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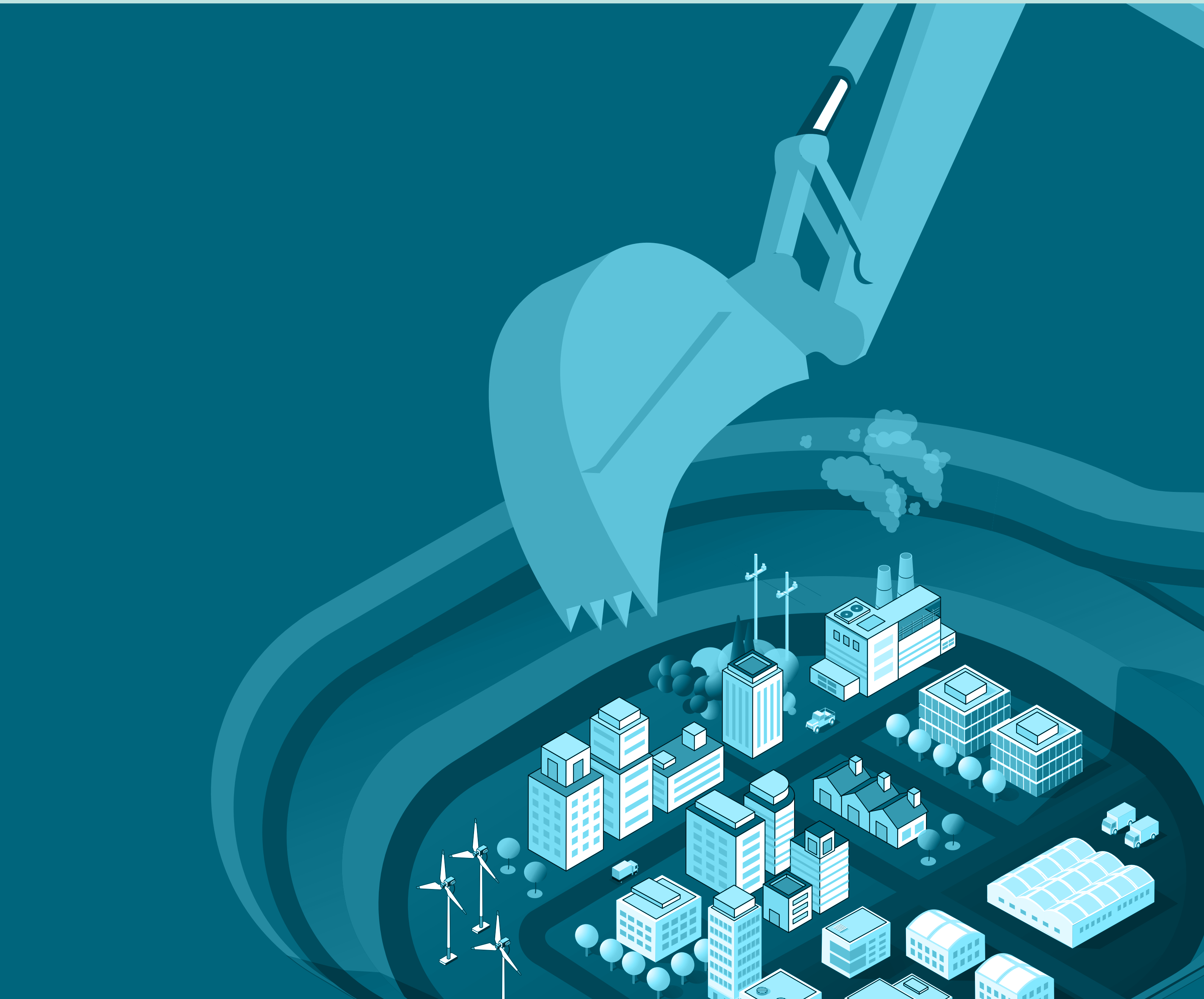
The promise and limits of Urban Mining



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The promise and limits of Urban Mining

Potentials, Trade-Offs and Supporting Factors for the Recovery of Raw Materials from the Anthroposphere

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Executive summary

People and everything made by people – from forks to skyscrapers and landfills – belong to the anthroposphere. Consequently, the anthroposphere contains a wide variety and vast amounts of materials. Urban Mining aims to manage and use these materials as a source of raw material supply, utilizing not only the waste of today but also anticipating and capturing the value contained in the waste of tomorrow. Urban Mining is an important part of the Circular Economy and provides a degree of independence from natural resources, increasing supply security.

> Urban Mining aims to manage and use the anthroposphere as a source of raw materials.

The amount of resources contained in the Urban Mine continues to grow. This follows from society's increasing raw material demand. The value of the materials contained in the anthroposphere is enormous, yet much lower than the value of the products they enable (e.g., the material value of a modern smartphone is well under two US dollars). Material recovery is, thus, a last resort in keeping the value of raw materials in the economy. Other circularity measures, such as extending service lifetimes, preserve the raw materials and the functions they provide more effectively. Reuse, repair and remanufacturing reduce the amount of raw materials needed for product replacement but limit the output from the Urban Mine (fewer discards to recover materials from). However, all products eventually reach the end of their useful lifetime and are a potential source of raw materials.

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The term Urban Mining implies both a connection to "conventional" mining of ores as well as a differentiation from it. Many mining concepts such as "resources" and "reserves" apply analogously to Urban Mining. All metals and minerals present in the Urban Mine originated from conventional mining, even if the material has been previously recycled. Urban Mining keeps metals and minerals in productive use for longer, thus decreasing the need for conventional mining and contributing to a more sustainable use of natural resources. As in the case of conventional mining, not all material present in the Urban Mine is recoverable.

> All metals and minerals present in the Urban Mine originated from conventional mining, even if the material has been previously recycled.

The potential of the Urban Mine is usually given as the sum of materials in buildings, infrastructures, products and landfills. This is misleading because much of this material remains in use. The current potential for raw material production from the Urban Mine depends on the outflow of buildings, infrastructures and products from service into waste management and recycling, together with the recovery from tailings ponds and landfills. From the quantitative point of view, Urban Mining is currently equivalent to recycling of end-of-life products; material recovery from landfills and tailings ponds is negligible. There is a gap between the raw material production potential given by the Urban Mine and the amounts of raw materials effectively recovered. This follows from the challenges – from organizational to technological to economic – facing the recovery of raw materials from a highly diverse and highly complex resource base distributed worldwide.

> From the quantitative point of view, Urban Mining is currently equivalent to recycling of end-of-life products.

Urban Mining is part of a network of interconnected goals and interests. Though the recovery of materials stored in the Urban Mine is a valuable alternative to the exploitation of natural resources, the more of the Urban Mine is recovered and maintained in the cycle, the higher the costs become. This follows from the inhomogeneity of the Urban Mine. Highly complex and diluted waste streams call for elaborate recycling processes with environmental footprints approaching that of conventional mining. The worldwide distribution of the products and the need for economies of scale in their recycling brings large logistical challenges. The material value in the products is not always enough to pay for complex logistics and processing. Some but not all materials can be recycled without loss of quality. The use of recycled materials is sometimes limited due to safety or environmental concerns such as reduced corrosion resistance or impurities that may wash out. Overall, considering all relevant aspects of a particular case may lead to less instead of more Urban Mining if challenges and concerns outweigh the benefits. It is necessary to be cognizant of such trade-offs not only when discussing Urban Mining but also measures unrelated to but affecting Urban Mining.

> Urban Mining is part of a network of interconnected goals and interests.

Different recycling indicators characterize the functioning of the Urban Mine. Some recycling indicators measure efficiency, others independence from mining of natural resources. All are different. These differences in definition mostly translate into significant differences in indicator values. Therefore, quoting a "recycling rate" is not sufficient to recognize and assess its information content. It is necessary to specify the definition or use an unequivocal name to avoid misinterpretation.

> Quoting a "recycling rate" is not sufficient to recognize and assess its information content.

The framework conditions for Urban Mining are essentially those for recycling because recovery from landfills is currently negligible. Not only lack of profitability but also regulatory hurdles for accessing and processing the landfilled material are a hindrance for raw material recovery from landfills. Recovery from mine tailings remains an exception to date. Important framework conditions for recycling include the existence of collection and recycling infrastructures, incentives for recycling, mandatory recycling schemes, mandated recycling rates, penalties for landfilling; availability and costs of labor and recycling technologies; regulation (and enforcement thereof) for environmental protection, public and worker's health and safety, and scrap trade. Generally, uniform conditions and regulation pro recycling contribute to channeling of secondary material to where the most value is conserved instead of where health and environment are less protected.

> Different actors can support the recovery of raw materials from the Urban Mine in a variety of ways.

Different actors can support the recovery of raw materials from the Urban Mine in a variety of ways. Policy targets, regulations and infrastructures are in the hands of governments and public entities. However, the success of collection efforts remains dependent on the support of a committed and well-informed public. Industry has an important role to play as both designer and provider of products as well as collector and recycler. Recognizing the need to consider repair and disassembly as much as possible as part of the design process, and conveying this information together with the products, would not only encourage more widespread repair & refurbishing but also contribute to allocating end-of-life products to the proper recycling routes, allowing for the maximal recovery of raw materials. Finally, with ever more complex products distributed all over the globe, the development of advanced recycling technologies and adequate access to these is a pre-requisite for effective recovery of the resource potentials of the Urban Mine.

01. What is Urban Mining?

People, everything made by people, and their interactions with other Earth systems (biosphere, atmosphere, lithosphere, etc.) constitute the technosphere or anthroposphere (Kuhn & Heckelei 2010; Zalasiewicz 2018). Urban Mining is the concept of using the materials present within the anthroposphere as a source for our raw material supply (Lanau et al. 2019; Müller et al. 2017).

There are enormous amounts of material in the anthroposphere. The potential of the Urban Mine – the anthropogenic stock – is the sum of all materials contained in products used or stored by society over a comparatively long time. This includes – among many others – buildings, electronic goods, waste and mine tailings. Products meant for direct consumption like fuels or food are not relevant for the recovery of raw materials and thus not part of the anthropogenic stock (Müller et al. 2017). Urban Mining sees the anthropogenic stock as a potential source of raw material supply, whether these are products in use, waste or landfilled materials.

One definition of Urban Mining is the "integral management of the anthropogenic stock with the aim to recover raw materials from long-living products, buildings, infrastructure and tailings" (Müller et al. 2017). Some definitions also consider the energetic use of discarded products through incineration (e.g., Baccini & Brunner 2012), but this is mostly excluded from definitions of Urban Mining because it generally impedes raw material recovery (Cossu & Williams 2015). The recovery of raw materials from the Urban Mine can contribute to long-term environmental protection, resource conservation, and provide economic benefits (Cossu 2013). All definitions of Urban Mining have the management of the anthropogenic stock in common, whether materials are currently available for recovery or not. This is an important difference in scope between Urban Mining and waste management: Urban Mining attempts to manage not only the waste of today but also anticipate and capture the value contained in the waste of tomorrow (cf. Müller et al. 2017). The focus of this overview is metals, but the ideas largely apply to other materials in the anthroposphere, such as industrial minerals, wood and stone.

The term Urban Mining implies both a connection to "conventional" mining of ores as well as a differentiation from it. The conceptual overlap is large despite obvious differences between recycling – a central component of Urban Mining – and mining. Mining aims at "securing raw material supply by exploration, extraction and refining of natural resources" (Müller et al. 2017). Changing a single word in this leads to a good description of Urban Mining as aiming at "securing raw material supply by exploration, extraction and refining of *anthropogenic* resources".

> Urban Mining attempts to manage not only the waste of today but also anticipate and capture the value contained in the waste of tomorrow.

Although mining is based on geological formations and Urban Mining on the anthroposphere, there are parallels in definitions, concepts and technologies. Like for mining, reasonable definitions exist or are in development for quantifying the potential of the Urban Mine (Heuss-Aßbichler et al. 2020). This parallel recognizes that, as is the case for metals and other raw materials present in the earth's crust, not all material present in the anthropogenic stock is recoverable (Bangs et al. 2016). The United Nations Framework Classification (UNFC) applied to anthropogenic resources recognizes them as a "concentration or occurrence of Anthropogenic Material of intrinsic economic interest, in such form, quality and quantity that there are reasonable prospects for eventual economic exploitation" (UNECE 2018), and different case studies show the applicability of the framework at different scales (UNECE 2020). The UNFC does not recognize "reserves" but uses different "classes" to qualify the viability of individual projects. However, there are obvious parallels in the criteria (UNECE 2018). Like in mining, considerations like element concentration, abundance, availability, speciation and partner minerals largely determine whether a particular Urban Mining project is economically feasible or not (Brunner 2011).

All metals and minerals present in the anthropogenic stock originated from mining, even if the material has been previously recycled (cf. Figure 1). It follows that both are in principle exhaustible sources of raw materials and Urban Mining is no absolute prevention for raw material depletion. However, Urban Mining leads to more circularity and extends the reach of known and yet-to-be-discovered geological resources.

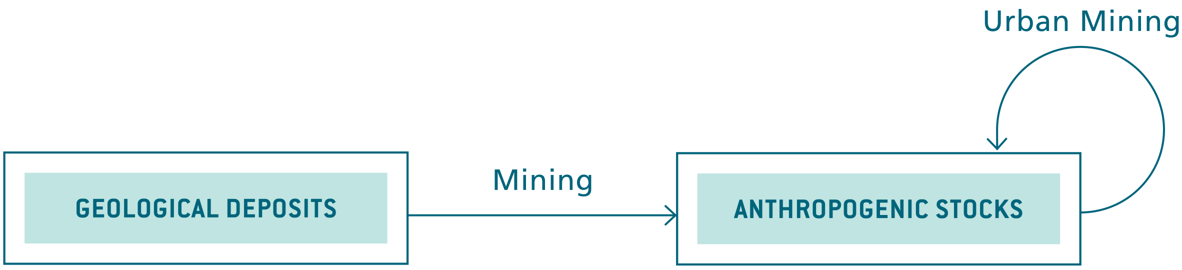


Figure 1: Shift of raw materials from natural deposits to the anthroposphere and their longer retention through Urban Mining.

Unlike mining, Urban Mining does not have the potential to increase the amount of materials included in the anthropogenic stock. Only the flow of discarded products and material recovered from landfills and tailings ponds can be used for the production of new products. These do not lead to growth of the anthropogenic stock in total, but represent a shift in the distribution of the material to different life cycle stages (e.g., from scrap to finished product in use). Only conventional mining has the potential to increase the anthropogenic stock by extracting raw materials from geological sites.

The resources in the Urban Mine sometimes have a higher concentration and thus are more valuable than ores for conventional mining (Bookhagen et al. 2020; Mazzarano 2020). The price for Urban Mining depends on the feedstock material and is not always advantageous. However, the recycling pathway is considerably more cost efficient than virgin mining for certain materials from secondary sources (Zeng et al. 2018).

> All metals and minerals present in the anthropogenic stock originated from mining, even if the material has been previously recycled.

A key limitation of Urban Mining is that its production cannot match current raw material demand. While Urban Mining conceptually comprises both material recovery from current/recent discards (recycling) and material recovery from mining waste and landfills stored for longer periods (landfill mining), recycling dominates quantitatively (e.g., Bio by Deloitte 2015; Passarini et al. 2018; see Chapter 4). Therefore, the output of the Urban Mine depends directly on the quantities and composition of the waste currently exiting the stock in use, which is independent of current raw material demand. It is not possible to expand the Urban Mine to match quantitatively and qualitatively the global quantities and mix of materials required by society. Mining is only limited in a similar way when it comes to raw materials extracted as co-products or by-products: Their production depends on the mining of the main raw material/metal (e.g., Lovik et al. 2016; Reuter et al. 2019).

> A key limitation of Urban Mining is that its production cannot match current raw material demand.

The spatial distribution of raw material sources is different in principle for mining and Urban Mining. In mining, raw material production can be strongly concentrated on certain areas, for example, 64% of the cobalt was mined in Congo in 2017 (Al Barazi 2018). The geological distribution of cobalt reserves is similarly concentrated, with over 50% located in the Democratic Republic of Congo (USGS 2020). In contrast, the raw materials in the anthropogenic stock are spread all over the world, either as products currently in use and concentrated in urban centers, or in tailings ponds and landfills. This creates the opportunity for countries poor in viable geological deposits of raw materials to capture the value of the Urban Mine and use it to become partly independent regarding their raw material supply. In many cases, this may significantly shorten transportation distances compared to mining in remote locations (Müller et al. 2017).

Finally, both mining and Urban Mining require the acceptance of the population living near production sites. While the image of recycling/Urban Mining is less tainted by high-profile incidents (Cornwall 2020) and the use of natural resources and landscape changes inherent to mining, recycling facilities can also cause pollution and face challenges, albeit in a much smaller scale (bangkokpost.com 2015; Sorge 2018). The difference in scale is due to Urban Mining generally having a smaller environmental footprint compared to mining (Müller et al. 2017; UNEP 2011, 2013b). However, recycling facilities are located closer to or in urban centers, making them more visible and sometimes subject to calls for relocation (e.g., McInnes 2012).

MINING	URBAN MINING
– Based on geological resources	– Based on anthropogenic resources
– Requires exploration and characterization of resources; standards available	– Requires exploration and characterization of resources; standards in demonstration
– Finite: Limited through availability of geological deposits	– Finite: Limited amount of materials in the anthroposphere
– Source of all metals in use	– Keeps metals in productive use longer
– Secures the majority of metal supply today	– Provides significant supply contributions for some metals
– Can expand to match increasing demand	– Cannot match increasing demand
– Can be strongly concentrated in few localities	– Concentrated in urban areas (especially in industrialized countries)
– Significant environmental impact	– Often lower environmental impact
– Difficult to secure support of the population	– Less difficult to secure support of the population
– Public not directly part of operations	– Public essential contributor to collection

Figure 2: Comparing mining to Urban Mining.

02. Urban Mining and the Circular Economy

The Circular Economy (CE) concept stands in contrast to the traditionally more "linear" consumption pattern of "take-make-dispose" (Ellen McArthur Foundation 2013). A more Circular Economy aims to keep the value of products and the materials they contain for as long as possible in the economy and to minimize waste generation (European Commission 2015). The individual elements of the CE are themselves not new. These include but are not limited to product design emphasizing reuse & repair, different energy and resource efficiency measures, innovative business models and end-of-life product recycling. However, the CE concept brings these elements together into a consistent whole, covering each step of the value chain from material extraction to material recovery (European Commission 2018; Tercero Espinoza 2020).

An inertia principle for products helps to create resource efficient raw material cycles compatible with the Circular Economy: "Do not repair what is not broken, do not remanufacture something that can be repaired, do not recycle a product that can be remanufactured" (Stahel 2010). Following this principle, a product becomes a source of secondary raw material only when it is not possible to keep it in use. Repair and remanufacturing extend the useful lifetime of products, providing needed functions without the additional expense, energy and resources required for material recovery and manufacturing of new products.

Eventually, every product reaches the end of its useful life. Even repeated cycles of reuse, repair and remanufacturing cannot avert this. At this point, the discarded product becomes a potential source of raw materials able to cycle back into the economy, either immediately (recycling) or later through recovery from stockpiles or landfills. This is where Urban Mining fits into the Circular Economy, as the last loop capturing discarded products and returning secondary raw materials to the economy. An effective collection and recycling of discarded products minimizes the residual waste and leads to a more sustainable raw material cycle. Thus, Urban Mining is an integral part of the Circular Economy and does not cover the whole concept (Cossu & Williams 2015). Processes like optimization of product design or the recycling of manufacturing scrap are part of the Circular Economy but are outside the Urban Mining concept.

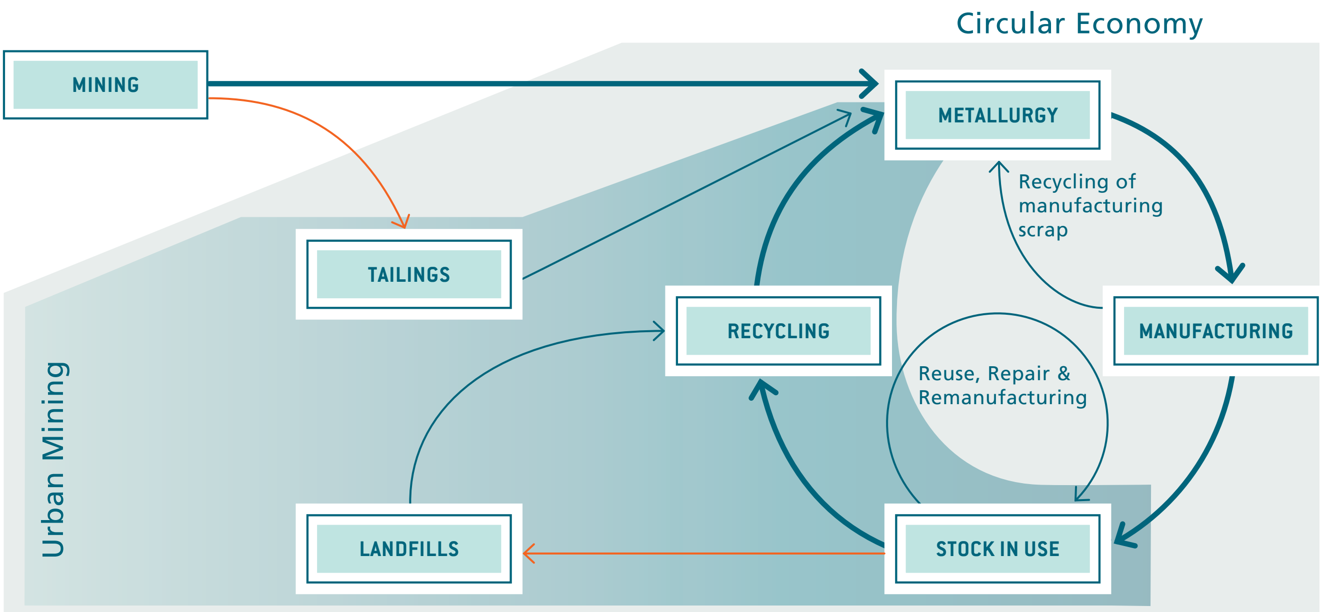


Figure 3: Urban Mining in the context of the Circular Economy.

03. Urban Mining and Critical Raw Materials

The issue of secure supply of raw materials gained prominence with increasing raw material prices starting around 2005. In 2008, the U.S. National Academy of Sciences issued a report on "Critical Raw Materials" CRM for the U.S. economy (NRC 2008). At the same time, the EU Commission launched a Raw Materials Initiative (Commission of the European Communities 2008), mandating the definition and periodic update of a list of Critical Raw Materials for the EU – a process that started 2009 and continues until today (European Commission 2010, 2020c). Since then, many different methodologies have emerged in different countries with different themes (Schrijvers et al. 2020). Naturally, producing countries see an opportunity to sell CRM to the world while net buyers see their supply at risk. Policy responses also follow the respective positions of countries as either suppliers or users. Examples of this are the establishment of the Critical Materials Institute in the U.S. aiming primarily at innovation in manufacturing to reduce reliance on CRMs vs. the Australian response based on innovation in mining (Ames Laboratory n.d; Barteková & Kemp 2016; Commonwealth of Australia 2019). However, the risk at the center of all criticality methodologies developed by both users and suppliers is that of a sudden interruption of a significant part of primary supply (Schrijvers et al. 2020).

Figure 4: Urban Mining as a risk-reducing filter in many methodologies for the identification of Critical Raw Materials.

The focus on primary supply is justified by the fact that mining fulfills the majority of society's necessities today and in the foreseeable future. In addition, all stock present in the Urban Mine originally comes from mining of natural resources. However, Urban Mining provides a largely independent source of raw materials both in time and geographically, and is therefore not immediately negatively affected by short-term disruptions to primary supply. This is widely acknowledged and generally taken into account explicitly in criticality methodologies (Schrijvers et al. 2020).

> Urban Mining provides a largely independent source of raw materials both in time and geographically.

While it is clear that Urban Mining serves to diversify supply and reduce supply risks, the types of risk that apply to supply from the Urban Mine and how to assess and interpret them are relatively unexplored issues. Early versions of the EU criticality methodology (and others elsewhere to-date) treat recycling globally by examining the share of post-consumer scrap in total supply (European Commission 2010; Schrijvers et al. 2020). This is tantamount to declaring sourcing from the Urban Mine as "riskless", which is not entirely true (Tercero Espinoza et al. 2020).

The Urban Mine in developed economies is both rich and diverse, and contains many metals not minded in the respective territories, potentially supplying metals and others raw materials at the location where they were last used. However, the location of last use and the location of new use (manufacturing) need not be the same. In addition, the capacity and incentives must exist to recover the material provided by the Urban Mine lest the material leaves and is recovered elsewhere. This is currently the case for rare earth magnets in e.g. electric motors and generators: Their use is distributed worldwide but manufacturing and capabilities for recycling are highly concentrated in China (Ansorge 2020). Similarly, there are no secondary copper smelters in the USA so that much copper scrap must leave the country (e.g., to China, Malaysia or Europe) if the material is to be recovered (Loibl & Tercero Espinoza 2020).

04. How the Urban Mine grows

A growing population in increasingly industrialized economies with improving standards of living requires more homes, infrastructure and products. This has driven per capita and total demand for raw materials despite efforts to decouple material demand from economic growth. This trend is expected to continue into the future (IRP 2019). Emerging and developing countries will drive material demand mainly for infrastructure and construction. Convergence of income and living standards across countries will also lead to a higher demand for a wide variety of other products. In other words, the gap in material footprint per capita between industrialized and developing countries will decrease. Further population growth will add to material demand as well (IRP 2019; OECD 2018).

Material extraction from natural deposits more than tripled between 1970 and 2017, from yearly 2.6 to 9.1 billion tonnes of metals and from 9 to 44 billion tonnes per year for non-metallic raw materials. If historical developments continue into the future, global metal extraction will rise to 18 billion tonnes per year and non-metallic minerals to 112 billion tonnes per year in 2060. Many structural and technological changes such as more efficient production technologies, a shift towards services or increasing recycling rates have an influence and can decrease the need for primary material in the next decades. Scenarios with many changes towards a more sustainable future predict that necessary metal extraction can be limited to 9 billion tonnes in 2060, equal to current extraction amounts. However, the demand for non-metallic minerals that are important for construction doubles also in the sustainability scenarios to about 90 billion tonnes of extracted materials in 2060 (IRP 2019; OECD 2018).

All material extracted from geological deposits enters the Urban Mine. A part of it never leaves mining sites, leading to large amounts of residual material stored in large engineered dam and dyke facilities called tailings ponds. The rest enters diverse manufacturing chains and, except for dissipation, either remains in use as some kind of product or leaves the material

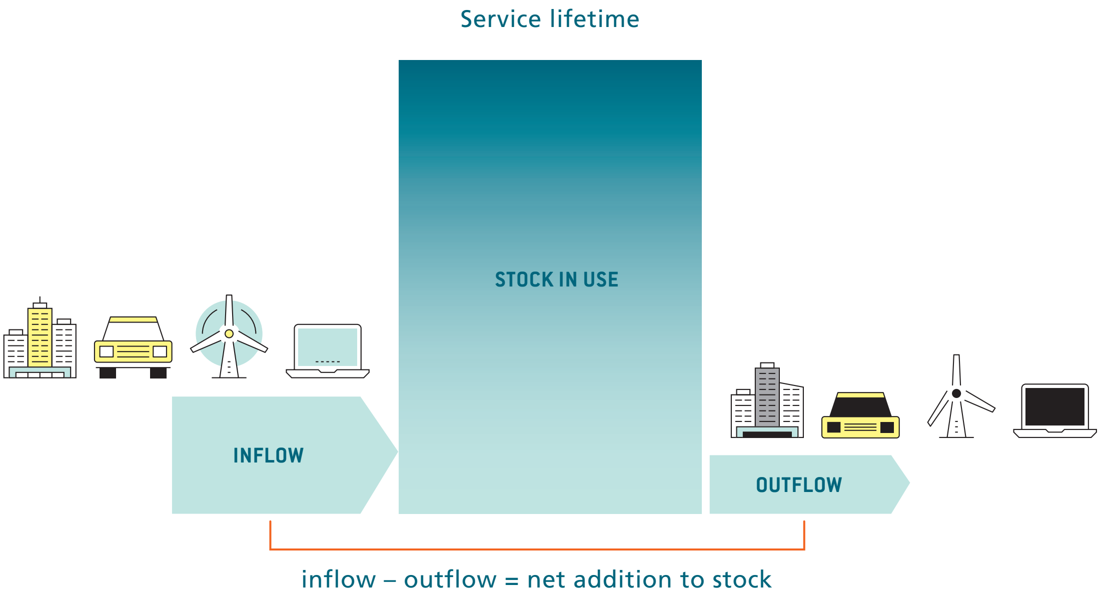


Figure 5: The sum of all materials contained in products used or stored by society grows as long as demand continues to grow. The longer the service lifetime of products, the larger the difference between inflow and outflow from the stock in use, and the faster the stock in use grows.

cycle at some point towards a landfill. All material in tailings ponds, in use and in landfills belongs to the Urban Mine. Thus, the amount of materials contained in the Urban Mine grows continuously with the extraction from natural deposits.

All three reservoirs-tailings, stocks in use, and landfills-contain significant amounts of material. For example, an estimated 650 Mt of copper were extracted from geological deposits between 1910 and 2010. Of these, 100 Mt were estimated to remain in tailings ponds, 350 Mt to be in use, and 140 Mt to have left the copper cycle to landfills. The balance is dissipation (30 Mt) and material lost to other metal cycles or otherwise deemed unrecoverable (30 Mt; Glöser et al. 2013). Despite large reservoirs of material in tailing ponds and landfills, recycling of products leaving the stock in use quantitatively dominates Urban Mining by far (Bio by Deloitte 2015; Passarini et al. 2018). Recovery from landfills is currently at the demonstration stage and does not play a role in raw material supply (see box below; Dürkoop et al. 2016; Loibl et al. 2020; Winterstetter et al. 2018). Similarly, the reprocessing of mine tailings is a topic of increasing importance but remains a niche. Most projects are still under research or development (e.g., Poggendorf et al. 2016). A sizable commercial operation reprocessing zinc tailings in Australia remains exceptional (Australian Mining 2020; Reuters 2018).

Recovery from landfills and tailings is in principle independent from current scrap generation but as described above quantitatively negligible to date. Therefore, the stock in use currently approximates the potential of the Urban Mine, and the scrap generation essentially determines the output of the Urban Mine today (i.e., the amount of material exiting the stock in use; cf. Figure 5).

RECOVERING MATERIAL FROM LANDFILLS ("LANDFILL MINING") VS. FROM DISCARDS (RECYCLING)

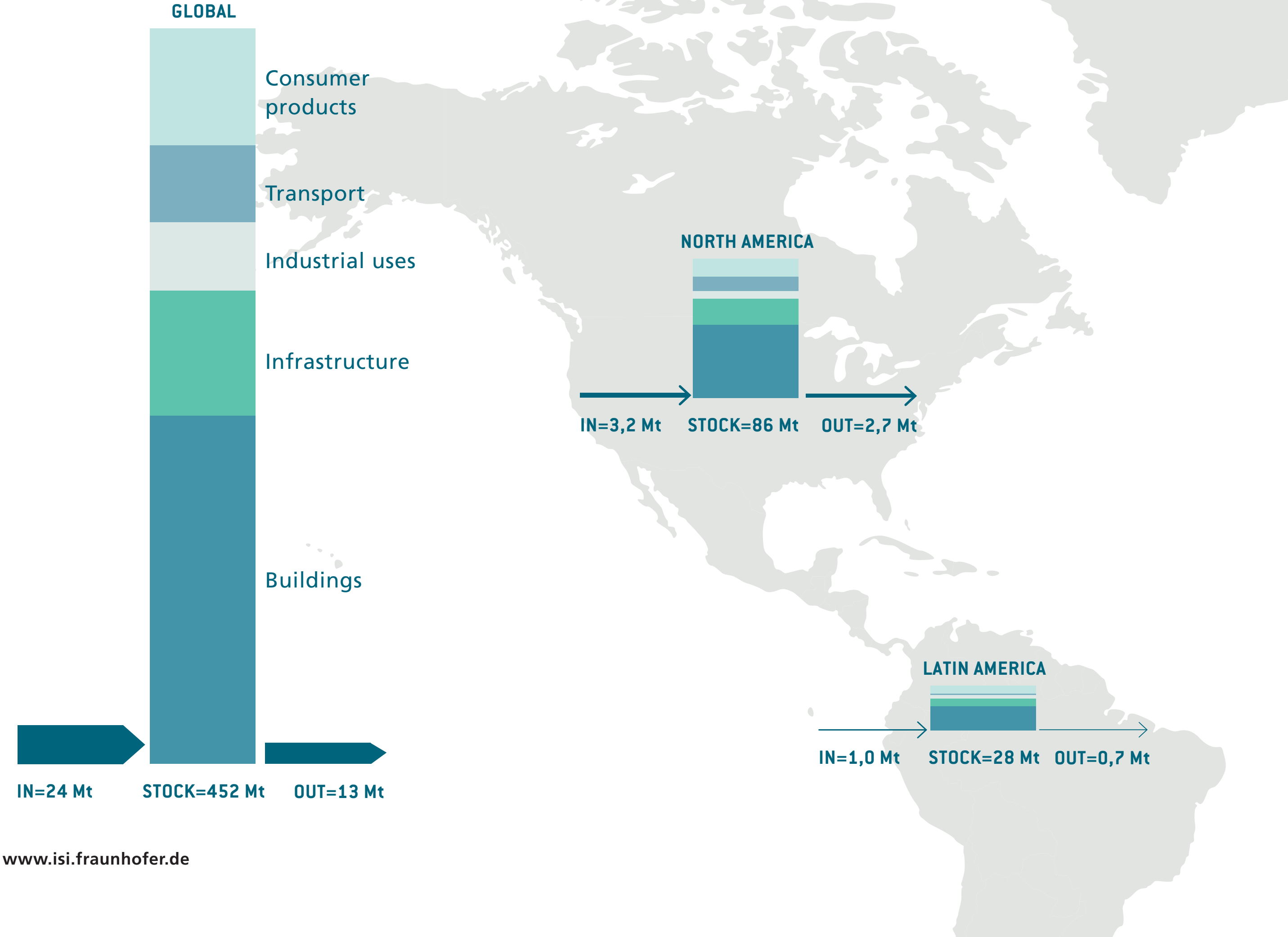
The potential of the Urban Mine theoretically encompasses all anthropogenic material contained in products used or stored by society, and includes mine tailings and material deposited in landfills. In practice, material recovery from current discards (recycling) is a significant source of raw materials but the recovery from landfills and tailings ponds is negligible. Many factors lead to this situation. Intuitively, effective separation of waste streams enables recycling in profitable, specialized processes. Consumers and businesses, who need to dispose of their waste regardless of the subsequent processing, generally bear the cost for collection and initial separation (insofar a separation is performed). Landfills contain material rich in valuable metals mixed with large amounts of other waste, which is often suitable for incineration at best. Some material stored in landfills is also hazardous waste and would need to be landfilled again after processing. Several projects have shown the technical feasibility of "landfill mining" but the unfavorable economics of such projects mean they will only be realized if other interests – such as remediation or reclaiming land – justify the effort (Dürkoop et al. 2016; Loibl et al. 2020; Winterstetter et al. 2016; Winterstetter et al. 2018).

05. The tonnage and value of the Urban Mine

The tonnage and value of materials contained in the Urban Mine is vast. To a first approximation, metals remain in use for their average service life. For long-lived products, service lives range from years to decades, leading to very large urban stocks. For example, electricians recommend rewiring homes and buildings after 30–40 years (Kolb Electric 2017; Whitney Electric & Plumbing 2019). Thus, to a first approximation, all the copper used for wiring homes and buildings in the last 30–40 years is still in use, is potentially recoverable, and has considerable value. Nevertheless, the material value contained in buildings is much less than the value of the buildings themselves. Similarly, the value of metals in the 7.4 bn smartphones sold between 2012 and 2017 amounts to over 8 bn US$. Three quarters of this value are gold, a further 10% the precious metals palladium and platinum. Impressive as those figures are, this corresponds to just over 1.10 US$ per smartphone in material value (at November 2019 prices; Bookhagen et al. 2020). It is important to realize that the material value of products is (much) lower than the value of products they enable, such that material recovery is generally a last resort in keeping the value of raw materials in the economy (Ellen McArthur Foundation 2013; European Commission 2018).

> The material value of products is (much) lower than the value of the products they enable.

Therefore, it is imperative to distinguish between the stock-in-use and the material exiting this stock and becoming available for recovery. Only the latter is relevant for the current material recovery potential of the Urban Mine, and is naturally a much smaller amount than the overall stock-in-use (cf. Figures 5 & 6).



GLOBAL AND REGIONAL URBAN MINES FOR COPPER

Copper is globally the metal with the third largest annual production after iron and aluminum. The high electrical and thermal conductivity as well as good formability and corrosion resistance of copper make it an indispensable building block of our society. The main applications are for electrical wiring and plumbing in buildings and for power transmission and distribution in general electrical infrastructure. Further uses include all sorts of electrical and electronic equipment and machinery from vehicles and industrial applications to consumer goods. In 2018, approximately 450 million tonnes (Mt) of copper were in use globally. Of those, 24 Mt were new products entering the use-phase while 13 Mt of copper left the use-phase as products at the end of their life and thereby became available for recycling. These numbers show a net addition of 11 Mt of copper to the stock of products in use in 2018. The amount of copper in the urban mine is rising and has been doing so continuously over the last decades. Since 1990, the amount of copper in use more than doubled from about 210 Mt to 450 Mt in 2018 (Glöser et al. 2013; ICSG 2019).

A more detailed analysis reveals regional differences between size and development of stocks of copper in use. North America and the European Union both have an estimated amount of 80–90 Mt of copper contained in the Urban Mine and currently show moderate growth of this material stock (Soulier et al. 2018a; Soulier 2018). In Japan, outflow and inflow to/from the Urban Mine are almost in balance so the stock of copper in use is barely growing anymore. On the other hand, China's strong economic growth is visible in the large net addition to the Chinese stock of products in use. The inflow of new products is much larger than the time-delayed outflow of products at the end of their life. The amount of copper in the Chinese use-phase stock is currently about 100 Mt, which is more than a fifth of the global amount of copper in use (Glöser et al. 2013; Soulier et al. 2018b).

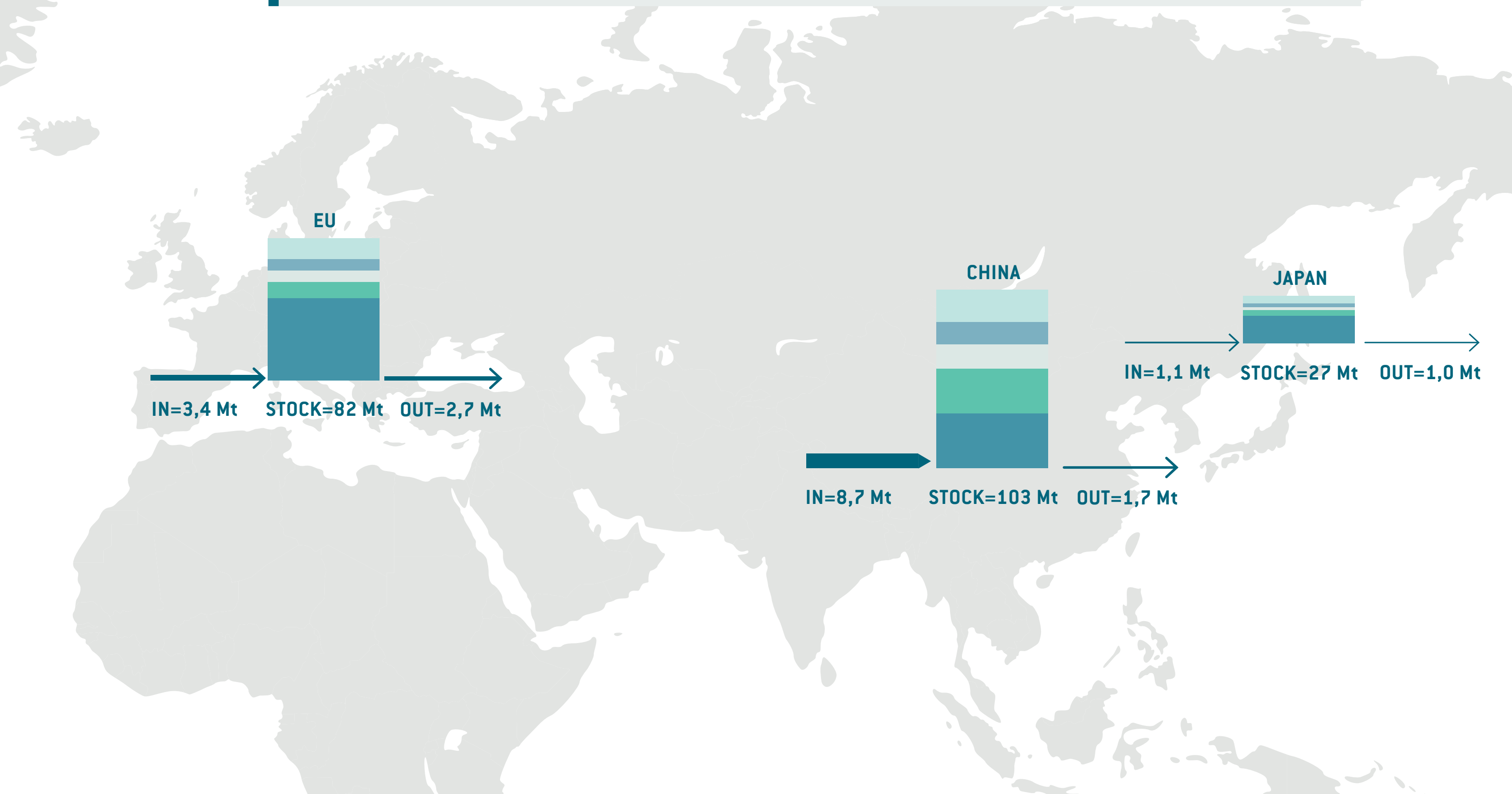


Figure 6: Global and regional Urban Mines for copper (2018). All figures in million tonnes (Mt) of contained copper.

06. Product lifetimes and the output of the Urban Mine

The service lifetime of products is often considered to be equivalent to the time span in which a product is functional (den Hollander et al. 2017). For Urban Mining, the relevant point in time is when a product becomes available for the recovery of raw materials. This can differ strongly from the technical useful lifetime of a product. Many fully functional products are discarded because of fashion or the acquisition of a new model. Many functional and non-functional products are "hibernating": They are no longer in use for any number of reasons, but still not thrown away (Glöser-Chahoud et al. 2019). A common example are mobile phones remaining in drawers as fallback devices, due to privacy concerns or the mere inconvenience of bringing them to an appropriate recycling point (Zhang et al. 2019).

In a growing economy, the quantity of products entering the use-phase usually grows over the years. Products with a short lifespan have a short time delay between production and disposal, and the amounts of EoL products available for recycling are close to the amounts of current manufacturing. For products with long lifetimes, the delay between production and disposal is larger. The amounts of EoL products available for recycling correspond to production numbers from potentially several decades ago, which were in general much smaller.

> The sensible extension of service lifetimes leads to a more resource efficient economy and thus to more sustainability.

One circularity strategy is to extend the lifetimes of products in use for as long as sensible through reuse, repair and remanufacturing (den Hollander et al. 2017). The longer the useful lifetime of products is, the lower the total raw material demand becomes because fewer products in the anthropogenic stock have to be replaced by new products. Consequently, the quantity of products becoming obsolete and thus available for recycling decreases with an extension of lifetimes, resulting in lower amounts of raw materials supplied by Urban Mining. Nevertheless, the sensible extension of service lifetimes leads to a more resource efficient economy and thus to more sustainability.

Product design has a significant influence on service lifetimes.

Ease of disassembly supports reparability, allowing replacement of parts with high wear and tear or otherwise defective. For example, it is obvious to repair a flat tire instead of discarding the whole bicycle (den Hollander et al. 2017), yet the opposite happens with many other products. Material selection also plays an important role in product longevity, especially in the face of adverse environmental factors (e.g., weather conditions influence the corrosion of metals, demanding appropriate corrosion protection). Planning for a certain assumed service lifetime is a part of product design, and manufacturers influence this through decisions about quality of components and assemblies. Timeless design can also have an effect on longer lifetimes, as product appearance is often a reason for new acquisition. Beyond design, maintenance and regular inspections generally lead to longer service lifetimes of products (Taylor et al. 2016).

> The quantity of products becoming obsolete and thus available for recycling decreases with an extension of lifetimes.

While design for circularity decreases the total amount of material available for recycling through longer service lifetimes, it also aims to increase the recyclability of products after discarding. Some aspects that contribute to longer service lifetimes also support Urban Mining. For example, the ability to easily exchange parts (reparability) also eases their separation for appropriate treatment. Material selection, however, has a different objective when designing for longevity vs. designing for recycling. The compatibility of material combinations with recycling processes is also important for Urban Mining. For example, some metals contaminate steel and aluminum and their removal is uneconomical or impractical because of thermodynamics. Especially electronic products contain a myriad elements that cannot all be simultaneously recovered by state-of-the-art recycling/metallurgical processes (UNEP 2013b). However, function is central to product design in general so that, in the hierarchy of design principles, design for recycling has a lower priority (Taylor et al. 2016).

LIFETIME EXTENSIONS FOR COPPER-CONTAINING PRODUCTS IN CHINA

Encouraging a product design that allows easy repair, reuse or refurbishment of parts or the whole device is a typical measure to achieve a more circular economy. The goal is to increase the time products stay in use before they turn into waste. The thinking behind this is that the stock in use provides the functions needed by society (Lanau et al. 2019). Therefore, increasing service lifetimes does not influence the quantity of products in the use phase. However, the longer the lifetime of products, the later they need a replacement and the lower the quantity of new products that need to enter the use phase every year. This directly decreases raw material demand and its footprint. Assuming increasing demand (the historical norm), longer product lifetimes also lead to decreasing amounts of products leaving the use phase as waste and becoming available for recycling. This directly reduces the output of the Urban Mine.

For example, in China, strong economic development during the last decades together with population growth, the change in standard of living and increasing urbanization brought along a strong increase in demand for new products and therefore raw materials. Moreover, with the currently projected development of China in the coming decades, the demand for raw materials will continue to increase. The amount of copper contained in products in use rose from approximately 40 million tonnes (Mt) in 2005 to 100 Mt in 2018, and the forecast estimates it will reach 650 Mt in 2100 (Dong et al. 2020; Soulier et al. 2018b). With current service lifetimes, this would require an inflow of 25 Mt of copper contained in new products to the stock in use and 23 Mt of copper leaving the stock as waste in 2100. If the lifetimes of copper containing products were to increase considerably starting now, only 16 Mt of copper would be necessary for new products entering the use-phase in 2100 and 14 Mt of copper would be contained in the waste stream that year. Since the amount of necessary products does not depend on their lifetime, the level of service (stock in use) is not affected and stays the same in both scenarios.

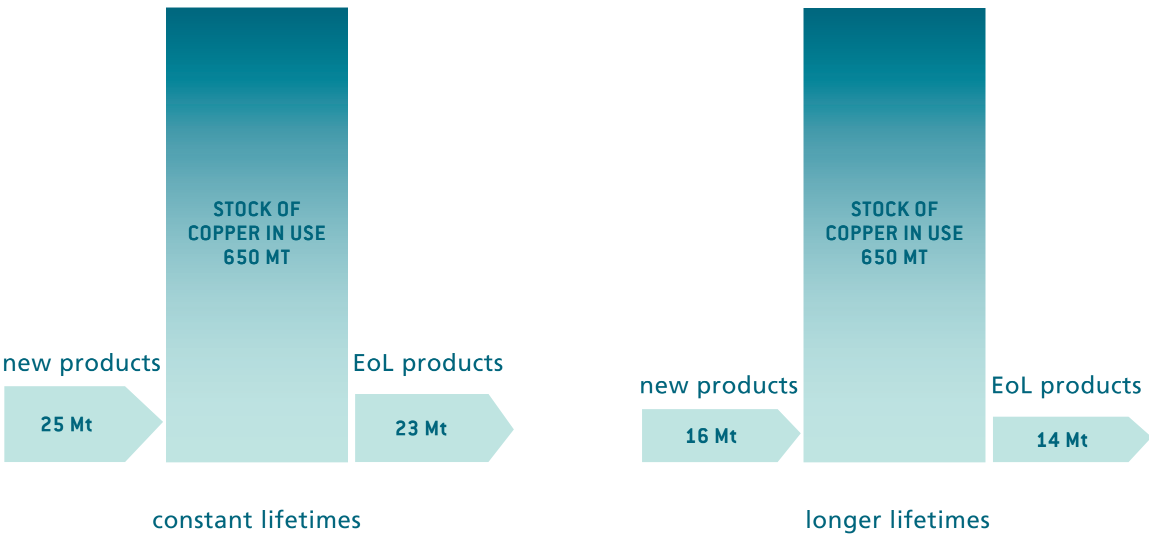


Figure 7: Effect of longer service lifetimes in the projected Chinese copper Urban Mine in 2100 (Dong et al. 2020).

07. Mining the Urban Mine: Theoretical vs. recoverable potential

The theoretical potential of Urban Mining is often presented as equivalent to the total anthropogenic stock. However, the recoverable potential of Urban Mining is much lower (Bangs et al. 2016; Restrepo et al. 2020). The anthropogenic stock includes all materials of the built environment and products in it (Lanau et al. 2019). The largest part of this stock are buildings, infrastructure and other products in use, which are not available for recycling and should, for more sustainability, remain in use for as long as possible. The theoretical potential for recycling is equivalent to the outflow from the in-use stock and additional short-term scrap stocks. Only the flow of discarded products and decommissioned buildings and infrastructure is a source of secondary raw materials, not the stocks in use themselves (Arora et al. 2020).

There is a gap between the recycling potential given by the Urban Mine and the amounts of raw materials effectively recovered. Different barriers and shortcomings lead to this gap, and can be mapped to different dimensions: economic, legal/legislative, technological & infrastructural, social & environmental, logistical & supply chain management, and business & managerial (Kazançoglu et al. 2020). Among these, the main factor determining whether a secondary resource is further processed for recycling is usually profitability – the economic dimension.

Profitability in recycling derives from the value of the raw materials recovered and the costs for the recycling processes (Zeng et al. 2018). Raw material prices can influence recycling rates. For instance, the presence of precious metals in products such as gold in electronics and platinum in autocatalysts constitutes a significant incentive for their recycling. In turn, this favors the recycling of the other materials contained in the respective products, as is the case for gold driving copper recycling from electronic devices. At the same time, a high material price does not guarantee recovery. This applies to many technology metals in electronics. They are valuable yet present in such small amounts that the costs of recovery surpass their material value, blocking recycling (European Commission 2020b). A good example for a valuable technology metal not recovered from post-consumer scrap is indium, currently worth up to approx. 1500 US$ per kg depending on purity (European Commission 2020b; Indium Corporation 2020; Licht et al. 2015).

The technological dimension strongly influences the profitability of Urban Mining. In addition to the concentration of a material in a product, the form in which materials are present is key to their recyclability. For example, zinc is used as metallic zinc (e.g., in zinc sheets), as chemical compound (e.g, zinc oxide) or as an alloy with other metals (e.g., in brass). Depending on this, the recycling pathway and associated expense varies significantly. While recycling a zinc sheet is as simple as remelting it, the extraction of zinc from chemical compounds needs more effort (Ng et al. 2016).

> The main factor determining whether a secondary resource is further processed for recycling is usually profitability

Given the existence of a technically effective recycling process, discarded products and scrap have to be delivered in sufficient quantities and qualities to ensure their operation. Advanced recycling processes generally require economies of scale for profitability (Bangs et al. 2016). Therefore, appropriate pooling of secondary resources with similar concentrations and qualities is important – the logistics and supply chain management dimension (Kazançoglu et al. 2020). The material value contained in the products/scrap must also pay for this in addition to the processing and other costs. Clearly, not all products/scrap meet this requirement. Economies of scale can also dictate the location of recycling operations (Ansorge, 2020; Furgeri, 2020).

The legal and legislative dimension sets the stage for Urban Mining. An effective legal framework is necessary to support recycling. In China, for instance, this is expected to be the most important dimension to support Urban Mining (Hu & Poustie 2018). High investment costs connected to building up the recycling infrastructure are a key barrier to Urban Mining especially in emerging markets (Kazançoglu et al. 2020). In this case, governmental support can give an initial impetus by e.g. subsidies or other kinds of (technical) support.

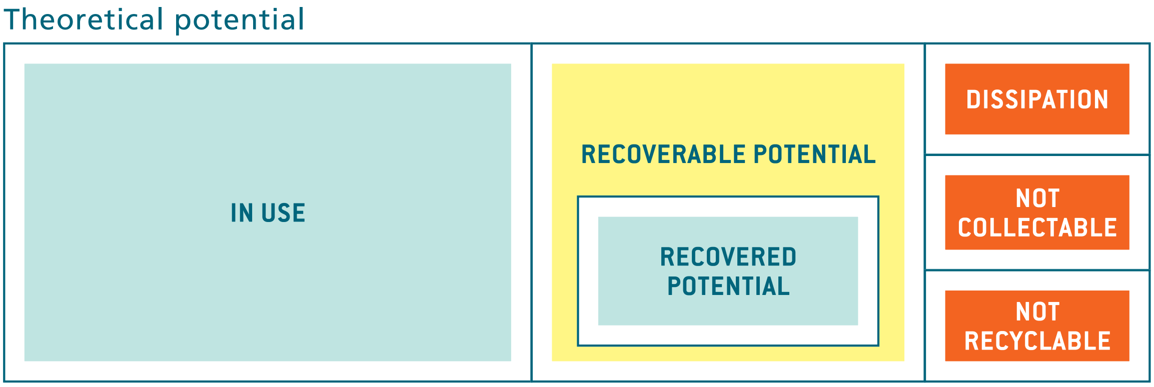


Figure 8: Breakdown of the theoretical potential of the Urban Mine. Products in use are currently not available for recycling. Materials are lost to the environment though dissipation (e.g., corrosion or abrasion) and are not available for recycling. Practical issues such as accessing the scrap (e.g., subterranean cables) or the presence of hazardous chemicals in products/scrap block collection and/or recycling.

RECOVERING RARE EARTH ELEMENTS FROM MAGNETS

High-performance rare earth magnets enable a wide variety of technologies, from small speakers in smartphones to very large offshore wind turbines. These magnets contain neodymium and praseodymium, often in combination with dysprosium and/or terbium. All four metals are classified as Critical Raw Materials by the EU (European Commission 2020c), and the newly created European Raw Materials Alliance (ERMA) focuses on rare earths, with rare earth magnet supply for electric vehicles and wind power being a key concern (ERMA 2020).

Though demand for vehicles and wind turbines has increased strongly and will continue to increase, the current stock in use and material becoming available for recycling is dominated by traditional applications in electronics, industrial motors, and small motors in conventional vehicles (Furgeri 2020; Glöser et al. 2016; Glöser-Chahoud et al. 2016). Recovering rare earth magnets from these sources poses exceptional challenges because of the low concentration (e. g., under 0.5 g in a smartphone), magnet coating, mounting by gluing into position, the brittleness of the magnets (they break easily under mechanical stress), and their strong magnetic properties (they stick strongly to ferromagnetic components in the waste and in processing equipment). Therefore, effective recovery of rare earth magnets requires manual labor or dedicated and flexible disassembly technologies, posing significant technical and economic challenges (ERECON 2015). Consequently, only small amounts of post-consumer rare earth magnet scrap are recycled today and ensuring a continuous and sufficient scrap flow remains a challenge for any recycling facility. These are currently concentrated in China and Southeast Asia, where recycling benefits from the availability of new scrap to provide a baseline capacity utilization (Ansorge 2020; Furgeri 2020).

The large-scale use of larger rare earth magnets in electric traction motors and especially in wind power generation could provide the basis for significant secondary material supply in the future. However, organizational, logistical and technical obstacles remain that must be mastered before this can become a reality (ERECON 2015; Furgeri 2020).

08. Recycling indicators and why they matter

Recycling indicators help to assess the functioning of the Urban Mine. However, they are manifold and reflect different aspects of anthropogenic metal cycles (UNEP 2011). The simple mention of a "recycling rate" is therefore not enough to know what information it conveys. Here, we group recycling indicators into those measuring efficiency and those measuring independence from conventional mining, to provide a functional overview of their meaning.

> The simple mention of a "recycling rate" is not enough to know what information it conveys.

The first group of recycling indicators, **measuring efficiency**, attempts to track how well the potential of the Urban Mine is being captured. This is not a trivial task, since the workings of the Urban Mine are generally more varied, more spatially distributed, and more complex than in a geological mine (cf. Figure 9). The first step in capturing the potential of the Urban Mine is collection. The "collection rate" measures the efficiency of collecting discards *for recycling*. Discards may be collected but not destined for recycling if (a) there are no appropriate processes for handling a particular type of post-consumer scrap or (b) if the processes are in place but the discards end up in the wrong bin. Therefore, the end-of-life collection rate (*EoL CR*)

$$EoL\ CR = \frac{\text{EoL products collected for recycling}}{\text{EoL products potentially collectable for recycling}}$$

measures how well the waste management system is capturing the stream of potentially recoverable metal emerging from the Urban Mine. This rate is most important when assessing cities, their collection infrastructures and the pertinent national and regional regulation, including efforts to collect particular waste types, such as WEEE.

WASTE ELECTRONIC AND ELECTRICAL EQUIPMENT (WEEE) IN THE TRASH BIN

Small electronic equipment is easy to misplace. This also applies at the end of its service life. Current estimates point WEEE generation of more than 7 kg per capita as a global average, of which only a minority (under 20%) is formally collected and documented. It is estimated that 8–9% of all WEEE (by weight) is disposed of as municipal solid waste in high-income countries (Baldé et al. 2020; Forti et al. 2020). Estimates for the UK point to more than half of all lamps/lighting equipment, medical devices, electrical tools and small household appliances being improperly discarded to municipal solid waste (Parker & Arendorf 2013). However, matched studies in The Netherlands for 2010 and 2018 show a decreasing trend in erroneous disposal of small electronic devices to municipal solid waste (Baldé et al. 2020; Huisman et al. 2012).

When collected properly, small electronic equipment can be recycled in modern facilities to recover a variety of metals (Bangs et al. 2016; UNEP 2013b). Shredding/crushing and separating facilitates plastic recycling, but small devices may also be treated directly in the metallurgical process, where the plastic burns and reduces the energy requirements. This also bypasses pre-processing (shredding, sorting), and the metal losses incurred there (Chancerel et al. 2009; Parker & Arendorf 2013).

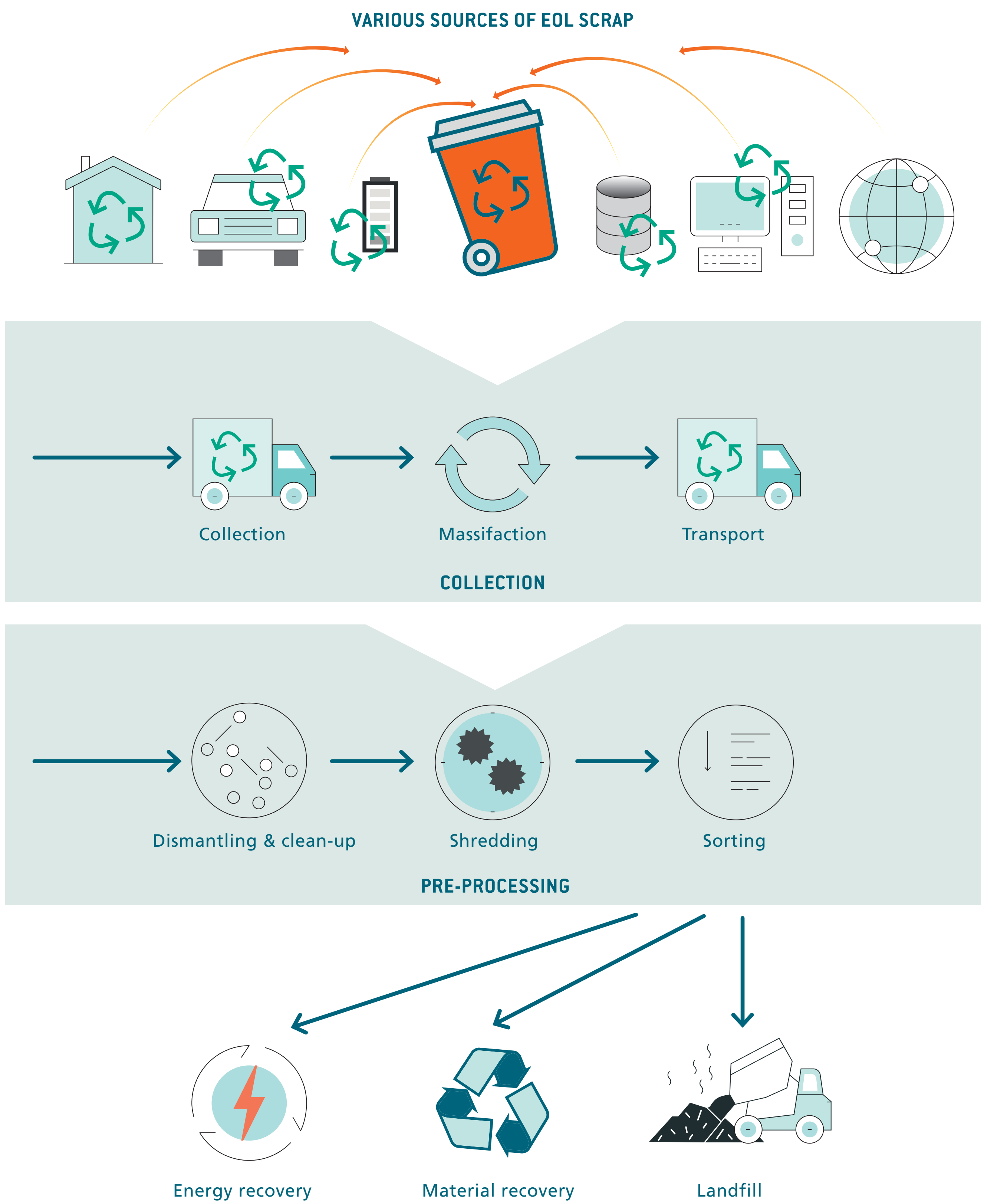


Figure 9: End-of-life (EoL) recycling chain. The path from discards to recovered raw materials is long and tedious. The entire chain is only as strong as the weakest link. Figure based on Horta Arduin et al. (2019).

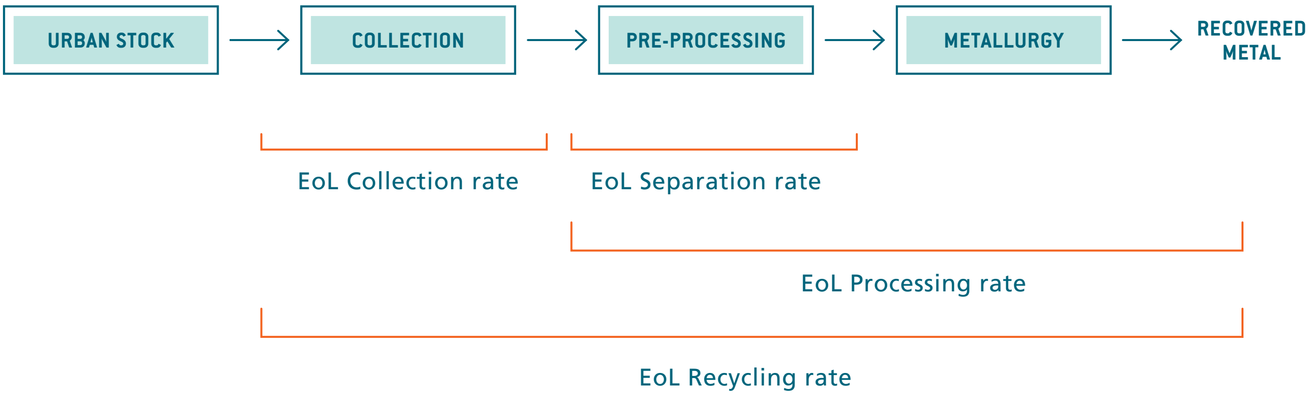


Figure 10: Recycling rates can measure the efficiency of material recovery from the Urban Mine at different points along the recycling chain.

The next step in capturing the recycling potential of the Urban Mine is pre-processing. This involves a combination of manual labor and machinery, and varies between products and locations. The "separation rate" measures the efficiency with which the recycling industry transforms discarded *EoL* products into appropriate feedstock for different (metallurgical) material recovery processes. The complex nature of EoL products implies sometimes surprisingly low separation rates, especially for minor metals – often present in very small quantities – despite their high value (Bangs et al. 2016). Thus, a low separation rate (*EoL SR*):

$$EoL\ SR = \frac{\text{Metal in feedstock for metallurgical recovery}}{\text{Metal in EoL products collected for recycling}}$$

highlights the need for more research & development into recycling technologies and design for recycling. The efficiency of the entire chain is measured by the end-of-life recycling rate (*EoL RR*):

$$EoL\ RR = \frac{\text{Metal recovered from EoL scrap}}{\text{Metal contained in generated EoL scrap}}$$

which combines the collection rate, the separation rate and the efficiency of the final metallurgical step (often high).

> The complex nature of EoL products implies sometimes surprisingly low separation rates.

The chain connecting material leaving the stock in use to the amounts of metal recovered from it is long and only as strong as the weakest link: Excellent recycling processes can only process material collected and delivered to the appropriate facilities, and collected material needs fitting processes for metal recovery.

Recovering metals from the Urban Mine reduces dependence on geological resources and conventional mining. Recycling indicators can also **measure independence** from geological resources. This is measured by comparing the contribution of secondary material to total metal production with the recycling input rate (*RIR*):

$$RIR = \frac{\text{Metal produced from secondary sources}}{\text{Total metal production}}$$

which contains both contributions from manufacturing scrap and post-consumer scrap. The contribution of Urban Mining to independence from geological resources is better measured by the end-of-life recycling input rate (*EoL RIR*):

$$EoL\ RIR = \frac{\text{Metal produced from postconsumer scrap}}{\text{Total metal production}}$$

which is smaller than the RIR. The reason for this is that scrap from manufacturing (included in the *RIR*) depends directly on current manufacturing and, consequently, to a large extent

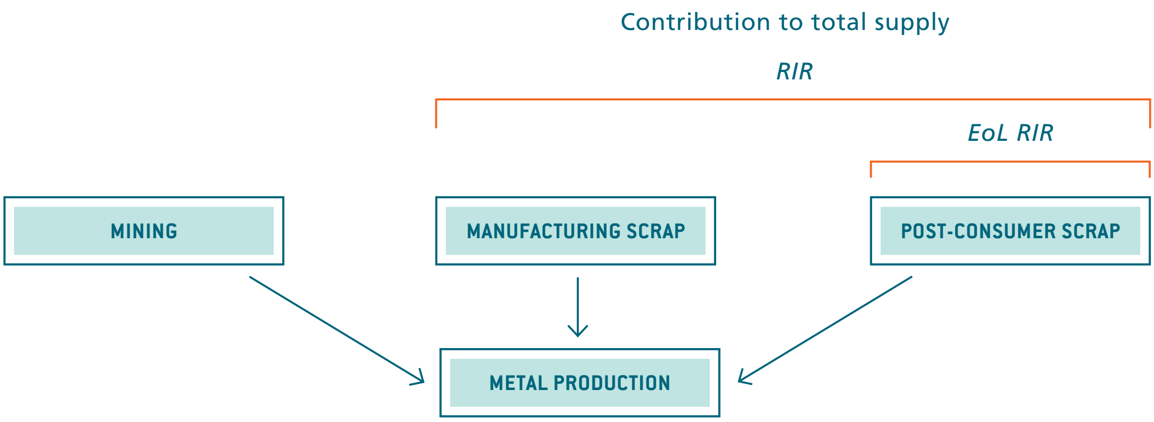


Figure 11: Recycling of manufacturing and post-consumer scrap supplements primary raw materials as feed to metal production. The generation of manufacturing scrap depends on current manufacturing. Recovering material from the Urban Mine (long-lived products, buildings, landfills) is independent of current manufacturing.

on primary raw materials. An extreme case of this is indium, used primarily for flat panel displays. Recycling of indium manufacturing scrap is very important and efficient (*RIR* is high); however, recovery of indium from post-consumer electronic scrap is impractical to date (*EoL RIR* is nil; Licht et al. 2015).

> Excellent recycling processes can only process material collected and delivered to the appropriate facilities.

Sometimes it is important to differentiate between metal production and metal use for the manufacture of end-use products. "Recycled content" denotes the contribution of secondary sources to manufacturing and is, at the global scale, equal to the recycling input rate. However, recycled content and recycling input rate can differ strongly at the country/regional level, also in the variants tailored to estimating the contribution of the Urban Mine to independence from geological resources. The difference comes from net imports of metal originating from a different mix of conventional mining and urban mining (Tercero Espinoza & Soulier 2018; UNEP 2011). For example, all Austrian aluminum production came from secondary sources in 2012 (RIR = 100%), but 56% of that was manufacturing scrap (EoL RIR = 44%). In contrast, Austrian manufacturing had a recycled content (RC) of 73% and an end-of-life recycled content (EoL RC) of 33% that same year. These numbers are all consistent with each other and differ because of metal imports. The difference emerges from the point of measurement (metal production or metal use for manufacturing; Buchner et al. 2015; Tercero Espinoza & Soulier 2018). The latest EU methodology for determining critical raw materials uses a modified version of the EoL RC to capture the contribution of Urban Mining to European supply (European Commission 2020c).

09. Trade-offs: Urban Mining vs. other legitimate interests

The recovery of materials stored in the Urban Mine is a valuable alternative to the exploitation of natural resources. It helps to conserve natural resources and contributes to security of supply especially for countries without natural deposits. Furthermore, the environmental burden for recycling processes is often lower than production of primary material (UNEP 2013a). Therefore, material circularity became an important political and societal goal in many countries in recent years. However, the costs of Urban Mining have to be taken into account. Urban Mining is a part in a network of interconnected goals and interests that influence each other in positive or negative ways (Figure 14). Awareness for potential trade-offs with other societal, political, economic or industrial interests allows for open discussion and conscious decision-making.

> Urban Mining is a part in a network of interconnected goals and interests.

In general, the more of the Urban Mine outflow is supposed to be recovered and to stay in the cycle, the higher the costs in terms of technical challenges, capital and operating expenses, and environmental burden of the necessary processes become. Not all dimensions of potential trade-offs can be discussed here since the network of aspects connected to Urban Mining is extremely wide. However, selected aspects serve to illustrate the manifold interactions and raise awareness for the complexity of the issue and the necessity of informed decision-making. In particular, it is worth remembering that the large, easily recyclable waste streams are already largely targeted for recycling today. In order to push further towards a more circular material use structure, more and more complex, diluted and/or small output streams of the Urban Mine have to be recycled, bringing the issue of trade-offs to the forefront.

> The more of the Urban Mine outflow is supposed to be recovered and to stay in the cycle, the higher the costs.

The transition to a more Circular Economy calls for both resource efficiency measures (doing more with less material) as well as Urban Mining. However, these do not necessarily go hand in hand. It is generally desirable to produce products with equal or better functionality while using less, cheaper or more easily available raw materials. Following this logic, devices have become smaller, layers thinner, and expensive metals have been substituted by cheaper ones or other materials such as plastics or ceramics. This is good for the consumer and for limiting resource use, but potentially detrimental to Urban Mining. For the recycling industry or Urban Mining in general, the lower content or value of contained material decreases the potential revenue from recycling while the effort of material separation increases due to the small size of devices. Good examples for this are precious metals in printed circuit boards or ongoing cobalt substitution in cathode materials for lithium-ion batteries. In the former, the precious metal content has decreased significantly (40% for gold, 30% for palladium and 70% for silver) while increasing performance (Bangs et al. 2016; Bookhagen et al. 2020). In the latter, cobalt-rich cathode chemistries are giving way to nickel-richer and even cobalt-free chemistries (Elwert et al. 2018; Hanisch et al. 2015). Both have the effect of lowering the material value per unit, thus downgrading the economic feasibility of later recycling.

> Highly complex or diluted waste streams call for elaborate recycling processes.

Many recycling processes have considerably lower carbon footprints compared to mining (UNEP 2013b). A commonly cited example is that of aluminum, where recycling of post-consumer scrap can reduce emissions by over 90% compared to primary aluminum (Liu et al. 2013). Therefore, the recycling industry and the development of a circular economy offer an important contribution in the effort to reduce greenhouse gas emissions and limit global warming. However, highly complex or diluted waste streams call for elaborate recycling processes. These processes potentially come with considerable environmental impacts equal to or even surpassing the environmental burden of mining natural resources (Loibl et al. 2020; Schmidt et al. 2020). The environmental footprint of recycling not only depends on the metal but also on the form in which the metal

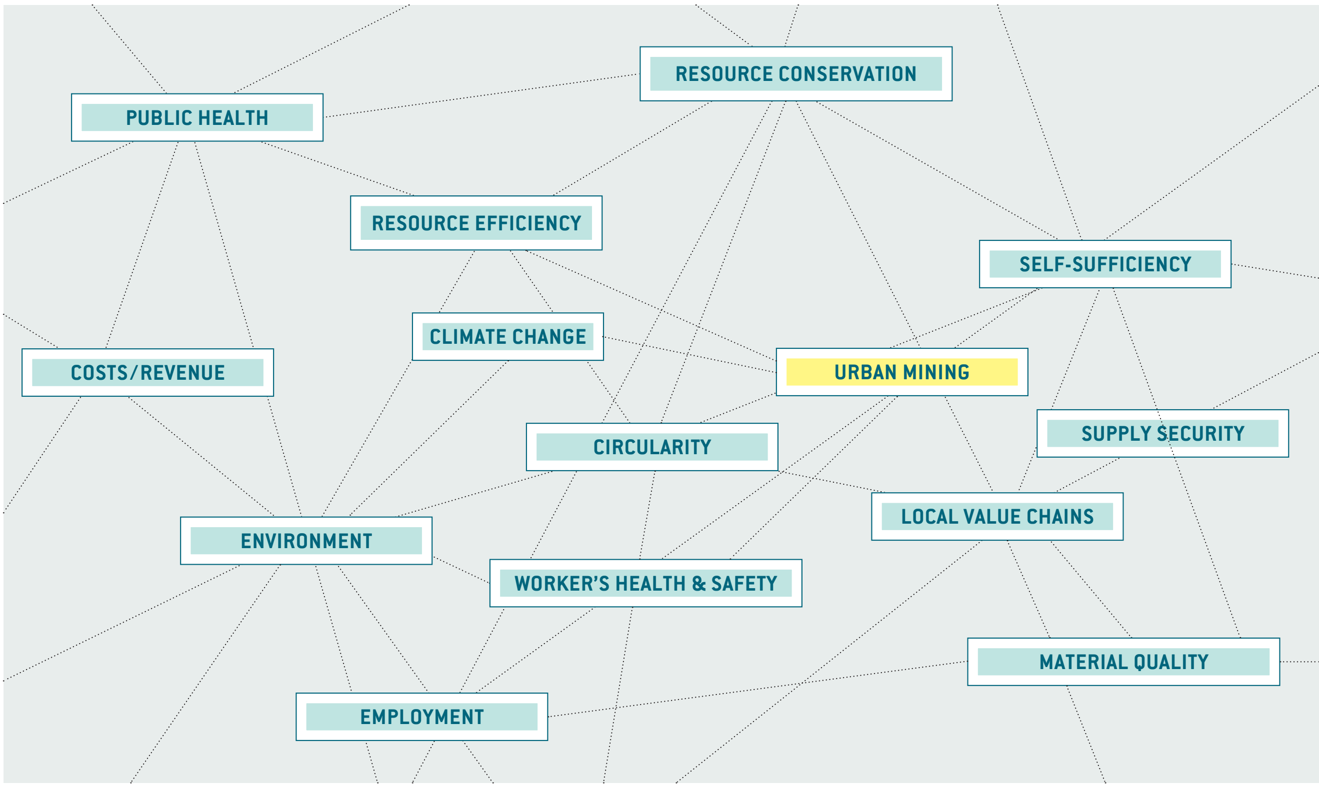


Figure 12: Urban Mining is one aspect in a network of interconnected goals and interests, influencing each other in different ways. Optimization is complex and often dependent on the individual point of view.

exists in discarded products or scrap. Recovering copper from cable and wire scrap usually requires only remelting once it is separated from the plastic insulation, and the global warming potential of the recycling process is very low. Recovering copper from C&D debris has a global warming potential almost three times as large and close to the range of conventional mining (Langner 2011; Schmidt et al. 2020). An extreme case would be indium recycling. Even though indium production from mining has a global warming potential more than 15 times that of primary copper, indium recycling from its main application (flat panel displays) would come with a footprint five times higher than primary indium (Schmidt et al. 2020). The EoL recycling rate of indium is nil despite its high value and issues of supply security (European Commission 2020b). These examples show that despite the clear environmental benefits of recycling in most cases, these do not necessarily extend to new processes as product streams become more dilute and complex. Current research and development projects already scratch this boundary, where metal recovery from complex scrap is environmentally more burdensome than mining (Loibl et al. 2020; Schmidt et al. 2020).

> In many cases the use of secondary material is regulated to protect public health and safety or the environment.

Another important issue for Urban Mining is the usability of recovered material. In many cases the use of secondary material is regulated to protect public health and safety or the environment. Urban Mining and the recycling industry, however, depend on the availability of markets for their products. Restrictions to those markets limit the potential or even threaten the viability of a recycling process. The use of secondary metals in aircraft construction, secondary magnesium in structural parts for vehicles, or of secondary plastics in medical or food applications are examples for safety restrictions put on the use of secondary materials (AFRA 2018; Ditze & Scharf 2008; EFSA 2008; FDA 2006). In addition, it is important to consider not only the main product but also by-products of the recycling processes such as slags from metal recycling. In many countries, slags are used as secondary material in cement or gravel (e.g. for road construction). However, the legal requirements have been tightened progressively in recent years, especially in Europe – a trend that is expected to continue. Reducing impurities further significantly increases the energy requirements in slag processing, leading to higher costs. This may lead to landfilling becoming the economically or energetically more feasible option for dealing with slags from metallurgical processes. This would effectively turn slags from a by-product (revenue & increased circularity) into waste (costs & reduced circularity), and increase pressure on the economic viability of metallurgical processes in Europe (Du et al. 2019; Loibl & Tercero Espinoza 2020).

These are but examples of conflicts between efforts to increase Urban Mining and fulfillment of other legitimate societal, environmental or economic interests. These interactions may not be immediately visible but are nevertheless important. Consideration of all relevant aspects may lead to less instead of more Urban Mining if other concerns outweigh the benefits of Urban Mining. In any case, it is necessary to be cognizant of such trade-offs not only when discussing Urban Mining but also measures unrelated to but affecting Urban Mining.

> Consideration of all relevant aspects may lead to less instead of more Urban Mining if other concerns outweigh the benefits of Urban Mining.

EFFECTS OF THE MINIATURIZATION OF ABS & ESC UNITS IN PASSENGER CARS

Miniaturization has been and still is a major trend in product design beyond consumer electronics. For the consumer, this means smaller and/or lighter, in other words, more convenient products. Producers reduce material costs and fulfill the political goal of increasing resource efficiency. Under the surface, many devices and components decreased in size in recent years, even if the overall product did not. This was the case for two vehicle safety systems: the antilock-braking system (ABS) and electronic stability control (ESC) units.

Restrepo et al. (2020) studied and described this connectivity between miniaturization and Urban Mining in detail for passenger cars in Switzerland. After market entry in 1978, more and more new cars were equipped with ABS. Market penetration reached a maximum in 2001. In that timeframe, the weight of the ABS unit decreased from 6.2 kg to 2.5 kg on average. After 2001, electronic stability control (ESC) units slowly replaced ABS. The ESC is a multifunctional system that integrates several unifunctional systems such as ABS. Again, the weight of the unit decreased over the years from 4.3 kg to 3.1 kg on average. Even lighter versions of ABS and ESC units are available on the market but are not standard. One possible explanation is the strong market penetration of heavier cars that require heavier ABS or ESC units.

The ABS/ESC unit is removed manually at the end-of-life stage from about 10% of cars. The remaining 90% of end-of-life passenger vehicles are shredded directly. Manual dismantlement allows for reuse of the unit or parts or for shredding of the unit with the more specific waste stream of electronic and electrical equipment (WEEE). However, time and effort (labor costs) do not correlate with the weight of the unit. It takes approx. 13 min to remove an ABS/ESC unit from a car regardless of its average weight. The potential revenue and therefore the economic feasibility of recycling, however, is connected to the cost per kg of material recovered. Even assuming constant labor costs in the respective timeframes, the costs per kg of recovered material increased by 60% for ABS units and by 30% for ESC units due to miniaturization. Similar considerations have to be taken into account for many electronic and other devices. Not considering the trend towards miniaturization over the last decades would lead to overestimation of the urban mine potential (Bangs et al. 2016; Restrepo et al. 2020).

10. Framework conditions for Urban Mining

In addition to physical and technological characteristics, numerous environmental, societal, regulatory and economic factors determine the exploitation of the potential of the Urban Mine. The general framework conditions for recycling essentially characterize the framework conditions for Urban Mining today since recovery from tailings ponds and landfills is currently negligible. Raw material recovery from landfills is hindered not only by lack of profitability but also by regulatory hurdles for accessing and processing the landfilled material (Poggendorf et al. 2016; Winterstetter et al. 2018). Recovery from mine tailings remains an exception to date (Australian Mining 2020; Reuters 2018). Framework conditions for recycling encompass or affect practical and procedural aspects of (potential) Urban Mining, such as the existence of collection and recycling infrastructures, incentives for recycling, mandatory recycling schemes, minimum recycling rates, penalties for landfilling; availability and costs of labor and recycling technologies; regulation (and enforcement thereof) for environmental protection, public and worker's health and safety, and scrap trade. In the following, we explore these with a focus on the European Union, USA and China.

The regulatory framework and the recycling system in the **EU** are relatively well developed. The EU hosts many fully closed recycling loops and ongoing regulatory efforts to promote increased recycling and circularity. Examples of such efforts include the EU Waste Framework Directive (European Parliament and Council 2008), the Circular Economy Action Plan (European Commission 2015, 2019, 2020a), and numerous specific directives/regulations, e.g., on waste electrical and electronic equipment (European Parliament and Council 2012).

> The EU hosts many fully closed recycling loops and ongoing regulatory efforts to promote increased recycling and circularity.

Despite these efforts, strong regional differences regarding the recycling infrastructures and, in particular, a (north-)west-east divide are evident in the EU: Northwestern EU countries like Sweden, Germany, Belgium and France have, in general, relatively strong recycling systems in comparison to eastern EU countries (Bonnin et al. 2013; COLLECTORS Project 2020; European Parliament 2017; Meester et al. 2019).

Recycling in the EU suffers from a combination of high labor costs and labor-intensive dismantling of complex products. As a result, many end-of-life products are shredded although manual disassembly would yield higher material recovery. Scrap exports for disposal or unsound recycling, especially to low-income countries, remain an issue (Manhart et al. 2020; Forti et al. 2020). Thus, not only technology and the availability of state-of-the-art recycling facilities in the EU are crucial but also the question of relative profitability of Urban Mining (Blengini et al. 2019; Ciacci et al. 2017; Gheorghiu et al. 2017).

There are many further potentially relevant framework conditions for recycling and Urban Mining in the EU, which often stem from local societal/value systems and are reflected in political debates and actions. Examples include the discussion about material criticality and the role of alternative material sources for increasing the degree of autarky of material supply as well as the increasing role of environmental values in policy agendas in some EU countries. All these tend to support Urban Mining.

The **USA** has a well-established metal-recycling tradition (Brooks et al. 2019). However, the increasing offshoring of metal-scrap treatment since the 1980s has led to a reduction in domestic metal-recycling activities. For example, there are no secondary smelters for copper today in the USA (Mackey et al. 2019).

At the federal level, recycling is regulated (rather indirectly) via a number of laws that apply to recycling processes, e.g., the Clean Air Act, Clean Water Act, Resource Conservation and Recovery Act, Comprehensive Environmental Response, Compensation, and Liability Act, and Toxic Substance Control Act (Brooks et al. 2019; EPA 2020; Wagger 2013). At the state level, the degree of recycling regulation varies widely across states: Only 27 out of 50 States have at least one mandatory recycling requirement. Furthermore, only a minority of States have

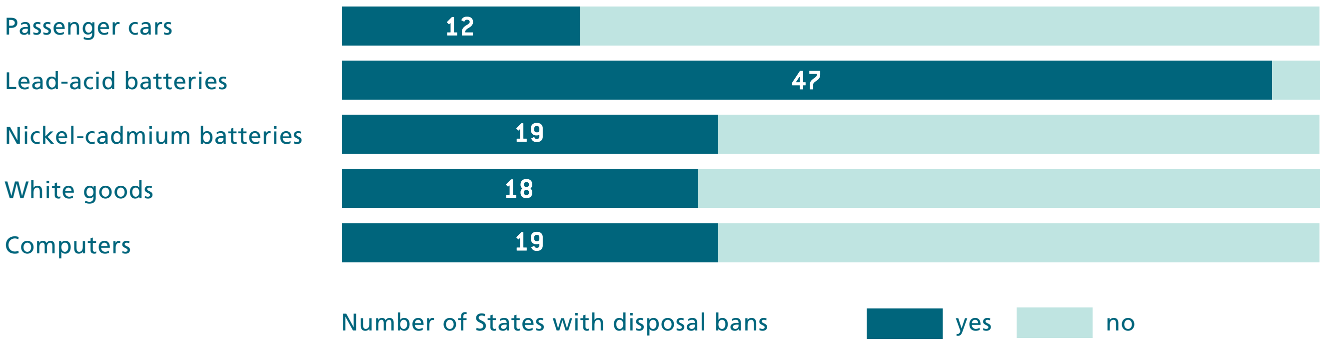


Figure 13: Lax and non-uniform regulation limits Urban Mining. For example, a majority of States in the USA allow landfilling of recyclable end-of-life products such as passenger cars, white goods and computers (NERC 2020).

disposal bans on automobiles, white goods and computers (12, 18 and 19 States, respectively; NERC 2020).

On the infrastructural side, landfill space is plentiful, and collection points for recycling are generally distant in non-urban areas. Moreover, because of the aforementioned reduction in recycling facilities for economic reasons (since the 1980s), considerable investments in skills and technology would be necessary to re-enable state-of-art (closed-loop) metal-scrap processing in the USA (Mackey et al. 2019).

There are nascent societal activities to foster a more circular economy in the USA, e.g., the collection of electronic waste and metals at schools, universities (University of California 2019), stores and communities' facilities (Waste Management 2019) and takeback programs of companies like Apple, Dell, HP and LG, among others.

China, the largest consumer of resources in the world, imports a great part of these resources from abroad. In particular, China is highly dependent on foreign iron, copper and aluminum, among others. China's resource demands are not only covered by primary material imports but also by scrap imports for domestic recycling (Hu & Poustie 2018; Wang et al. 2017a; Zhang et al. 2014), though these have greatly declined following the Green Fence policy.

Political, economic and infrastructural programs are expected to generate large resource demands and, thus, challenges for resource supply and opportunities for recycling. Examples of such programs include the development of a number of megacities (e.g., the Pearl River Delta project), the Belt and Road initiative, high-speed rail networks and other infrastructure projects (Central Committee of the Communist Party of China 2016; Copper Alliance 2016; Routley 2018; World Bank 2019).

Facing questions of the sustainability of its (foreign) resource-dependent development strategy and environmental impact mitigation, China has induced a number of regulatory efforts and programs directly affecting the local (and global) recycling situation. Some recent include:

- a new agenda for environmental and resources policies in the current Five-Year Plan requiring, among others, more recycling from Chinese firms (Central Committee of the Communist Party of China 2016)
- support of the Paris Agreement and the Sustainable Development Goals
- the Green Fence policy for protecting China from other countries' waste (EUWID, 2019; Holtbrügge and Dögl, 2014; Resource Recycling, 2018; Reuters, 2019)
- the Urban Mining Demonstration Base Construction program started in 2010 (Hu & Poustie 2018).

China's resource demands are not only covered by primary material imports but also by scrap imports for domestic recycling

To some extent, these lead to large recycling capacities accompanied by scrap scarcity.

As studied in the case of waste electric and electronic equipment (WEEE), Chinese households have little information about formal waste collection, and have low environmental awareness (Wang et al. 2017b). Such societal factors, which are not only restricted to WEEE, lead to less efficient collection of household scrap and landfilling of valuable resources. The development of a social scoring system for its citizens on behalf of the Chinese government is a factor that may affect the future social behavior in China significantly. This system is now being tested and will so on expand to all citizens and more issues (Kobie 2019).

11. What could support Urban Mining?

Examination of the issues discussed above allows some generalization as to who can support Urban Mining and how. First, governments are responsible for regulation and recycling infrastructures. Recovery of raw materials from the Urban Mine generally benefits from clear and strict regulation for recycling. Here, the economic competition between landfill costs and recycling costs/profits is very relevant, as is the uniformity of (environmental) regulation across borders. Laxer environmental regulation and enforcement together with lower labor costs helped propel China into a quantitative leadership position in recycling. This also continues to support (illegal) exports of electronic scrap from industrialized countries to developing countries despite ongoing efforts to curb this practice. In a world of strict and equivalent regulation pro recycling, it would be easier to direct secondary material to where most value is conserved instead of where the environment and worker's health are less protected or are out of sight.

> Governments are responsible for regulation and recycling infrastructures.

Governments also have a responsibility to provide effective and accessible infrastructures for recycling. These pertain primarily to the collection of different end-of-life products and scrap. However, the best collection infrastructures fail without the support of a committed and well-informed public. This weakness is evident, e.g., in the deficient collection of small electronic equipment even in the presence of attractive collection schemes. Therefore, sensibilization of the public for the issues behind Urban Mining is an important effort to which not only governments but also industry and NGOs can significantly contribute.

> The best collection infrastructures fail without the support of a committed and well-informed public.

Industry plays an important role both as designer and provider of products as well as collector and recycler. Product manufacturing can contribute to more Urban Mining by recognizing the need to consider repair, disassembly for reuse and separation

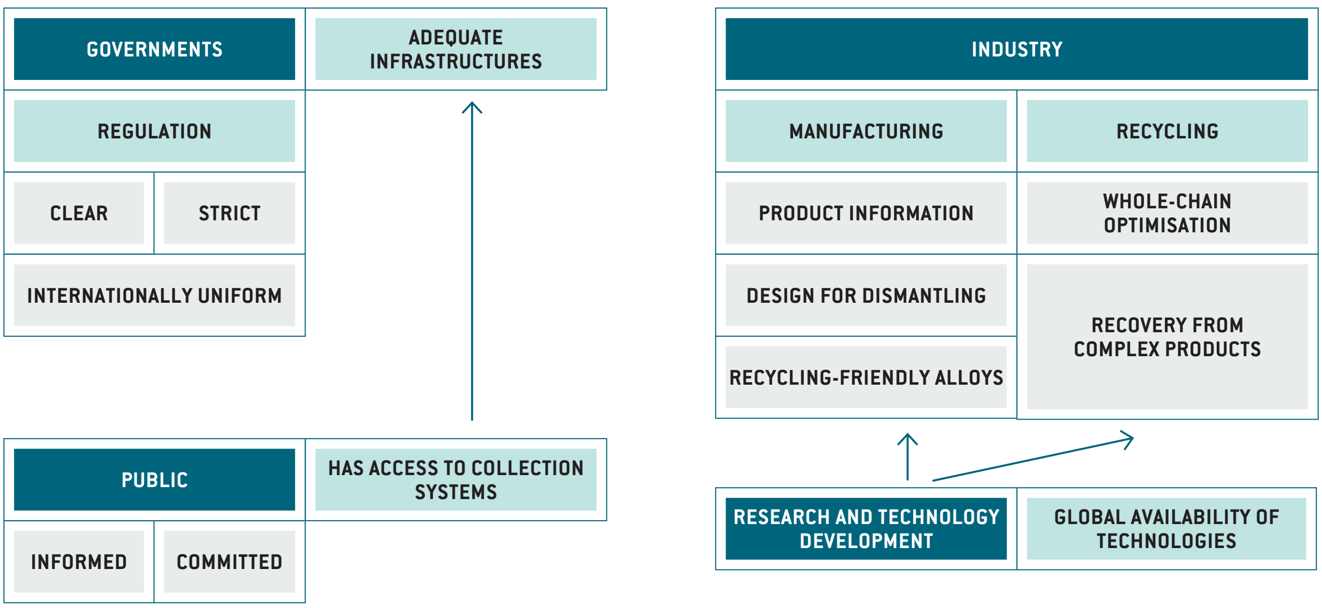


Figure 14: Interactions between actors and their respective contributions for more Urban Mining.

for recycling as much as possible a part of the design process (design for circularity). This, coupled with access to more detailed product information would not only favor repair & refurbishing through easier identification of replacement parts but also contribute to allocating end-of-life products to the proper recycling routes. This is particularly important for products that can be manufactured in different ways but have a common exterior, e.g. different battery chemistries or electric motor designs with/without permanent magnets of different types. The recycling industry will have to continue to invest in modern facilities and tackle organizational challenges in order to keep up with the increasing amounts, diversity and complexity of post-consumer scrap. In addition, better communication across the recycling value chain (from collection through to metallurgy) and optimization of entire chains, not just individual links, would help increase the output of the recycling industry as a whole.

Finally, with ever more complex products distributed all over the globe, there is a necessity for effective reverse logistics delivering post-consumer scrap to the appropriate facilities. Access to adequate technologies for the products of today and the timely development of fitting recycling technologies for the products of tomorrow is a pre-requisite for effective recovery of the resource potentials of the Urban Mine, and an ongoing challenge for R&D efforts worldwide.

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