - r_D))y_D}_{\text{Critical material purchasing costs}}.
\]

Likewise, the recycler’s problem is written as:

\[
\max_{r_D \geq 0} \mathbb{E}_A [\pi^R_D(r_D | A)] \quad \text{subject to} \quad r_D \leq (1 - \kappa)y_D,
\]

\[
\pi^R_D(r_D | A) = (A + b(y_D - r_D))r_D - \alpha r_D^2 - \alpha 1_{r_D > 0}.
\]

The recycler and the producer make their optimal decisions simultaneously. There exist three possible Nash equilibria, described in Proposition A3.

**Proposition A3.** There exists a critical investment cost threshold \( \hat{\alpha}(\mu, \kappa) \) and a threshold \( \bar{m}_\alpha(\kappa) < 1 \), such that the Nash Equilibrium between the producer and the recycler is one of the three following cases:

- a. \((y_D^*, r_D^*) = \left( \frac{(2\mu(1 - \kappa)^2 - 2\kappa(1 + 2\kappa))}{\mu \kappa}, \frac{\kappa}{2\kappa} \right) \) is chosen whenever the scarcity of the critical material is mild, i.e., \( \mu < \bar{m}_\alpha(\kappa)p \), and the investment cost is lower than the threshold, i.e., \( \alpha < \hat{\alpha}(\mu, \kappa) \).

- b. \((y_D^*, r_D^*) = \left( \frac{p - \kappa}{2\kappa}, (1 - \kappa) \frac{\kappa}{2\kappa} \right) \) is chosen whenever the scarcity of the critical material is medium to severe, i.e., \( \bar{m}_\alpha(\kappa)p \leq \mu \leq p \), and the investment cost is lower than the threshold, i.e., \( \alpha < \hat{\alpha}(\mu, \kappa) \).

- c. The recycler chooses not to engage into urban mining whenever \( \alpha > \hat{\alpha}(\mu, \kappa) \). The producer then chooses a production quantity equal to the benchmark, i.e., \( (y_D^*, r_D^*) = (q_D^*, 0) \).

**Proof of Proposition A3** In a Nash Equilibrium, each player plays the best response against the others simultaneously. Let \( f^P_D(y_D) \) be the objective function of the producer’s problem in the independent recycler case given in Equation A.3, and let \( L^P_D(y_D, \lambda) \) be the Lagrangian of the recycler’s problem given in Equation A.4. We find the best response function of the producer as the optimal material purchase quantity \( y_D^*(r_D) \) as a function of the recycler’s chosen recycling quantity \( r_D \). Likewise, we find the best response function of the recycler as the optimal recycling quantity \( r_D^*(y_D) \) as a function of the producer’s chosen purchase quantity \( y_D \). Since \( f^P_D(y_D) \) is strictly concave in \( y_D \), the first-order condition is sufficient to characterize the best response function of the producer \( b_{r_D}(r_D) = y_D^*(r_D) = (\frac{p + br_D - \mu}{2b})^+ \). Likewise, since the Hessian of \( L^P_D \) is negative definite, the KKT conditions are sufficient to characterize the best response function of the recycler as:

\[
br_{r_D}(y_D) = r_D^*(y_D) = \begin{cases} \frac{\mu + by_D}{2b + 2c} & \text{if } y_D < \max \left( \frac{\mu}{b - 2\alpha + 2(1 - \kappa)c}, \frac{1}{b} \left( \sqrt{4(b + c)\alpha - \mu} \right) \right) \\
(1 - \kappa)y_D & \text{if } y_D \in \left( \frac{\mu}{b - 2\alpha + 2(1 - \kappa)c}, \frac{1}{b} \left( \sqrt{4(b + c)\alpha - \mu} \right) \right) \\
0 & \text{otherwise} \end{cases}
\]

Let \( \bar{m}_\alpha(\kappa) = \frac{2c(1 - \kappa) + b(1 - 2\kappa)}{2c(1 - \kappa) + b(1 - 2\kappa)} \) and \( \hat{\alpha}(\mu, \kappa) = \frac{(b+c)(\alpha+\mu)^2}{(b+4c)\alpha} \) if \( \mu \leq \bar{m}_\alpha(\kappa)p \) and \( \hat{\alpha}(\mu, \kappa) = \frac{(b+c)(\alpha+\mu)(\alpha+\mu)}{(b+4c)\alpha} \) if \( \mu \in (\bar{m}_\alpha(\kappa)p, p) \).

Then, three Nash Equilibria as defined in Proposition A3 exist, depending on the values of parameters \( \mu \) and \( \alpha \). \( \square \)
The optimal solutions for the producer in the vertically integrated supply chain, i.e., \((q_D^*, r^*)\) as described in Section 3.3.3, and the equilibrium decisions in supply chain with an independent recycler, i.e., \((q_D^*, r_D^*)\) as developed here, verify the properties described in Proposition A4.

**Proposition A4.** For the vertically integrated setting:

- The expected supply chain profits are greater, i.e., \(E_A[\pi^V(q_D^*, r^*) | A] \geq E_A[\pi_D^R(r_D^*) | A] + E_A[\pi_D^e(y_D^*) | A]\).
- The critical urban mining investment threshold is higher, i.e., \(\alpha(\mu, \kappa) \geq \alpha(\mu, \kappa)\).
- The total recycled quantities and the total energy generation are greater, i.e., \(e_i^V \geq D \) and \(r^* > r_D^*\).

**Proof of Proposition A4** In the case of an independent recycler, the expected supply chain profits are the sum of the producer’s and the recycler’s expected profits, i.e., \(\Pi^SC_D = E_A[\pi^R_D(r_D^*) | A] + E_A[\pi_D^e(q^*_D | A)]\). In the vertically-integrated case, the supply chain profits are the producer profits, i.e., \(\Pi^SC_V = E_A[\pi(q^*U, r^*) | A]\).

Following Propositions A3 and 3, we can compute the expected supply chain profits in both cases as:

\[
\Pi^SC_D = \begin{cases}
-\alpha + \frac{(\mu + p)^2(b + c_r)}{2(3b + 4c_r)^2} + \frac{(2p(b + c_r) - \mu(b + 2c))}{2} & \text{if } \mu < \mu_a(\kappa)p \\
0 & \text{otherwise}
\end{cases}
\]

\[
\Pi^SC_V = \begin{cases}
-\alpha + \frac{(\mu - p)^2}{4b} + \frac{p^2}{4c_r} & \text{if } \mu < \mu_a(\kappa)p \\
-\alpha + \frac{(\mu - p)^2}{4b} + \frac{p^2}{4c_r} & \text{if } m_a(\kappa)p \leq \mu \leq m_a(\kappa) \\
0 & \text{otherwise}
\end{cases}
\]

It can be verified that \(\Pi^SC_D < \Pi^SC_V\) for any value of \(\mu\). In particular, for \(\mu < \min(m_a(\kappa)p, m_a(\kappa)p)\), the inequality \(-\alpha + \frac{(\mu - p)^2}{4b} + \frac{p^2}{4c_r} \geq \alpha\) is always true. Assume without loss of generality that \(\mu_a(\kappa) = \min(m_a(\kappa)p, m_a(\kappa)p)\). For \(\mu \in [m_a(\kappa)p, m_a(\kappa)p]\), we can check that \(-\alpha + \frac{(\mu - p)^2}{4b} + \frac{p^2}{4c_r} \geq \alpha\) is true. For \(\mu > m_a(\kappa)p\), the inequality \(-\alpha + \frac{(\mu - p)^2}{4b} + \frac{p^2}{4c_r} \geq \alpha\) is always true. Finally, note that if \(m_a(\kappa)p = \min(m_a(\kappa)p, m_a(\kappa)p)\), the inequality \(-\alpha + \frac{(\mu - p)^2}{4b} + \frac{p^2}{4c_r} \geq \alpha\) is true for that range of values of \(\mu\).

We can show that critical urban mining investment threshold is higher in the vertically integrated setting than in the independent recycler setting, i.e., \(\alpha(\mu, \kappa) \geq \alpha(\mu, \kappa)\) by verifying that, when the required initial investment is \(\alpha(\mu, \kappa)\), the producer in the vertically integrated setting still gets positive profits. Assume \(\alpha = \alpha(\mu, \kappa)\). Then, by definition, we have \(E_A[\pi^R_D(r_D^*) | A] = 0\). The supply chain profits in the vertically integrated setting are greater than in the independent recycler setting. Assume \(\mu < p\), and thus \(q_D^* > 0\). It follows that \(E_A[\pi^V(q_D^*, r^*) | A, \alpha = \alpha(\mu, \kappa)] \geq E_A[\pi^R_D(r_D^*) | A, \alpha = \alpha(\mu, \kappa)] + E_A[\pi_D^e(y_D^*) | A, \alpha = \alpha(\mu, \kappa)] \geq 0 \)

\(\Pi^V < \Pi^R_D\) if \(\mu \geq p\), \(\alpha(\mu, \kappa) = 0\) and thus the inequality is always true.

Finally, it can be verified that \(r^* > r_D^*\) for any value of \(\mu\). Specifically:

- If \(\mu \in [0, \min(m_a(\kappa), m_a(\kappa))p]\), the inequality \(\frac{p}{2c_r} > \frac{p^2}{3b + 4c_r}\) is always true.
- If \(m_a(\kappa)p = \min(m_a(\kappa)p, m_a(\kappa)p)\) and \(\mu \in [m_a(\kappa)p, m_a(\kappa)p]\), then it can be shown that \(\mu < m_a(\kappa)p \rightarrow r^* > r_D^*\) in that domain.
- If \(m_a(\kappa)p = \min(m_a(\kappa)p, m_a(\kappa)p)\) and \(\mu \in [m_a(\kappa)p, m_a(\kappa)p]\), then it can be shown that \(\mu < m_a(\kappa)p \rightarrow r^* > r_D^*\) in that domain.
• If \( \mu \in [\max(m_a(\kappa), \bar{m}_a(\kappa))p, p) \), \((1 - \kappa) \frac{\mu - \kappa \mu}{2b\kappa^2 + 2cr(1 - \kappa)^2} > (1 - \kappa) \frac{\mu - \kappa \mu}{2b\kappa^2} \) is always true.

• Finally, if \( \mu \geq p \), we have \( r^* = 0 = r^*_D \).

A similar argument can be made when comparing \( e^*_U = q^*_U + r^* \) (as defined in Proposition 3) and \( e^*_D = y^*_D \) to verify that \( e^*_U \geq e^*_D, \forall \mu \geq 0 \). □

Proposition A4 highlights the consequences of decoupling production and urban mining. In the presence of scarcity, separating the production and the recycling activities leads to lower supply chain profitability and clean energy generation. Such degraded outcomes are caused for two reasons. First, the decoupling of manufacturing and urban mining leads to a double marginalization which reduces the producer’s profitability and energy generation. Second, because the producer and the recycler are not integrated, the recycled material is sold to the commodity market and is thus potentially purchased by actors in other industries. This second phenomenon contributes to additional material leakage from the closed system, which hurts production and ultimately recycling volumes.

G. Rate-dependent reverse logistics costs

Reverse supply chains often display two types of costs related to product recovery:

Volume-dependent reverse logistics costs scale with the volume of recycled products. These costs may be related to the scale of collection, transportation, disassembling, shredding or separation of the components, etc. In many reverse supply chains, such costs display diseconomies of scale in the processed volume. Following the sustainable OM literature (Ferguson and Toktay 2006, Ovchinnikov 2011, Atasu et al. 2009, Atasu and Souza 2013), our paper assumes volume-dependent costs for the urban mining process as convex in the recycling volume \( r_i \), i.e., as \( c_r r^2 \).

Rate-dependent reverse logistics costs, on the other hand, are associated with securing a supply of used products to be collected (e.g., advertising). A common modelling choice is to set the level of investment necessary to reach a certain collection rate as a convex function of such rate (Savaskan et al. 2004) - in our case, this would imply a cost function that would be convex increasing in \( \frac{r}{q_U + r} \). In this case, the partial derivatives of the recycling costs would satisfy: \( \frac{\partial c_r(q_U, r)}{\partial q_U} < 0 \) and \( \frac{\partial c_r(q_U, r)}{\partial r} > 0 \). We could incorporate this into the model by writing the producer’s problem in urban mining as:

\[
\max_{q_U, r_I} \pi_U(q_U, r_I | A) = (q_U + r_I)p - (A + bq_U)q_U + cr_I > 0 - c_I \left( \frac{r_I}{q_U + r_I} \right)^2
\]

subject to \( r_I \leq (1 - \kappa)(q_U, r_I) \)

(A.5)

(A.6)

The formal derivation of results in this section are omitted in the interest of space, and are available from the authors upon request. Rate-dependent costs result in greater virgin material purchases both at the interior and boundary solutions of the Urban Mining equilibrium. Furthermore, rate-dependent costs can cause the producer to source a larger share from virgin material compared to recycling. Thus, whenever the virgin purchases are constrained by high scarcity levels (as \( \mu \) grows), the profitability of the strategy falls quickly despite the greater installation volumes. Thus, under rate-related costs, the areas of Urban Mining incentive misalignment - i.e., the set of parameters for which there is more clean energy installations under
Urban Mining but the producer does not choose to invest in it - are exacerbated. Intuitively, hitting the systemic leakage boundary leads to a fixed rate of recycling and thus a fixed cost to acquire it. However, as scarcity increases, revenues and volumes fall, and such fixed cost might be too important and leads to Urban Mining becoming unprofitable and to the producer choosing another strategy.

In a more realistic set-up, both types of costs could be present, although, considering them simultaneously makes the model lose tractability (Atasu et al. 2013). Yet, we expect a mixed modelling choice to favor urban mining. We use our calibrated example on PV panels to compute the regions where each strategy would be optimal when considering the following expression for the producer’s profit under the Urban Mining strategy:

$$\max_{q_U(\rho), r(\rho)} \pi_U(q_U, r|A, \rho) = \max_{q_U(\rho), r(\rho)} \left( (q_U + r)p - (A + bq_U)q_U - \alpha \mathbb{1}_{r > 0} - \rho c_v r^2 - (1 - \rho)c_I \left( \frac{r}{q_U + r} \right)^2 \right)$$

Where $\rho$ represents the relative importance of volume-related recycling costs versus rate-related recycling costs. Our current modelling choice is $\rho = 1$, whereas $\rho = 0$ gives the cost structure studied in Equation G, and $0 < \rho < 1$ gives a mixed cost structure.

We plot the resulting chosen strategy in Figure EC.13. As expected, when $\rho$ decreases, Urban Mining is favoured for low scarcity values (i.e., whenever virgin material can be purchased abundantly), but loses profitability for high scarcity values because whenever the producer is constrained by the availability of virgin materials, the cost of reaching a fixed rate of recycling becomes too high.

**Figure EC.13** Producer strategies under different reverse-logistics cost structures.

Note. Panels depict optimal producer strategy with pure Rate-dependent costs (i.e., $\rho = 0$), Mixed costs (with $\rho = 0.5$), and Value-dependent costs (i.e., $\rho = 1$), resp. Here, $p = 1.74$, $b = 0.0000006$, $c = 0.2$, $\gamma = 0.065$, $\phi = 2M$, $c_R = b$ and $c_I = 1M$. 


H. Details of the calibrated numerical study

Solar energy is essential to the clean energy transition and represents the majority share in clean capacity expansion plans (Nijsse et al. 2023). The photovoltaic panel market is dominated by crystalline silicon (c-Si) technologies, which depend on silver as a conductor in their solar cells (IEA 2021). The demand for silver is expected to grow in the coming years, driven largely to the photovoltaic industry which will make up for 30% of the silver demand by 2030, up from 14% today (Silver Institute 2023). Meanwhile, existing supply constraints and flat to declining stocks are driving silver prices up (Laursen 2024). Overall, solar panels and silver are a good illustration of a key clean energy technology’s reliance on a scarce material. We provide here a detailed description of the methods and sources that we have used to calibrate our models and figures throughout the paper by following a similar approach to Agrawal and Bellos (2017).

In our calibration, we use euros (€) and MWh as our standard units. For currencies, we use the currency conversion rate of the European Central Bank (i.e., 1€ = 1.1393$ on average over the past 10 years). For material weights, we estimate the needs of material equivalent to producing 1 MWh of solar energy. Since material weights are often given in terms of the capacity (in Watts or Megawatts) of a panel rather than on the energy produced by it, we need to make an assumption about the total number of hours that a PV panel produces energy. We do so by assuming 6 hours of insolation a day in France, 365 days a year, for a lifetime of 20 years and with a 0.5% yearly degradation in capacity (NREL 2018). Note that this is a rather optimistic estimation, as solar panels might be replaced earlier than their estimated lifetimes due to consumer choices or early deterioration (Duran et al. 2022b, IRENA 2020), and insolation might be lower at higher latitudes. Given that a modern PERC solar panel uses around 15.05 mg of silver per peak-capacity Watt (Hallam et al. 2023), approximately 0.36 grams of silver are needed to produce 1 MWh of solar energy. We will call this amount a "unit" of silver throughout our numerical calibration.

We estimate the cost of recycling solar panels $c_r$ through the activity reports of 2021 and 2022 of Soren, France’s Producer Responsibility Organization dedicated to the recycling of solar panels (Soren 2021, 2022). In their reports, Soren estimates that 0.032% of the mass of the panels is silver, which gives us the approximation that around 1.1-1.2 tons of silver are treated each year. We then estimate the parameter $c_r$ as the operating costs divided by the square of the units of silver treated each year. Both years give us very close numbers (2.92e−7 and 3.08e−7): we use their average in future calculations, namely $c_r = 0.0000003€/unit^2$.

We infer the efficiency loss upon engaging in material reduction $\gamma$ by comparing the increase in silver consumption (in mg of silver per solar panel cell) versus the improvement in efficiency (in mg of silver per W) when switching from SHJ and TopCon technologies to PERC technologies. We find that, with the same amount of silver, 57% more cells of PERC than TopCon can be produced, but that they only produce around 54% more in W. Similarly, with the same amount of silver, 136% more of PERC cells can be produced than SHJ cells, but they only yield 125% more energy (Hallam et al. 2023). This gives us an estimate of the efficiency loss of 0.053 − 0.083, of which we take the average and use $\gamma = 0.068$.

We take the price of the clean energy product $p$ as the price of the module given by the NREL net of all costs not related to silver cost Woodhouse et al. (2019). Namely, we input the EBIT (0.06 $/watt) plus the price of the silver paste (0.013 $/watt). We then scale this figure to the amount of MWh that can be
produced with 1 Watt of solar panel capacity over its lifetime. This gives us an estimate of $p = 1.6158$/MWh. Likewise, we convert the price of silver in 2020-2024 from 238$/troy (INSEE 2024) to $\mu_{\text{silver}} = 0.379$/unit.

We can infer an upper bound for the additional processing costs upon engaging in material reduction (i.e., $c$) through the remaining direct manufacturing costs for cell conversion in Woodhouse et al. (2019), which gives us a range $c \in [0, 0.531]$$/unit if we assume that at most 50% of them will be linked to material reduction. In most plots, we use an intermediate value of $c = 0.2$. In the extensions described in Appendices B, E and I.2, we set values of $c$ close to 0 for exposition purposes.

We provide a range of values for the effect of the virgin purchases on material price ($b$) in relation to the cost of recycling $c_r$. We study three scenarios: (1) the effect of the virgin purchases on the material price is low compared to the recycling costs ($b < c_r$), (2) the effect of the virgin purchases on the material price is similar to the recycling costs ($b = c_r$), and (3) the effect of the virgin purchases on the material price is high compared to the recycling cost ($b > c_r$). Intuitively, higher values of $b$ would suit a situation where the price elasticity of the supply of the good is lower because the mining capacity is more rigid or takes longer to build. We fit our figures to $b = 0.5c_r$, $b = c_r$, and $b = 2c_r$.

We estimate the R&D costs of Material Reduction ($\phi$) based on the observed historical yearly $\beta^*$ in the silver industry as well as the rest of the parameters. Hallam et al. (2023) find that over the past 10 years, the silver industry has reduced its silver consumption from 51.8-65.1 mg/W to 19.5 mg/W. This allows us to estimate $(1 + (1 - \gamma)\beta^*)^{10} \in [51.8/65.1]$, which gives us an approximate $\beta^*$ of 11.0 - 13.7% - i.e., with each unit of silver, $\beta^*$% additional units of solar panels can be built. According to our model, $\phi = \frac{1}{48} \left[((1 - \gamma)p - c)^2 + \frac{(p - r - c)\gamma}{\beta^*}\right]$. By calibrating this expression with the other parameters, we get six possible values of $\phi$ depending on the value of $b$ and $c$, which are in the range of 1.8 - 78M€. For $c = 0.2$, this range of values becomes 1.8 - 5.3M€. Thus, we use $\phi = 1.8M$ for the scenario where $b = 0.5c_r$, we use $\phi = 3.75M$ for the scenario where $b = c_r$, and we use $\phi = 5.3M$ for the scenario where $b = 2c_r$. Note that our estimation of these costs is adapted in the two period model to $\phi = 15.7$ because the price used in that extension is, in practice, $p + \Delta p$, and also we set $c = 0$ and $\gamma = 0$ as discussed in Appendix E.

Finally, we calibrate our model in two geographies with vastly different waste processing systems for solar panels, and thus different systemic leakage values. In the US, recycling is not mandated by federal regulations and discarding them in a landfill is a fraction of the cost. While the numbers vary between states, current proper disposal rates are around 10%, i.e., $\kappa_h = 0.9$ (Crownhart 2021). In Europe, we use the WEEE targets of 65-85% recovery of solar panels from 2018 on to set $\kappa_l = 0.2$ (European Commission 2012).

I. Extensions for the Unit Energy Price $p$
I.1. Stochastic and exogenous selling price

We consider an extension where the price of electricity is a random variable $X$ with cumulative distribution function $F_X$ and expected value $p$, i.e., $E[X] = p$. In this case, we further assume that the price of the critical raw material is deterministic, and set as $s(q, A) = s(q, \mu) = \mu + bq$. With this extension, all production quantities and ranges of production are identical to those in our main model since the producer makes decisions based on the expected profit functions $E_X[\pi_U(q_U|X)]$, $E_X[\pi_M(q_M, \beta|X)]$ and $E_X[\pi_C(q_C, r|X)]$, which are all linear in $p = E[X]$. However, the ex-post profits of the producer are sensitive to the stochasticity
of the unit selling price, which leads us to revisit Proposition 10. Let $\tilde{\Pi}_i(\cdot)$ denote the ex-post profits of the producer under strategy $i$, and let $\tilde{\rho}_i$ be the probability of negative ex-post profits for the producer conditional on strategy $i$ being chosen. Specifically, let $\tilde{\rho}_B = P(\tilde{\Pi}_B(q_B^*) < 0|\mu \in \Delta)$, $\tilde{\rho}_M = P(\tilde{\Pi}_M(q_M^\ast, \beta^\ast) < 0|\mu \in \Delta)$ and $\tilde{\rho}_U = P(\tilde{\Pi}_U(q_U^\ast, r^*) < 0|\mu \in \Delta)$.

**Proposition A5.** Material reduction always increases the probability of negative profits for the producer. Furthermore, there exists a threshold $\hat{\alpha}_{\text{price}}(\mu, \kappa) \in (0, \hat{\alpha}(\mu, \kappa))$ such that, if $\alpha \leq \hat{\alpha}_{\text{price}}$, urban mining always reduces the probability of negative profits for the producer. In other words, if $\alpha \leq \hat{\alpha}_{\text{price}}$, $\tilde{\rho}_M > \tilde{\rho}_B$ and $\tilde{\rho}_U > \tilde{\rho}_B$ whenever $q_B^* > 0$, $q_M^0 > 0$, and $q_U^\ast$. Furthermore, as scarcity increases (i.e., for $\mu$ close to $p$), this condition becomes equivalent to the participation constraint $\alpha < \hat{\alpha}(\mu, \kappa)$. Finally, there exists a threshold $\hat{\alpha}_{\text{price,M,R}}$ such that if $\alpha \leq \hat{\alpha}_{\text{price,M,R}}$, urban mining leads to a lower probability of negative profits for the producer than material reduction.

We have $\tilde{\rho}_B = P(\tilde{\Pi}_B(q_B^*) < 0|\mu \in \Delta) = P((2X - p - \mu) \frac{\alpha - \mu}{4} \leq 0|\mu \in \Delta) = P(X < \frac{\alpha + \mu}{2}) = F_X(\frac{\alpha + \mu}{2})$. Similarly, $\tilde{\rho}_M = P(\tilde{\Pi}_M(q_M^\ast) < 0|\mu \in \Delta) = F_X(h(p, \mu))$, where $h(p, \mu) = \frac{8\phi - 2(1 - \gamma + \gamma - 1)(\mu + (\gamma - 1)p)}{\phi \cdot 4b \alpha - (\gamma - 1)(\mu + (\gamma - 1)p)}$. It can be shown that the concavity condition, i.e., $\phi > \frac{1}{2\alpha^2}$ implies that $h(p, \mu) > \frac{\alpha + \mu}{2}$. Thus, $\tilde{\rho}_B < \tilde{\rho}_M$.

We also have that:

$$\tilde{\rho}_U = P(\tilde{\Pi}_U(q_U^\ast, r^*) < 0|\mu \in \Delta) = \left\{ \begin{array}{ll} F_X(\frac{4abc - 2c_r \mu ^2 + c_r p^2}{2p - 2\kappa \mu}) & \text{if } \mu \leq m_a(\kappa) p \\ F_X(\frac{4(1 - \kappa)^2 c_r + 4\alpha c_r^2 + 2c_r \kappa \mu + 2c_r p}{2 \mu - 2p}) & \text{if } \mu \in [m_a(\kappa) p, p] \end{array} \right.$$  

It can be shown that $\alpha < \hat{\alpha}_{\text{price}}(\mu, \kappa, \gamma)$ implies that $\frac{4abc - 2c_r \mu ^2 + c_r p^2}{2p - 2\kappa \mu} < \frac{\alpha + \mu}{2}$ whenever $\mu \leq m_a(\kappa) p$ and that $\frac{4a \delta b ^2 + 4c \alpha c_r + 4\alpha c_r^2 + 8\alpha c_r \kappa \mu + \kappa \mu^2 + 2c_r p^2}{2p - 2\kappa \mu} < \frac{\alpha + \mu}{2}$ whenever $\mu \in [m_a(\kappa) p, p]$, where:

$$\hat{\alpha}_{\text{price}}(\mu, \kappa, \gamma) = \left\{ \begin{array}{ll} \frac{\alpha \mu}{4(1 - \kappa)^2} & \text{if } \mu \leq m_a(\kappa) p \\ \frac{\kappa \alpha \mu + m_a(\kappa) p}{2c \kappa^2 + 4 \alpha c_r} & \text{if } m_a(\kappa) p \leq \mu \leq p \end{array} \right.$$  

Furthermore, $\hat{\alpha}_{\text{price}}(p, \kappa) = \hat{\alpha}(\mu, \kappa)$, i.e., both functions converge as $\mu \to p$.

Finally, whenever $\alpha \leq \hat{\alpha}_{\text{price,M,R}}(\mu, \kappa)$, we have $\tilde{\rho}_U < \tilde{\rho}_M$, where $\hat{\alpha}_{\text{price,M,R}}(\mu, \kappa)$ is defined as follows:

$$\hat{\alpha}_{\text{price,M,R}}(\mu, \kappa) = \left\{ \begin{array}{ll} \frac{\alpha \mu}{4(1 - \kappa)^2} & \text{if } \mu \leq m_a(\kappa) p \\ \frac{\kappa \alpha \mu + m_a(\kappa) p}{2c \kappa^2 + 4 \alpha c_r} & \text{if } m_a(\kappa) p \leq \mu \leq p \end{array} \right.$$  

Proposition A5 guarantees that all of our results continue to hold provided that the fixed investment costs of urban mining are bounded. Otherwise, all of our results would hold except for Proposition 10, and urban mining would not be the strategy that leads to the lowest probability of negative ex-post profits.

**I.2. Endogenously determined selling price**

We consider an extension where the producer has pricing power, rather than restricting the producer to be a price-taker as in § 3. That is, rather than an exogenous and fixed unit selling price $p$ for the clean energy product, we assume an inverse demand function $p(e_i(q))$ that relates the price to the quantity of energy supplied by the producer, denoted $e_i(q)$ (with $i$ representing each strategy, $i \in \{B, M, U\}$, and $q$ representing the amount of material input in production). For simplicity, we assume that the inverse demand function is linear, i.e., $p(e_i(q)) = p(1 - \nu e_i(q))$. Note that the price decreases in the level of generation capacity put into the market, that is, $\frac{dp(e)}{de} < 0$ and setting $\nu = 0$ leads to our original formulation where the producer is a price-taker.
### I.2.1. Benchmark strategy

Under the benchmark model, the producer solves the following concave problem:

$$\max_{q_B \geq 0} \mathbb{E}_A [p(1-\nu q_B)q_B - (A + bq_B)q_B]$$

which results in the optimal solution $q_B^* = \frac{p-\mu}{2(1+\nu p)}$.

We note that the optimal virgin purchase decreases with scarcity, akin to our original model, and no installations take place when $p < \mu$. Furthermore, both profits and installations decrease with the producer’s pricing influence.

### I.2.2. Material reduction strategy

In the material reduction strategy, the energy supplied by the producer is $e_M(q_M) = (1 + (1-\gamma)\beta)q_M$, and the producer solves:

$$\max_{q_M \geq 0, \beta \geq 0} -\phi \beta^2 + \mathbb{E}_A [\pi'_M(q_M|A,\beta)]$$

where

$$\pi'_M(q_M|A,\beta) = (1 + (1-\gamma)\beta)q_Mp(1-\nu(1+(1-\gamma)\beta)q_M) - (A + bq_M)q_M - (1+\beta)cq_M.$$ 

We find that the optimal virgin material purchase and the level of material reduction investment reduces when the producer has pricing power. That is, letting $(q_{M,\text{endo}}^*, \beta_{M,\text{endo}}^*)$ denote the optimal solution to the producer’s problem given in Equation (A.7), we find that $q_{M,\text{endo}}^* \leq q_M^*$ and $\beta_{M,\text{endo}}^* \leq \beta^*$. Figure EC.14 numerically approximates the optimal material reduction investment $\beta_{M,\text{endo}}^*$, the optimal virgin material procurement $q_{M,\text{endo}}^*$, and the resulting clean energy generation $e_M(\beta_{M,\text{endo}}^*, q_{M,\text{endo}}^*) = (1 + (1-\gamma)\beta_{M,\text{endo}}^*)q_{M,\text{endo}}^*$ for various values of the pricing power $\nu$. Observe that the optimal level of material reduction investment becomes non-monotonic with the level of scarcity when $\nu > 0$ and the producer has some power over the price of energy. Since higher levels of energy supplied implies a lower selling price, investing in ever higher levels of material reduction is no longer profitable as in the absence of pricing power. Therefore, the incentives to invest in high levels of material reduction might be the highest for intermediate values of scarcity.

Finally, Proposition A6 below shows that the key result related to the Jevons paradox in our original setting continue to hold with an endogenously set selling price under certain conditions. Specifically, when the producer has pricing power, Jevons paradox holds when either the scarcity is high enough or the producer’s pricing power is low enough. Otherwise, the producer purchases less virgin material under the material reduction strategy and there is no scarcity rebound effect.

**Proposition A6.** Let $\nu > 0$, and let the original problem presented in equation (2) be concave. There exists a threshold $C(b, p, \mu, \phi) \geq b$ such that Jevons paradox always holds for $\nu \leq C(b, p, \mu, \phi, c)$. Otherwise, there exists a threshold $\mu_{\text{endo}}(c, b, p, \mu, \phi)$ with $\mu_{\text{endo}}(0, b, p, \mu, \phi) = 0$ such that Jevons paradox holds when $\mu > \mu_{\text{endo}}(c, b, p, \mu, \phi)$.

**Proof** One can easily verify that the Hessian of the objective function of the producer’s problem given in Equation A.7 is negative definite, which means that the objective function is concave. Let $f_{\text{endo}}(q_{\text{endo}}, \beta_{\text{endo}}|\nu)$ be the objective function of the producer’s problem given in Equation A.7. Note that
By definition, Jevons paradox holds when some algebra, this is equivalent to energy generation \( e_M(\beta^*, q^M) \) as a function of scarcity level \( \mu \), for various levels of pricing power. No pricing power means that \( \nu = 0 \), and low/medium/high pricing power means that \( \nu = 0.5b/\nu = b/\nu = 2b \), respectively. Our parameter space is \( p = 1.615, b = 0.0000003, \phi = 3.74M, c = 0.01 \) and \( \gamma = 0.068 \).

\( f_{endo} \) has strictly decreasing differences in \( \{\beta, \nu\} \) and in \( \{q_M, \nu\} \), because \( f_{endo}(q_{endo,M}, \beta_{endo} | \nu) \) is supermodular in \( (q_{u,endo,M}, \beta^*_u,endo, - \nu) \). Thus, for any \( \nu_1 > \nu_2 \), then \( \beta^*_u,endo(\nu_1) \leq \beta^*_u,endo(\nu_2) \) and \( q^*_u,endo,M(\nu_1) < q^*_u,endo,M(\nu_2) \), where \( q^*_u,endo,M, \beta^*_u,endo \) is the unconstrained optimum of \( f_{endo}(q_{endo,M}, \beta_{endo} | \nu) \).

Assume that the producer opts to invest in Material Reduction and thus \( \beta^*_endo > 0 \). Since the profit function is concave, the first order conditions are sufficient to find \( q^*_endo,M = \frac{c(1 + \beta^*_endo(1 - \gamma)) - (\beta^*_endo + 1)c - \mu}{(2 + \nu p)(\beta^*_endo - (\beta^*_endo + 1)c) + \mu} \). By definition, Jevons paradox holds when \( q_{endo,M} > q^*_endo,M \), or \( q^*_endo,M = \frac{\nu - \mu}{2(b + \nu p)} < \frac{p(1 + \beta^*_endo(1 - \gamma)) - (\beta^*_endo + 1)c - \mu}{2 + \nu p(\beta^*_endo - (\beta^*_endo + 1)c)} \). With some algebra, this is equivalent to \( b(p(1 - \gamma)\beta^*_endo - c(1 + \beta^*_endo)) > \nu p(c(1 + \beta^*_endo) - (1 - \gamma)\beta^*_endo) \). Since we assumed \( \beta^*_endo > 0 \), the left side of the inequality is always positive, so the inequality is always true whenever \( \mu > \frac{(1 + \beta^*_endo)}{(1 - \gamma)\beta^*_endo}c. \) Otherwise, the inequality is true if \( \nu < \frac{\mu(p(1 - \gamma)\beta^*_endo - c(1 + \beta^*_endo))}{p(c(1 + \beta^*_endo) - (1 - \gamma)\beta^*_endo)} \).

I.2.3. Urban Mining strategy Finally, in the urban mining model, the energy supplied by the producer is \( e_U(q) = q_U + r \), so the producer solves the following problem:

\[
\max_{q_U \geq 0, r \geq 0} -\alpha + \mathbb{E}_A [(r + q_U)(p - p \nu(r + q_U)) - (A + bq_U)q_U - cr^2]
\] (A.8)

subject to the recycling material availability constraint \( r \leq (1 - \kappa)(q_U + r) \).

There exists an investment threshold \( \alpha_{endo} \) and a scarcity threshold \( m_{a,endo}(\kappa)p \in [0, p) \) such that the unique optimal strategy for the producer is given by (a full proof that follows the steps outlined in the proof of Proposition 3 is available from the authors upon request):

\[
r_{U,endo}^* = \begin{cases} \frac{pb + \nu p}{2c\nu r + 2b(c + \nu p)} & \text{if } \mu \leq m_{a,endo}(\kappa)p \\ \frac{1 - \kappa}{2(1 - \kappa)c_\nu + 2c_\nu b + 2b\nu} & \text{if } \mu > m_{a,endo}(\kappa)p \end{cases}
\]

\[
q_{U,endo}^* = \begin{cases} \frac{pc_\nu - \mu p + \nu p}{2c\nu r + 2b(c + \nu p)} & \text{if } \mu \leq m_{a,endo}(\kappa)p_0 \\ \frac{1 - \kappa}{2c\nu r + 2c\nu b + 2b\nu} & \text{if } \mu > m_{a,endo}(\kappa)p_0 \end{cases}
\]

The structure of the solution under the Urban Mining strategy with pricing power is very similar to our main model without pricing power. We plot the equilibrium virgin and recycling quantities chosen by the
producer in Figure EC.15. It can be easily verified that both \( (q^*_U,endo, r^*_U,endo) \) are decreasing in \( \nu \) in their respective intervals. Furthermore, \( m_{a,endo}(\kappa) = \frac{c_r(1-\kappa) - \beta \kappa}{c_r(1-\kappa) + \nu p} \) is also decreasing in \( \nu \), which leads to a smaller interval where the interior solution holds. Interestingly, within the interior solution, the recycling quantities increase with the level of scarcity when there is some pricing power (left plot in Figure EC.15), instead of remaining constant as when the producer has no pricing power. Intuitively, this happens because the producer prefers to moderate its clean energy generation \( e^*_U,endo \) to avoid a very low selling price, and as scarcity increases, recycled material has better cost advantage over virgin material. Note that the threshold for the investment cost \( \alpha \) under which the producer chooses to invest in Urban Mining decreases with \( \nu \), as optimal recycling quantities are lower and thus the investment provides lower additional revenues.

\[ m_{a,endo}(\kappa) = c_r(1-\kappa) - \beta \kappa \]

\[ m_{a,endo}(\kappa) = c_r(1-\kappa) + \nu p \]

**Figure EC.15** Producer decisions in urban mining with pricing power.

**Note.** Optimal recycled material \( r^*_U,endo \), optimal virgin material procurement \( q^*_U,endo \), and resulting clean energy generation \( e^*_U,endo \) as a function of scarcity level \( \mu \), for various levels of pricing power. No pricing power means that \( \nu = 0 \), and low/medium/high pricing power means that \( \nu = 0.5b / \nu = b / \nu = 2b \), respectively. Our parameter space is \( p = 1.615 \), \( b = c_r = 0.0000003 \), and \( \kappa = 0.2 \).

**I.2.4. Optimal strategy** We find numerically the conditions under which each of the strategies is chosen by the producer. The lines in Figure EC.16 show the producer’s optimal strategy for various levels of the pricing power parameter \( \nu \).

For low values of \( \nu \) (upper row in Figure EC.16), the producer’s strategy selection is similar to our original setting (where \( \nu = 0 \)): the producer invests in Material Reduction for low values of scarcity \( \mu \) and high values of investment cost \( \alpha \). For intermediate values of \( \nu \) (left and middle plot in the bottom row), the producer only invests in Material Reduction for intermediate values of scarcity, because the incentives for choosing a large \( \beta \) decrease when the scarcity is very high or very low (as investigated in §I.2.2). The range of values of scarcity for which Material Reduction is chosen shrinks with \( \nu \). For large values of \( \nu \), Material Reduction is not chosen over Benchmark for any scarcity value, and the producer arbitrates only between Urban Mining and Benchmark. All in all, higher pricing power seems to undermine the incentives to invest in either strategy, as greater values of \( \nu \) reduce the parameter ranges for which other strategies than Benchmark are chosen.
Finally, the shadowed areas in Figure EC.16 plot the regions where the producer's incentives are not aligned with the policy objectives. The misalignment in the material reduction strategy almost disappears as with pricing power, material reduction is almost never the best strategy in terms of clean energy generation. Beyond a certain level of pricing power, Urban Mining outperforms every other strategy in terms of clean energy input, and incentive misalignment areas are defined by the ranges of $\alpha$ where Urban Mining is not chosen.

Figure EC.16 Producer strategies and their alignment with policymaker goals for various levels of pricing power $\nu$.

Note. Here, $p = 1.615$, $b = e_c = 0.0000003$, $\phi = 3.75M$, $\gamma = 0.065$, $c = 0.01$, $\alpha = 0$, and $\kappa = 0.2$.

References


Carrera et al.: *Clean Energy, Material Scarcity and Urban Mining*