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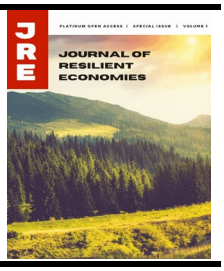

Stockpiling of Critical Metals as a Risk Management Strategy for Importing Countries

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Abstract

Following the triumph of post-fossil technologies, the global demand for critical raw materials in the form of rare metals will increase dramatically in the coming years. From the perspective of importing countries, dependence on these raw materials poses a host of new risks. In this respect, building up reserves of raw materials can be a sensible policy option for the short term. It can help reduce both supply-side and price-related risks. This is particularly true in cases where markets are characterised by high price volatility and/or the risk of supply disruptions is significant. Moreover, if there is a high degree of market concentration, stockpiling can also serve as a strategic tool for long-term price dampening. At the same time, the institutional design of stockpile management is crucial. In view of the economic risks associated with publicly managed stockpiles, we argue for a policy aimed primarily at promoting stockpiling incentives within the private sector. Central reserves managed by the public sector are only advisable as a basic hedge against the extreme scenario of massive supply interruptions. In any case, a stockpiling strategy should be accompanied by efforts to diversify supply sources in the long run.

Keywords: Critical Metals, Resource Stockpiling, Raw Material Strategy, Commodity Markets, Macroeconomic Resilience

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1. Introduction

The parallel occurrence of numerous external shock events in recent times has exposed the vulnerability of our fragmented international supply chains. The beginning of the chains, i.e. access to raw materials, is in particular focus, as the entire downstream value creation depends on it. Looking to the future, this applies especially to rare metals, which represent the transition to a post-fossil, digital age. In importing regions such as Europe, calls for a strategy for dealing with these critical raw materials have increased. The EU Commission has announced a comprehensive legislative proposal with concrete instruments for next year (European Commission, 2022). In addition to the development of domestic production capacities, regulatory guidelines for the development of strategic reserves of rare metals, such as lithium, rare earth, cobalt, etc., are to be part of this framework. In the medium term, such reserves could be one building block for raising resilience in the raw materials supply.

From a physical point of view, stockpiling rare metals poses fewer problems than in the case of oil and gas: they are solids, the respective demand quantities are significantly lower, and there are no complications due to seasonal demand patterns. From an economic perspective, however, new challenges arise due to the unpredictability of the markets: a high geographical concentration of supply meets a trend of strongly increasing global demand, with only very incomplete information about the existence and future exploitability of geological deposits. Therefore, specific strategies for stock management are needed that hedge against the different types of risks while avoiding undesirable market effects.

So far, there are only a few concrete ideas on the type and implementation of such stockpiling. The proposals debated in the literature and the public sphere cover a broad spectrum of forms of intervention. As the mildest type of intervention, the introduction of a central information system for reserve management is proposed, while the reserves themselves are built up and managed independently by the member states or private companies. As an opposite extreme solution, the establishment of a kind of "metal bank" is being discussed, which would manage European reserves in a centralised manner and influence the global commodity markets with its transactions. In between, there is a broad spectrum of options.

This article examines the potential and challenges of building up a strategic reserve of critical metals. It presents its own risk systematics and classifies the possible role of reserve holding as a building block of risk management from the perspective of resource-importing countries. It analyses the economic rationale of commodity stockpiling in light of the specificities of rare metals. Finally, it assesses different options for the institutional design of reserve management based on the example of the European Union.

1.1 Current supply situation and risks

The variety of future technologies that will shape our path into a digital, post-fossil age have one thing in common: they depend on the use of rare minerals (mostly metals) that are currently almost impossible to replace in production due to their physical-chemical properties. Rare earth metals, lithium and cobalt, are the most prominent examples, but particularly rare metals such as gallium and germanium also fall into this category (European Commission, 2020). Their common feature is that both extraction and processing are currently concentrated in a few countries. First and foremost among these is China (Wolf, 2022). Turning away from fossil resources thus threatens to replace old dependencies with new, undesirable ones. The current structure of global resource supply entails multi-dimensional risks for importing countries. In the following, we distinguish three types of risk: supply-related, price-related and ecological-social. The dimensions cannot be considered independently of each other but correspond in many ways. For example, a growing supply risk should usually be reflected in rising prices in the commodity markets; conversely, low prices in the long term can have a negative impact on the supply situation. Existing risks of an environmental and social nature, on the other hand, can partly be a consequence of price pressure, but in the long term, they can also affect the supply situation. Moreover, higher environmental standards can entail higher production costs and market prices.

The assessment of the supply situation depends not only on global availability but also on its geographical distribution. For most of the raw materials under consideration, the existing reserves are concentrated to a considerable extent in one or a few countries. In the case of cobalt, for example, this is the Congo (Dem. Rep.); in the case of platinum metals in South Africa, and the case of vanadium and rare earth metals, the People's Republic of China. These are largely the producers that already dominate today (USGS, 2022). Table 1 presents an overview of the supply situation for eleven metals/metal groups currently assessed as critical by the EU (European Commission, 2020).

For most metals, the most important supplier was responsible for more than half of global mining production in 2020. The dominance of China is particularly striking. In 2020, the People's Republic was not only the world's most important supplier of six of the eleven raw materials but also held a market share of over 50% for five of them, for gallium of even more than 90%. Only the Congo (Dem. Rep.) has a similarly

prominent position in cobalt production. In smelting, China's overall dominance is estimated to be even greater; it currently extends to cobalt and lithium, for example (European Commission, 2020).

Table 1- Risk indicators for the global supply situation in 2020

Indicator	Share the biggest supplier	Political stability (Top 3 suppliers)	Control of Corruption (Top 3 suppliers)	Access to social protection (Top 3 suppliers)	Environmental Performance (Top 3 suppliers)
Source	USGS (2022)	World Bank (2022)	World Bank (2022)	ILO (2022)	Wolf et al. (2022)
Unit	*% global mining*	*Index (-2.5 to 2.5)*	*Index (-2.5 to 2.5)*	*% population*	*Index (0 to 100)*
Metal/metal group					
Cobalt	69.0% (Congo, Dem. Rep.)	-1.50	-1.36	24.47	39.45
Gallium	96.9% (China)	-0.29	-0.06	71.35	37.44
Germanium	67.9% (China)	-0.29	-0.07	70.80	37.30
Indium	56.3% (China)	0.04	0.27	74.82	49.75
Lithium	48.1% (Australia)	0.42	1.21	86.19	62.53
Platinum-group metals	48.4% (South Africa)	-0.48	-0.39	60.87	45.19
Rare earth metals	58.3% (China)	-1.33	-1.11	29.80	39.06
Scandium	No information	-0.42	0.06	62.26	42.74
Tantal	37.1% (Congo, Dem. Rep.)	-0.38	0.08	59.24	47.20
Titan-Minerals	32.6% (China)	-0.37	-0.22	72.76	40.43
Vanadium	66.7% (China)	-0.29	-0.06	71.35	37.44
Average level EU-Countries		*1.03*	*0.99*	*89.56*	*70.67*

Source: USGS (2022); World Bank (2022); ILO (2022); Wolf et al. (2022); own calculations

There are also significant differences in the reliability and stability of the main producing countries. In international studies, the World Bank's Worldwide Governance Indicators (WGI) is usually used as a benchmark (World Bank, 2022). Table 1 shows exemplary comparative results for two key WGI indicators, each calculated as a volume-weighted average of the Top 3 supplier countries. Particularly low scores with respect to both political stability and corruption control are observed for cobalt and tantalum. In both cases, the dominance of the Democratic Republic of Congo as a producing country is causal. A comparison with the average values of EU members shows that mining other metals also occurs predominantly in countries that are significantly more unstable and more exposed to corruption than the EU region.

Sustainability risks associated with commodity supply chains are more difficult to detect, as producer countries tend to have little interest in ensuring transparency of mining conditions. Several environmental issues arise with rare metals. This begins with the greenhouse gas emissions that result from mining and smelting. These can be both direct (escape of gases from the ground) and indirect (material and energy consumption along the supply chain) in nature. For some critical metals, toxins associated with deposits, such as arsenic and mercury, may also pose an environmental risk, especially if contamination of groundwater cannot be ruled out (Huang et al., 2016; Kaunda, 2020). In the case of lithium, depending on geological conditions, high water consumption can also be added as a problem (Bustos-Gallardo et al., 2021). Serious conflicts with international standards are also reported regarding the social situation of miners and safety standards during mining (Sovacool, 2021).

Although the differences between mining conditions in different countries cannot be measured directly, a look at general country indicators on social safety and environmental protection provide some clues. Table 1 shows the situation in the main mining countries in terms of social security (ILO estimate of the proportion of the population with access to at least one social security measure) and environmental protection (Environmental Performance Index from Wolf et al. (2022)), calculated as a weighted average of the three main supplier countries. According to the index, cobalt and tantalum also perform particularly poorly in terms of minimum social standards in the producing countries. The environmental rating is worst for gallium and germanium. The level of the EU countries is only reached for lithium.

Moreover, as a side effect of the high market concentration, the industrial and trade policies of the leading exporting countries have a big influence on price developments. The example of rare earth metals has demonstrated this in recent years. In the course of a major change in its industrial strategy, China subjected its once export-focused production of rare earth metals to increasingly rigid export quotas in the early 2000s and even imposed an export levy in 2007 (Nicoletopoulos, 2014). In 2010, a significant reduction in export quotas led to drastic price jumps; in 2011, the average price more than tripled. The subsequent abandonment of the export quota policy then led to a significant easing of the price situation (Mancheri, 2015).

1.2 Stockpiling as part of a raw materials strategy

From the perspective of an importing country, the question of the appropriate policy strategies to reduce or at least better manage existing risks arises. One such strategy could be the promotion of domestic supply chains. The development of domestic production capacities in the raw materials sector requires extensive investments in tangible (capital) and intangible (know-how) goods and is time-consuming. Moreover, in view of the Chinese market dominance in smelting, it needs to go beyond the raw materials extraction stage (Seaman, 2019).

Due to the unclear market reaction of the established producers, it harbours new price risks, and the occurrence of ecological risks in future mining regions cannot be ruled out at present. An alternative is the increased entry into secondary production (raw material recycling). Here too, however, a build-up of capacities needs time. The diversification of a region's portfolio of trading partners could represent an alternative demand-side strategy, but in many cases also requires long-term capacity building on the side of partners. Building up raw material reserves is the only strategy that could already be effective in the short term. At the same time, it is also the option that has been least present in the debate on raw material policies until now.

By building up reserves, raw materials are temporarily withdrawn from their utilisation cycle. The most visible form is the build-up of stocks on the part of mining companies and the processing industry.

The complex production chains for rare metals basically offer the possibility of storing them in the most diverse combinations and processing stages: as ore, in smelted form, in chemical compounds required for certain end applications (e.g. as a component of an alloy). Thinking beyond this, however, other stations along the entire value chain can also serve to hold reserves. This begins with the availability of metals in the soil. In international raw material statistics, those geological deposits are referred to as "reserves" whose extraction would be economical under current conditions (USGS, 2020). Depending on expectations about future market developments, it may be a rational strategy to refrain from mining today. The raw materials deliberately left in the ground represent a geological stock from which to draw when market conditions are more favourable. Reserve management can also be differentiated according to whether it is decentralised (i.e. at the level of individual market participants) or centralised (coordinated by state institutions or private associations). Different models are also conceivable with respect to the management of accumulated stocks. Reserve management can be limited to purely passive management of stocks, but it can also use them as a basis for market intervention.

Different models can be based on different objectives. To the extent that reserves are not the outcome of economic planning errors (e.g. overestimation of market demand) but of a conscious decision, they are a form of intertemporal optimisation. From the perspective of a commodity-importing country, reserve management can be primarily an instrument to counter the various forms of market risk. For example, stockpiling can be an attempt to protect against the risk of future supply disruptions along international supply chains. But it can also be done with a view to existing price risks. Here, a distinction must be made between short-term and long-term price uncertainty on the one hand and between passive hedging and the desire to exert an active influence on the other. In the short term, the focus may be on irregular price fluctuations in the commodity markets.

Reserve holding can be an instrument for risk-averse players to individually hedge against price volatility. However, it can also stem from the motivation to have a price-stabilising effect on the markets themselves if the inventory is dynamically adjusted to the respective price situation. In the long term, a positive trend in (real) commodity prices represents another form of risk. Here, too, stockpiling can either serve as a passive hedge against rising prices or be motivated by the hope of a long-term price-dampening effect. Finally, reserve stocks could be a means of coping with environmental and social risks if they are deliberately procured from regions with reliable environmental and social standards.

At present, only a few countries can be considered possible role models for building up national reserves of critical raw materials. In China, reserves are centrally managed by the National Food and Strategic Reserves Administration, the successor to the Strategic Reserve Bureau, which has been active in this field for a long time. In the past, purchases mainly served to reduce domestic surplus production in phases of weak global demand (Reuters, 2020). The USA has possessed a National Defense Stockpile of raw materials since 1939, managed by the Defense Logistics Agency (DLA) - Strategic Materials (Chappell et al., 1983). The Trump administration's 2019 commodity strategy emphasises stockpiling as an important short-term measure to increase resilience in times of crisis.

There are signs that this has also led to practical consequences. For example, a significant increase in US imports of rare earth magnets was observed during the increase in trade tensions with China in 2019 (Theodosopoulos, 2020). The increasing importance attached to the stockpiling of critical raw materials by US policy-makers has recently been confirmed by the Biden administration (Biden, 2021). In Japan, the security of the supply of imported raw materials was proclaimed early on as the main goal of energy policy. Since 1983, Japan has had a national rare metal strategy (Ting & Seaman, 2013). In the Strategic Energy Plan of 2014, the maintenance of rare metal storage facilities was identified as a key instrument for increasing national resilience, in addition to the increased promotion of recycling activities. The stocks serve both economic and military purposes and are actively managed by the Japan Oil, Gas and Metals National Cooperation (METI, 2014). In all cases, details on the extent and characteristics of the stockpiled resources are unknown.

2. The economics of strategic metal reserves

2.1 Literature Insights

Since the oil crises of the 1970s/80s and the discussion on natural limits to economic growth initiated by the Club of Rome, the use of scarce resources has frequently been the subject of economic research. The problem of the optimal exploitation of a finite resource over time, as studied by Hotelling (1931), often serves as the basis for resource economic analyses. According to Hotelling's rule, the extraction of a resource should be distributed over time such that the price increase of the resource corresponds to the return on alternative forms of investment on the market. In this way, for every tonne of resource left in the ground, non-extraction would yield exactly the same return as investments in the financial markets.

There would no longer be an incentive to adjust today's extraction rates upwards or downwards. According to this reasoning, continuously decreasing extraction quantities and continuously increasing resource prices would be the logical consequence. There is no room for forms of stockpiling in such a concept: with a fixed extraction and price path, there would be no motivation for either suppliers or consumers to build up stocks as a precautionary measure.

The price of stockpiling (lost interest on alternative investments) would be just as high as the expected price increase of the stored resource. Even a short-term deviation from these paths due to singular events would not change this. If, for example, there is a temporary price collapse, this would create an incentive on the demand side to extend the purchase of resources beyond what is immediately needed. However, this would fail because the reaction of the suppliers in view of the higher expected return (stronger future price increase) would be to restrict current production, which in turn would stabilise prices (Mason, 2011).

In reality, however, commodity price developments are usually far from the pattern of a continuous upward trend. Seemingly random fluctuations, spontaneous level shifts and sometimes unclear long-term trends are the predominant features of most commodity markets, especially in recent times. Economists have shown, however, that relaxation of assumptions makes the Hotelling concept compatible with these phenomena. In particular, temporal changes in extraction costs and unpredictable fluctuations in commodity demand (business cycles, exogenous shocks) are put forward as possible explanations (Gaudet, 2007). In a market concept modified in this way, stockpiling can be a rational and permanently practised strategy for risk hedging. The optimal level of stockpiling for a commodity-importing country depends on the forms of risk it is intended to hedge against and the alternative instruments available.

The economic literature has dealt with the role of resource stockpiling in the context of both supply and price risks. The classic ideal instrument for hedging against such risks would be complete and fair insurance, i.e. a contract that, in the event of a loss, provides for full compensation for the damage incurred and premium payments in the amount of the ex-ante expected loss (Klein, 2014). In the commodities sector, however, such a contract is inconceivable. To fully hedge against the risk, an insurance company would have to be able to balance the risk in its portfolio with other risks that are independent of it. Events in the commodity markets are in many ways related to sectoral and macroeconomic developments; the degree of risk correlation would thus require a significantly higher premium.

Stockpiling, on the other hand, can be practised autonomously on the part of commodity consumers. Its fundamental disadvantage, however, is that it can never be completely risk-free. This is because reserves to hedge against the risk of future disruptions must already be built up today and remain existent regardless of the occurrence of a disruptive event in the future. Since the build-up of reserves is always associated with costs in the form of foregone consumption or investment, the reserve holder will never be indifferent between the occurrence and non-occurrence of a disruptive event. However, the holding of reserves can reduce existing risks. This can be explained most intuitively with regard to supplying risks that commodity-importing countries face on the international commodity markets. The risk of a future shortfall in the supply of raw materials due to unforeseeable events (natural disasters, pandemics, trade restrictions, etc.) can be reduced by bringing forward purchases. The amount of reserves built up will be determined by the cost of stockpiling and the degree of risk aversion, in addition to future commodity needs.

But how does stockpiling differ from the alternative precautionary strategy of boosting domestic resource extraction? McGuire's (2006) analysis provides interesting insights. He analyses a simple scenario of two countries that produce two goods and can trade with each other. Each country specialises in the production and export of one of the two goods because of its natural advantages. One good can be a raw material, the other a manufactured good (produced without the use of the commodity in question). In the future, there is an (exogenous) risk that the raw material-exporting country will impose a trade embargo on the raw material-importing country. The raw material-importing country has two options to deal with this risk in the present: Build up commodity stocks through increased imports or shift domestic production towards the raw material sector (and thus away from the manufactured product).

McGuire (2006) shows that the two strategies are fundamentally different in their effects. Relocation of production implies a loss of productivity for the raw material-importing country: labour and capital are withdrawn from the more productive industrial sector. Reserve accumulation through raw material imports, on the other hand, does not affect the production structure of the present, but is associated with a reduction in consumption. As a consequence, both strategies lead to a situation in which the raw material-importing country can mitigate its loss of raw materials through domestic production in the event of an embargo but has to live with a surplus of raw materials (with lower consumption of the industrial good) otherwise. However, there is a difference between the strategies in the intensity of the effects. The build-up of reserves through imports can mitigate the raw material deficit of an embargo more strongly, but on the other hand causes a comparatively stronger raw material surplus if the embargo does not take effect. The reason is that the reserve build-up through imports can take place independently of the limited domestic production possibilities and therefore leads to a stronger raw material transfer between the two stages. It follows that the more likely the occurrence of supply disruption is, the more suitable stockpiling as a hedging strategy (McGuire, 2006).

However, a limitation may be set by market price reactions. If there is evidence that the risk of a future supply shortfall is increasing, this could cause rising commodity prices in the present. Building up reserves would thus become more expensive as the risk increases. The crucial question is to what extent the respective commodity markets are able to correctly anticipate the likelihood of such extraordinary events and translate them into price signals.

The question of how well commodity markets process existing information about future risks is also central to the contribution of reserve holdings to the avoidance of price risks. If the efficient market hypothesis is valid, the current price level would have to reflect all market-relevant information, including estimates of the objective probabilities of future shock events (Malkiel, 1989). Under these conditions, an importing country cannot hope to dampen long-term price increases or reduce price fluctuations by holding reserves. This is because all market-influencing events known today are already priced in, and future price developments are random from today's perspective.

In this case, however, reserve management still has a useful function as a passive hedging instrument against future price volatility. If, on the other hand, the expectations of the market participants are subjectively different, or if irrational behaviour patterns can be observed, the current prices can be in contradiction to the fundamental data. Provided the importing country has sufficient market information, wise reserve management could be used here to exploit price anomalies in a targeted manner. However, it is difficult to predict how a reserve

purchase (or its announcement) will affect the expectations of other market participants under these conditions.

The case is different if the market structure allows a form of direct strategic interaction between suppliers and buyers. For example, if a commodity market is characterised by the occurrence of market power among actors on both the supply and demand sides, stockpiling can become the object of a strategic game. Nichols & Zeckhauser (1977) highlight the consequences the case of a supply cartel that faces one or more large importing countries as buyers.

Building up reserves through increased imports today helps to reduce future dependence on the supplier cartel (and thus the risk of extortion). Present income is thus exchanged for the power to keep the import price at a low level in the future. For the reserve-creating institution, this is a costly strategy: it invests in an asset whose value is deliberately kept low. However, this can be offset by a gain in consumer surplus in the importing country

The longer the time horizon, the more beneficial such a strategy becomes. In a multi-period world, stockpiles are not regularly consumed after the reserve-building period. Instead, they can only be of strategic value if they are permanently maintained under normal market conditions, i.e. as long as no interruption in market supply requires their consumption. The supplier cartel does not undermine this process, as it also benefits: Part of its future profits is shifted to the present. In such a constellation, stockpiling is not simply a weapon against market power, but a mutually beneficial instrument for improved market coordination.

The prerequisite is that individual players among the importing countries are large enough to be able to lead the way in building up price-stabilising reserves. If, on the other hand, the build-up is carried out in an uncoordinated manner by a large number of small importing countries, an incentive problem arises in the form of the well-known free-rider problem: individual countries profit from the price effect of the reserves held by other countries without having to bear the costs of holding the reserves themselves. Reserve holding thus becomes an international public good. A possible solution, in this case, would be buyer alliances, provided that a binding commitment can be ensured through sanctions (Nichols & Zeckhauser, 1977).

2.2 Application to rare metals

Much of the literature discussed above explicitly refers to the stockpiling of fossil energy resources. The question arises to what extent the arguments presented are also valid for critical raw materials in the form of rare metals. The raw materials currently identified as critical by the EU Commission differ in terms of their technical properties and supply chains. For all their heterogeneity, however, many of these materials share a number of characteristics that influence the economics of stockpiling. They exist as solids at natural temperatures. In terms of volumes, demand is significantly lower than for standard metals. Both of these characteristics facilitate storage and have a cost-reducing effect on the build-up of economically relevant stocks. In addition, the following characteristics are economically relevant.

Uncertainty about geological resources

For many critical raw materials, there is only very limited information on the extent, type and spatial distribution of the geological resources that can be exploited in the future. For metals that are physically particularly rare and only used in small quantities, such as gallium and germanium, there are not even official estimates of the global stock of economically exploitable deposits (USGS, 2022). For many commodities, the official information on geographical location is limited to information on a few producing countries that are already active on a large scale today. There are several reasons for this. On the one hand, the raw materials are usually not directly available in the ground in their pure form (in the form of raw materials), but often as a small proportion of ores in terms of weight. The continuous development of extraction and smelting technologies leads to changes in the utilisation rates of existing deposits. Estimates of the quantities that can be profitably exploited are, therefore particularly difficult. In view of the market situation, this leads to additional price uncertainty. For example, the discovery of large economically exploitable deposits in so far inactive regions can significantly influence the market architecture. Against this backdrop, stockpiling as an instrument to hedge against price fluctuations takes on additional significance.

Occurrence in complex combinations

The rare metals are often associated with other economically important minerals within the ores. This affects the economics of resource extraction. The extraction path depends not only on the price development of the markets for rare metals but also on markets for the co-extracted minerals. In the case of the group of rare earth metals, the individual elements always occur in mixed form, whereby the mixing ratios can be very different. This technical complementarity creates a coordination problem in the commodity markets (Binnemans & Jones, 2015). This is exacerbated by the fact that demand for individual metals is subject to significant fluctuations for technological reasons (Bardi et al., 2016). Against this background, strategic reserves in the form of stockpiling can mitigate market imbalances over time and smooth out related price fluctuations.

Environmental risks in extraction and refinery

As discussed above, the mining and smelting of rare metals pose significant environmental risks. Unlike in the case of fossil resources, the focus here is usually not on greenhouse gas emissions but on locally acting pollutants. As the damage is local, its extent depends strongly on the local ecological conditions. There is also a lack of a standardised methodology for quantifying the damage. This makes it easier for producing countries to conceal the extent of damage and contributes to their incentive to keep environmental standards low to reduce costs. Building up strategic reserves in the form of raw material stocks can thus be counterproductive regarding the ecological dimension of raw material risks under current supply conditions.

Diversity of material requirements

Rare metals such as lithium have far more than just one field of application. They are used in various industries and processes and fulfil different functions (e.g. as catalysts, alloying components, components of chips and batteries). Accordingly, the demands on quality and processing form that different products place on one and the same metal are heterogeneous. For example, with regard to the use of the metal titanium for electrical applications, a significantly higher degree of purity is required than for its use as a component in the aerospace industry (Marscheider-Weidemann et al., 2016). A central reserve stock that aims to ensure maximum independence along the supply chains would have to take these different needs into account. This can complicate the management of central stocks considerably. Developments in demand in individual sectors would have to be considered when compiling reserves unless stockpiling is restricted to early processing stages from the outset.

Substitution risk due to technological progress

The example of rare earth metals also shows the sometimes rapid changes to which the usability of rare metals for certain processes is subject. For example, the rare earth metal europium was for a long time one of the most critical rare metals due to its use in the production of cold-beam lamps. The advent of LCDs and LED lamps then led to a significant drop in demand within a few years (Binnemans & Jones, 2015). This creates an additional substitution risk with a view to reserve management. Stocks of rare metals that would no longer be needed due to technological progress would lose their function and, at the same time, suffer a value loss.

Concentration on global markets

As explained above, the markets for rare metals are characterised by a concentration of a few large, geographically focused suppliers. At the same time, at the level of processing stages for industrial end-use (e.g. permanent magnets, lithium-ion batteries), there is still a certain geographical concentration on the demand side in those regions that play a leading role in the dissemination of future technologies. There should therefore be scope for strategic interaction along the lines of Nichols & Zeckhauser (1977) in many cases. Coordinated stockpiling, whether organised by law or driven by private joint ventures, can thus become a strategic asset for importing countries to dampen long-term price developments in markets with a high degree of monopolisation.

Trade on OTC-Basis

Unlike gas, oil and many standard metals, rare metals are not traded directly on commodity exchanges but exclusively in the form of over-the-counter (OTC) contracts. The markets for rare metals can, therefore not benefit from the central advantages of exchange trading: Transparency through standardisation, lower transaction costs, and higher liquidity in trade. Given the variety of chemical manifestations and processing stages in which rare metals can occur in trade, the lack of standardisation has a significant impact on the information and transaction costs of actors in the procurement side. This also applies to the process of stockpiling. At the same time, the absence of an exchange platform also means that there is less scope for purely speculative trading. Phenomena such as price bubbles generated or intensified by speculation are therefore less likely than on standardised markets. This eliminates a possible motive for hedging through stockpiling.

The discussed specifics influence the cost-benefit ratio of stockpiling, and thus its optimal level, in different ways (see Figure 1). However, they do not change the basic economic reasoning laid out above. At the same time, the significance of technology also shows that stockpiling requires continuous monitoring of markets, not only for the raw materials themselves but along the entire value chain concerned.

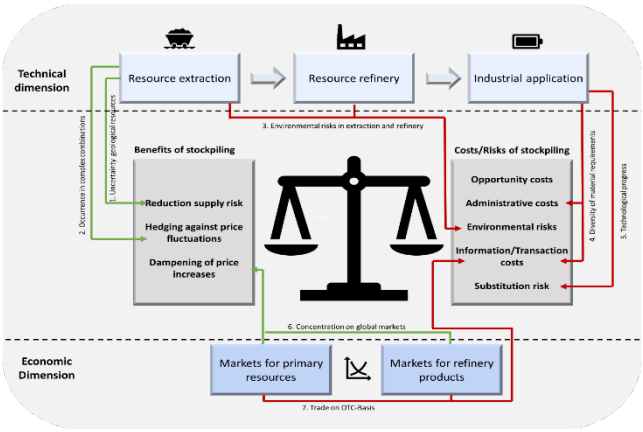

Figure 1- Consequences of the specifics of rare metals, Source: own representation

3. The institutional design of reserve management

3.1 Implementation

The impact of strategic raw material reserves also depends on how their development and management are organised. First, it must be clarified to what extent a political impulse is needed. The economic literature discussed in the previous section provides arguments in favour of autonomous stockpiling by companies. The question, however, is whether incentives are sufficient to achieve an economically optimal level of hedging via purely decentralised stockpiling. Since no figures are available on the overall level of current inventories, this cannot be clarified empirically.

However, economic theory provides evidence that a purely decentralised build-up of stockpiles can lead to underprovision. This concerns both the functions of commodity storage to hedge against supply risks and to dampen long-term price developments. In both cases, there is a risk of free-riding behaviour, as discussed in the previous section. Companies based in commodity-importing countries could use stockpiling to hedge each other against the risk of a supply shortfall by exporting countries. In the event of an actual shortfall, access via the internal market would still be ensured even without its own warehouses. Regarding the price-dampening effect of stockpiling, firms could benefit from the price impact of other firms' stockpiles, even without building up their own reserves.

Another reason for suboptimal private stockpiling cited in the literature is the existence of economies of scale in inventory management. Accordingly, larger inventories only cause less than proportionally higher storage costs. This would imply that large centrally coordinated warehouses are economically more cost-efficient than decentralised warehousing at the company level. This, too, cannot be empirically proven for rare metals at present. However, the existence of such economies of scale is plausible since even small warehouses are likely to incur considerable fixed costs in the area of warehouse security and administration, given the high market value of low-weight inventories. Finally, the problem of disincentives through taxation is also pointed out. If a company makes extensive provisions through stockpiling, it can become a crisis winner in the event of longer-term supply disruption: The value of its inventories is likely to rise significantly. For reasons of general fairness, policymakers could feel compelled in such a situation to skim off the windfall profits by imposing a special levy. The knowledge of this danger, in turn, reduces the incentives for companies to build up inventories (Nichols & Zeckhauser, 1977).

Therefore, to the extent that stockpiling goes beyond pure hedging against price volatility, underprovision in the situation of purely individual stock management is likely. This raises the question of suitable policy instruments to address this undersupply. In the following, we discuss different intervention strategies taking the European Union as an example. We distinguish four archetypal forms of regulation that together cover a broad spectrum of intervention types. Model 1 represents the conceivable maximum degree of centrality and coordination.

The EU (or affiliated institutions) would have the task of creating a central stockpile of rare metals for the entirety of its member states. First, this would require the creation of competencies for the purchase and management of large resource stocks by the EU. Second, a transparent mechanism would have to be established to determine under which circumstances, based on which key and to which partners (to traders? to member states? directly to industrial companies?) stocks would be released.

Model 1: Implementation at EU level
Model 2: Implementation at level of member states, with strict guidelines by EU
Model 3: Implementation at level of member states, with loose coordination by EU
Model 4: Implementation by private companies, promoted with policy incentives

Figure 2- Four types of EU strategies concerning the build-up of stockpiles, source: own representation

Models 2 and 3 also envisage the mandatory creation of public reserves in the EU area, but in the delegated form at the level of the member states. In Model 2, the EU would set relatively narrow guidelines for the member states on the circumstances and extent to which they would be active in purchasing and distributing stocks. Such requirements should take into account differences in economic strength and sectoral structure between countries in order to reduce transaction costs and ensure rapid allocation of raw materials in the event of a crisis. Model 3 also provides for an obligation to hold reserves at the member state level, but only in the form of a (needs-based) minimum stockpile of rare metals. The current requirements for holding oil stocks for emergencies could serve as a model for this. Under these, member states are required to maintain oil stocks at all times in an amount equal to either at least 90 days of daily average net imports or 61 days of daily average domestic consumption (European Union, 2009). The existence of such minimum stocks would then have to be regularly documented to the EU. If, in addition, the member states are not free to distribute their reserves in the event of a crisis, but if - as in the case of the oil reserve directive - some form of internal EU coordination is initially prescribed, we can speak of a hybrid form of Models 2 and 3.

Finally, Model 4 continues to rely on purely decentralised storage at the company level, but is supplemented by regulatory incentives. Monetary incentives would be particularly useful in addressing the public-good problem of the hedging effect. By giving companies a direct financial benefit from the government for expanding their stockpiles, the positive externality for supply security of the general public could be at least partially internalised. The challenge with such incentives is that they should precisely reward the build-up of additional reserves, and not simply the purchase of rare metals as such. Otherwise, there is a risk of consumption-side distortions in material use.

Regarding the possible form of such incentives, considerations have existed since the time of the oil crises. At the level of tax policy, for example, incentives could be created by accelerating the depreciation of inventories (and thus reducing the profit tax burden). Investments in the build-up of inventories could also be promoted directly, for instance by reducing the cost of corresponding loans through guarantees. Incentives in the form of subsidies for private-sector joint ventures in the area of inventory investments are also conceivable.

All of the options discussed could be pursued beyond the EU area through the formation of international buyer alliances. The goal of such alliances with state institutions or companies from third countries could be to gain more leverage on commodity markets, and to exchange know-how in the field of risk management.

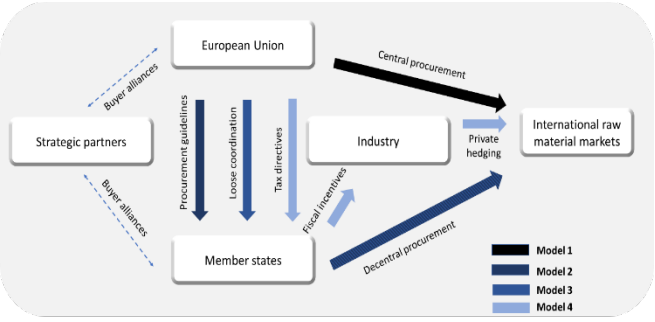

Figure 3- Overview of implementation options, source: own represetation

The greatest advantage of a centralised solution (Model 1**)** is evident that it most consistently addresses the coordination problems inherent in stockpile development. The establishment of a central location at EU level solves the free-rider problem that exists between member states and EU companies. In this case, the transaction costs arising from the purchase and storage of reserves should also be lower than in the case of decentralised storage at the level of individual companies. Finally, a centralised purchase of large stocks of raw materials, especially in less competitive markets, would also offer the possibility of enforcing more favourable pricing conditions.

Table 2- Strengths and weaknesses of different implementation options,

Implementation option	Transaction costs	Danger of planning errors	Free rider problems	Danger of crowding-out	Availabili in crisis
1. Implementation at EU level	Low	High	No	High	Slow
2. Implementation at level of member states, with strict guidelines by EU	Medium	High	No	High	Medium
3. Implementation at level of member states, with loose coordination by EU	Medium	Medium	Yes	Medium	Medium
4. Implementation by private companies, promoted with policy incentives	High	Low	Depends	Low	Fast

Source: own representation

In contrast, the assessment of the administrative costs of operating raw material warehouses is ambiguous. On the one hand, centralised warehouses could better exploit economies of scale (e.g., related to security costs and space rent). On the other hand, the variety of configurations in which rare metals are required can pose major problems for the management of central warehouses. To the extent that stockpiling is not limited to the earliest process stages of raw materials, rational stockpile management would have to be based on demand forecasts for a wide range of industries and production processes.

Other considerations clearly speak against an EU-based central solution. For example, the high demand for information, but also the fact that warehouse planners are not directly facing monetary consequences, harbours the danger of planning errors. Inefficiency in the type and scope of inventories could also be the result of a deliberate political strategy in such a centralised solution. For example, the EU could be trying to gain leverage over the member states in terms of industrial policy by means of a central stockpile that is excessively large from a risk point of view. This argues for permanent control of such instruments by the member states via the relevant councils of ministers.

Another risk of a centralised solution is the danger of crowding out private precautionary activity. By shielding domestic companies from market risks in the commodity sector, the EU reduces their incentive for risk reduction through their own initiative. This concerns their own stockpiling but potentially also proactive measures to reduce the relevance of possible risk events, e.g. R&D investments in technical substitutes or their own diversification activities in the international mining sector. Finally, another problem lies in the speed of stock availability in the event of a crisis. If there is an interruption in the supply of raw materials, it may be necessary to quickly supply raw material-intensive sectors to avoid devastating multiplier effects along value chains. This poses a major challenge for a centralised solution. If European reserve stocks are simply released into the market in such a case,

industrial companies would have to pay high prices. It is also doubtful whether, in such a case, the raw materials would reach the most system-relevant players with priority. The alternative of a market-independent direct distribution to industrial companies at the European level (e.g., via auctions) would also be complex in terms of design.

Models 2 and 3 should mitigate the latter problem. In the event of a crisis, the member states could distribute their stocks directly to their companies according to their own criteria without having to go through EU institutions. Even with these models, however, there is a crowding-out risk with regard to private sector activities. In the case of the minimum reserve model (Model 3), however, this risk is likely to be less acute, provided that the minimum requirements are only dimensioned for supply over a short period of time. In this case, there would be somewhat more flexibility than in the case of a reserve policy strictly prescribed by the EU. This would also tend to reduce the risk of planning errors. On the other hand, looser requirements for member states could increase the risk of free-rider behaviour. This is because companies in member states that only maintain the prescribed minimum level of reserves could also indirectly draw on the stocks of other EU countries via the internal market.

Model 4 is likely to entail higher overall transaction costs in the event of uncoordinated action. The decisive advantage here, however, is that reserve management remains in the hands of those who directly bear the economic risk of raw material dependence. The risk of planning errors should be comparatively low due to the market knowledge of the actors involved. Moreover, a significantly lower level of public information is required, since each company only has to plan its own technology-specific requirements. At the same time, availability in the event of a crisis is guaranteed the fastest. The existence of a free-rider problem will depend heavily on the design of monetary incentives.

If the positive externality associated with the individual inventory build-up for the domestic market can be internalised, the danger of free-rider behaviour will be contained. Special write-downs on inventories and loan guarantees for inventory investments are targeted means. However, their incentive effect is only temporary without further accompanying measures. To create incentives for companies to maintain stable reserve stocks in the longer term, direct support could also be provided for cooperative ventures in the reserve stockpiling of critical raw materials, for example by means of state subsidies for joint ventures. This would also have the advantage of reducing transaction costs in procurement and improving the possibilities of enforcing lower procurement prices.

4. Management and competencies

The build-up of raw material reserves generates fixed assets that could be managed actively or passively. In the case of purely decentralised stockpiling, management lies with the companies concerned. In the case of publicly mandated stockpiling, on the other hand, the management of stockpile

resources should be the subject of explicit regulation. This includes, on the one hand, the question under which circumstances a (partial) liquidation of stockpiles is indicated and how this is to be carried out. On the other hand, it must be clearly regulated whether and in what form active management of inventories is permitted, irrespective of the occurrence of crisis situations. Three basic cases can be distinguished.

Model 1: Purely passive administration
Model 2: Passive administration with long-term adjustments to resource demand
Model 3: Active market engagement (Metal Bank)

Figure 4- Three types of EU strategies concerning the management of stockpiles, source: own representation

The first two models are designed solely to provide sufficient raw materials in the event of a crisis. Stock management assumes a passive function vis-à-vis trading on the commodity markets. This does not rule out the possibility that the existence of reserves may also have a market-influencing function via repercussions on market demand (see section 3.1). However, the commodities held in stock are not actively traded. In Model 1, inventory management would only include monitoring of legally stipulated inventory levels. Model 2 would additionally provide for a continuous adjustment of stocks to consumption developments on the basis of ex-ante-defined rules. This corresponds to the design of the EU directive for petroleum reserves. For rare metals, however, longer-term adjustment periods would be appropriate.

Model 3 includes scheduled inventory adjustments and an active role for the administrating institution on the commodity markets. It is given the authority to make targeted purchases or sales of raw materials on the market depending on the market situation (supply, price development), and, thus to dynamically adjust inventories to market developments. The motivation for such market interventions can be, on the one hand, to constantly adjust the commodity portfolio to changes in the risk assessment. On the other hand, they can also represent an attempt to use recurring price fluctuations for value enhancement by limiting purchases to low-price phases and sales to high-price phases. Finally, extensive forms of intervention may also be motivated by the desire for price stabilisation. A distinction would have to be made between whether such market interventions may be carried out on a discretionary basis or whether they are tied by law to specific conditions (e.g. minimum markups of prices over a certain period of time).

Against this background, Bardi et al. (2017) have brought the concept of a public "metal bank" into play. It envisages not only the reserve storage of rare metals but also their active trading for the purpose of both risk hedging and profit generation. This trade would not have to include the physical transfer of the metals but could be done through the issuance of certificates by the metal bank. These would be fully covered by the quantities in stock. The idea is to create its own parallel markets by trading with certificates, which would be anchored in the real availability and thus the events on the international commodity markets. The aim of this approach is to create a closed circuit of investors in order to limit the influence of speculation on commodity prices and to achieve a price-smoothing effect on the commodity markets (Bardi et al., 2017). The scope of competence of such a bank evokes associations with the European Central Bank (ECB).

From a transaction cost perspective, the concept of a market-intervening, public commodity bank would be relatively efficient to implement for rare metals. The lower market volume compared to bulk commodities would limit the amount of strategic trading necessary for a market-influencing effect. Physical trading costs could also be avoided via a certificate solution. However, the general reservation against central reserve management that the lack of direct involvement increases the risk of planning errors applies even more strongly to this model. The decision-makers of a metal bank are not directly affected by the long-term consequences of a physical shortage of raw materials. They will be tempted to focus their activities on immediately visible successes. This could include, above all, the achievement of short-term profits in the commodity markets.

The focus on such a target may conflict with the fundamental principle of reserve holding, the precaution against supply risks. For example, in the short term, sharply rising prices could encourage a metal bank to sell stocks. However, if the price increases are the consequence of increased supply risk, this would be exactly the opposite of what would be expected from responsible reserve management in such a situation. Even the concept of trading stocks only indirectly in the form of certificates does not change this. This is because their value is only derived from the expectant right to the resource. And the tendency to redeem this right grows with increasing supply risk. This shows how much comparison with the ECB is misleading: A metal bank would have no possibility to create its own market supply but would always remain dependent on the global availability of raw materials. The attempt to prevent unintentional risk-promoting market behaviour by imposing tight intervention rules is also not very promising. This is because the same type of intervention could be understood quite differently by the other market players and trigger unexpected market reactions. It is difficult to cover the diversity of such reactions with a set of rules. Finally, an institutional conflict with the ECB's sphere of interest is also conceivable. To the extent that a metal bank can effectively intervene in price formation on the international commodity markets, it would have an indirect influence on macroeconomic inflation rates that should not be underestimated.

5. Implications and limitations

Following the arguments of economic theory, building up stocks can represent an effective means for an importing country to reduce supply risk and hedge against price fluctuations. Moreover, in the case of concentrated markets, it can also be a strategic instrument for reducing the threat potential posed by dominant suppliers. At the same time, differences in supply chains and application technologies between the critical metals require careful market monitoring to be part of any stockpiling strategy.

Furthermore, we argued that the institutional design is likewise crucial for achieving an optimal stock allocation. This results in some recommendations for policy-makers in importing countries and regions. In view of the economic risks

associated with state-managed stockpiles (danger of planning errors, crowding-out risk), we advocate a policy aimed primarily at promoting stockpiling incentives on the part of the private sector. Increased monetary incentives for industrial companies to stockpile rare metals could help to combat the "public goods" problem of supply risk. Concrete instruments could be tax incentives in the form of special depreciation on inventories or government guarantees to secure more favourable loans for financing stockpiling investments.

A supplementary public stockpile may nevertheless make sense for two reasons: as a geopolitical signal to raw material exporting countries and as a form of basic hedging against extreme supply scenarios. However, to limit costs and avoid a crowding-out of private stockpile investments, it should better be limited to a form of basic reserve, covering only the metals most critical in terms of macroeconomic risk potential. Competencies of the managing institution should be restricted to updating the scale and scope of stockpiles to long-term demand projections. This approach not only avoids the incalculable risks of market intervention but also sets lower information requirements concerning price developments and risk profiles.

In general, stockpiling is a suitable strategy to hedge against existing risks, but it cannot fundamentally alter an importing country's exposure. In the long run, to eliminate existing raw material risks, current import regions like Europe have no alternative but to fundamentally reorganise their procurement structure. Sources of supply must be diversified while at the same time paying attention to the reliability and regulatory proximity of new partners. Strategic partnerships with third countries in the raw materials sector represent one promising instrument for establishing stable new supply channels and diverting market shares away from China (Schmid, 2020). For instance, the EU is currently seeking to significantly expand its still limited portfolio of partners (European Commission, 2022).

In the short term, priority should be given to working with countries that are not only rich in resources but also feature a well-developed infrastructure and regulatory proximity, making them suitable for the rapid establishment of joint supply chains. Raw materials cooperation with countries in which the supply capacities are still in the development stage should be viewed more as long-term projects. Here, efforts should first be directed toward exploration and institutional cooperation before economic integration is pursued. When selecting partners, care should be taken to avoid creating new one-sided dependencies. In addition to alliances with countries rich in raw materials, strategic buyer alliances with other importing regions are a potentially suitable measure, as they increase the common weight on global raw materials markets.

To avoid any conflict with sustainability targets, regulatory cooperation should be pursued before establishing joint supply chains in partner countries with low environmental and safety standards. However, the extent to which a direct transfer of domestic standards is technically feasible and politically enforceable can only be assessed on a case-by-case basis. In any case, importing countries must be aware of the likely trade-off between environmental standards and procurement costs.

Promoting circularity in the processing of rare metals should be the second central pillar of a long-term raw materials strategy. With increasing industrial use, the treasure trove of raw materials buried in everyday products is becoming ever more attractive. The term "urban mining" describes strategies to make this treasure economically viable through waste management and reprocessing. The advantages of such so-called "anthropogenic" raw material stores are obvious. Access is gained without the environmental risks associated with mining and free from the price fluctuations and supply risks on the world markets (Tercero et al., 2020). Moreover, anthropogenic repositories are concentrated in urban areas and thus generally in close proximity to production sites.

At the same time, however, the establishment of corresponding recycling chains represents a major technical and organisational challenge. The first practical challenge to recycling is securing the products at the end of their use phase. On the consumer side, this presupposes sufficient incentives for proper disposal.

For electrical appliances, the costs to the consumer tend to be higher than for household waste, as additional knowledge is required (location of depot containers, recycling centres) and more time is needed (Otto et al., 2015). Following this, an efficient collection and sorting system is required that sorts the resource-rich waste according to the type of re-use and separates out non-recyclable material. And finally, the individual raw materials, which are often only present in small quantities and in the form of chemical compounds, must be extracted from the remaining mixture of substances in the largest possible proportions. One economic problem, however, is the high capital intensity of such complex, multi-stage processes. This requires major economies of scale as the use of such processes is only worthwhile if large quantities of recyclable materials are involved (KU Leuven, 2022).

The main limitation of our theory-based reasoning is the lack of empirical evidence on the determinants and impacts of strategic resource stockpiles. This is a consequence of the current data situation: only very few countries currently have official central reserves of critical metals. Those countries that already have reserves do not publish figures on their extent, partly for reasons of national security. The extent of decentral stockpiling of critical metals at company level is also not yet recorded in official statistics. The implementation and regular updating of corresponding estimates would be an important basis for monitoring stockpiling policies in the future. In general, further improvement of the information situation is required for active risk management in the rare metals segment. The EU has made considerable progress in this area in recent years through its expanded criticality monitoring and the data collection of the Joint Research Centre (EU JRC, 2022).

However, continuous risk monitoring would require the development/consideration of still more indicators (especially on the market situation and the use side), as well as a more differentiated evaluation system. In addition, more attention should be paid to the dimension of environmental risks in raw material analysis.

6. Conclusion

The variety of new risks and dependencies that the transition to non-fossil technologies entails for raw material importing countries makes more active risk management urgently necessary. Measures to diversify procurement sources and to promote domestic supply channels are indispensable. However, they will only take effect in the medium to long term. To reduce procurement risks earlier on, the build-up of reserves of critical raw materials is a sensible supplementary measure. Our analysis argues that stockpiling can help reduce both supply-side and price-related risks. This is particularly true in cases where markets are characterised by high price volatility and/or the risk of supply disruptions is significant. Moreover, if there is a high degree of market concentration on both the supply and demand sides, storage can also be used as a strategic tool for long-term price dampening. Unlike alternative measures such as subsidies for the domestic mining sector, no hostile counter-reactions are to be expected from the globally dominant exporters, as they are also likely to benefit.

At the same time, it must be borne in mind that stockpiling, like any other form of insurance, can never be free of charge. In addition to the operating expenses for building up and managing inventories, the opportunity costs (lost market return on alternative investments) of building up reserves must also be considered in the cost-benefit analysis. The aim of using raw material reserves to cushion risks in the future always goes hand in hand with foregoing consumption in the present. In view of the very dynamic development of technology and the susceptibility of the raw material markets to political intervention, intelligent stock management also requires permanent market monitoring.

Against this background, the question of practical responsibility is of decisive importance. Stockpiling should primarily be the responsibility of those actors who, due to their knowledge of the market and their personal involvement, are best able and willing to implement changes to the risk exposure. In principle, this speaks in favour of decentral stockpiling at the level of raw material-consuming industrial companies. However, since there is a tendency toward underprovision, private storage should be supported by government incentive instruments. This could include special depreciation on raw material reserves, government guarantees for storage credits or subsidies for purpose-related joint ventures. In addition, state reserves of raw materials would be useful as a basic hedge for the extreme scenario of massive supply restrictions. However, these should be restricted to a selection of a few particularly critical raw materials. Their task should be limited to passive hedging in the event of a crisis and should not include an active role as a market player.

References

Bardi, U., Jakobi, R., & Hettiarachchi, H. (2017). The metal bank: A management model for rare mineral resources in a circular economy. United Nations University. Policy Brief No. 1/2017. https://doi.org/10.53325/DXWR6615

Bardi, Ugo, Rolf J., & Hettiarachchi, H. (2016). Mineral resource depletion: a coming age of stockpiling?, BioPhysical Economics and Resource Quality, 1.1, 1-9. https://doi.org/10.1007/s41247-016-0004-x

Biden, J.R. (2021). Executive order on the designation to exercise authority over the national defense stockpile. October 31, 2021. Presidential Actions.

Binnemans, K., & Jones, P. T. (2015). Rare earths and the balance problem. Journal of Sustainable Metallurgy, 1(1), 29-38. https://doi.org/10.1007/s40831-014-0005-1

Bustos-Gallardo, B., Bridge, G. & Prieto, M. (2021). Harvesting Lithium: water, brine and the industrial dynamics of production in the Salar de Atacama, Geoforum, 119, 177-189. https://doi.org/10.1016/j.geoforum.2021.01.001

Chappell, C. G., Gainer, R., & Guss, K. (1983). America's stockpile: an organisational history. National Defense Stockpile Center.

EU JRC (2022). EU Science Hub – Raw Materials Information System (RMIS). Joint Research Centre of the European Union. https://rmis.jrc.ec.europa.eu/?page=geological-data-157d8a

European Commission (2020). Critical raw materials resilience: charting a path towards greater security and sustainability. Communication from the European Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions. (2020) 474 final.

European Commission (2022). State of the union address by President von der Leyen.

European Union (2009). Council directive 2009/119/EG imposing an obligation on Member States to maintain minimum stocks of crude oil and/or petroleum products.

Gaudet, G. (2007). Natural resource economics under the rule of Hotelling. Canadian Journal of Economics, 40(4), 1033-1059. https://doi.org/10.1111/j.1365-2966.2007.00441.x

Hotelling, H. (1931). The economics of exhaustible resources. Journal of Political Economy, 39(2), 137-175. https://doi.org/10.1086/254195

Huang, X., Zhang, G., Pan, A., Chen, F., & Zheng, C. (2016). Protecting the environment and public health from rare earth mining. Earth's Future, 4(11), 532-535. https://doi.org/10.1002/2016EF000424

ILO (2022). Sustainable Development Goal indicators. SDG indicator 1.3.1 - Proportion of population covered by social protection floors/systems (%) in 2020. International Labour Organization.

Kaunda, R. B. (2020). Potential environmental impacts of lithium mining. Journal of energy & natural resources law, 38(3), 237-244. https://doi.org/10.1080/02646811.2020.1754596

Klen, R.W. (2014). A primer on the economics of insurance. Manuscript.

KU Leuven (2022). Metals for clean energy: Pathways to solving Europe's raw materials challenge. Report for Eurometaux.

Malkiel, B. G. (1989). Efficient market hypothesis. In: Finance (pp. 127-134). Palgrave Macmillan, London. https://doi.org/10.1007/978-1-349-20213-3_13

Mancheri, N. A. (2015). World trade in rare earths, Chinese export restrictions, and implications. Resources Policy, 46, 262-271. https://doi.org/10.1016/j.resourpol.2015.10.009

Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L., & Espinoza, L. T. (2016). Raw materials for emerging technologies. German Mineral Resources Agency: Berlin, Germany.

Mason, C. F. (2011). On stockpiling natural resources. Resource and Energy Economics, 33(2), 398-409. https://doi.org/10.1016/j.reseneeco.2010.05.008

McGuire, M. C. (2006). Uncertainty, risk aversion, and optimal defense against interruptions in supply. Defence and Peace Economics, 17(4), 287-309. https://doi.org/10.1080/10242690600612688

METI (2014). Strategic energy plan. Technical report. Ministry of Economy, Trade and Industry. http://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/4th_strategic_energy_plan.pdf

Nichols, A. L., & Zeckhauser, R. J. (1977). Stockpiling strategies and cartel prices. The Bell Journal of Economics, 66-96. https://doi.org/10.2307/3003487

Nicoletopoulos, V. (2014). European policies on critical raw materials, including REE. In Proceedings of the 1st European Rare Earth Resources Conference.

Otto, S., Henn, L., Arnold, O., Kibbe, A. (2015). Die Psychologie des Recyclingverhaltens. In: Recycling und Rohstoffe – Vol. 8. TK Verlag Karl Thomé-Kozmiensky, Neuruppin.

Reuters (2020). A brief history of China's metals stockpiling programmes https://www.reuters.com/article/us-china-metals-stockpiles-ahome-idUKKBN22D56X

Schmid, M. (2020). Challenges to the European automotive industry in securing critical raw materials for electric mobility: the case of rare earths. Mineralogical Magazine, 84(1), 5-17. https://doi.org/10.1180/mgm.2020.9

Seaman, J. (2019). Rare earths and China: A review of changing criticality in the new economy. Policy Commons, Report.

Sovacool, B. K. (2021). When subterranean slavery supports sustainability transitions? Power, patriarchy, and child labor in artisanal Congolese cobalt mining, The Extractive Industries and Society, 8.1, 271-293. https://doi.org/10.1016/j.exis.2020.11.018

Tercero, L., Rostek, L., Loibl, A., & Stijepic, D. (2020). The Promise and Limits of Urban Mining. Fraunhofer Institute for Systems and Innovation Research ISI.

Theodosopoulos, V. (2020). The geopolitics of supply: towards a new EU approach to the security of supply of critical raw materials? Institute for European Studies Policy Brief.

Ting, M. H., & Seaman, J. (2013). Rare earths: future elements of conflict in Asia?. Asian Studies Review, 37(2), 234-252 https://doi.org/10.1080/10357823.2013.767313

USGS (2020). Appendices – Mineral commodity summaries 2020. US Geological Survey. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-appendixes.pdf

USGS (2022). Mineral commodity summaries. US Geological Survey. https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries

Wolf, A. (2022). Europe's position on raw materials of the future. cepInput No.11/2022.

Wolf, M. J., Emerson, J.W., Estay, D.C., Sherbinin, A., & Wendling Z.A. (2022). 2022 Environmental Performance Index. New Haven, CT: Yale Center for Environmental Law & Policy.

World Bank (2022). Worldwide Governance Indicators. https://info.worldbank.org/governance/wgi/