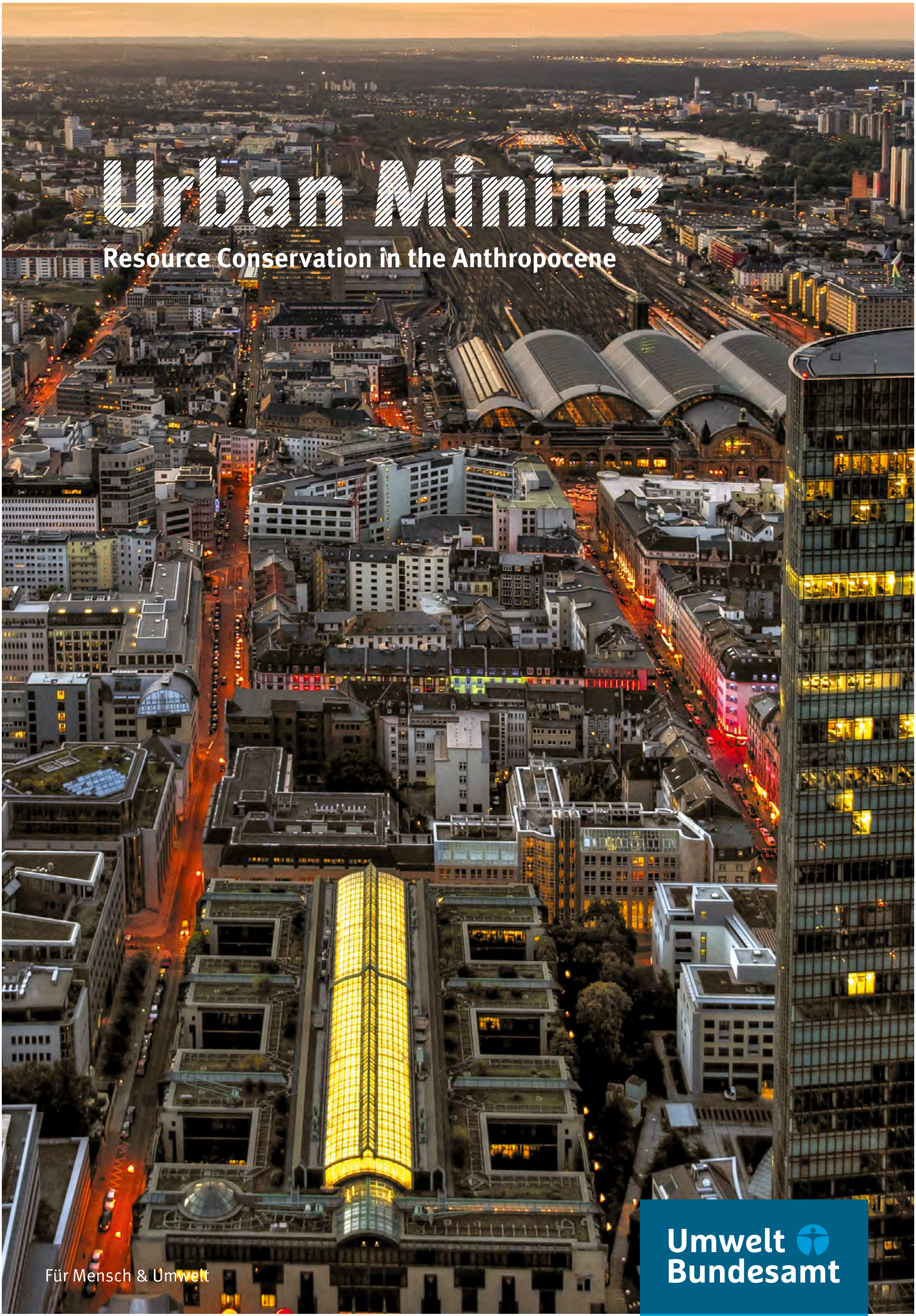
Urban Mining

Resource Conservation in the Anthropocene



Für Mensch & Umwelt

Umwelt Bundesamt

Maria Krautzberger
President of the German Environment Agency

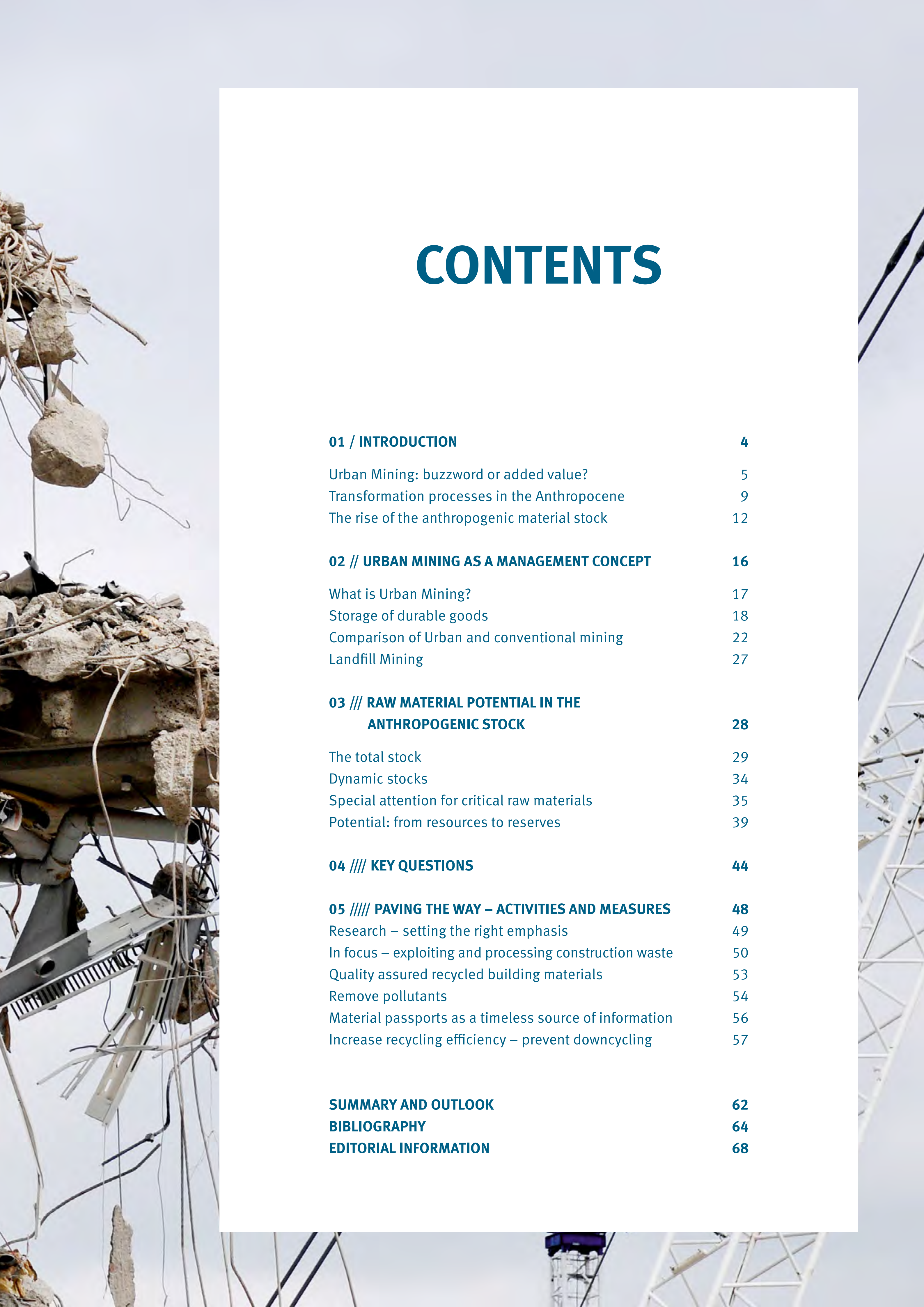
Over the centuries, and especially in the post-war decades, our country's citizens have accumulated an enormous but hidden wealth: we are surrounded by a man-made or anthropogenic stock of over 50 billion tonnes of materials. Much of it is in buildings, our infrastructure, installations and consumer goods. This anthropogenic material stock is still growing by a further ten tonnes per inhabitant every year and represents a substantial resource for future generations.

Previously used but inaccessible materials can be extracted, reused and recycled. Mineral materials such as concrete, gypsum or brick, base metals such as steel, copper or aluminium, special technology metals such as neodymium, cobalt or tantalum, as well as other materials such as plastics, asphalt or wood become accessible as secondary raw materials. For Germany, a country considered "poor in raw materials", this is a tremendous wealth, especially in view of an increasing international competition for the Earth's scarce raw materials and the need to reduce the high global environmental impact caused by primary raw material extraction and processing. The extent to which the anthropogenic stock can make an important contribution to securing the livelihood of current and future generations depends on how well we are able to meet these challenges. After all, the extensive variety of materials and products, complex usage cascades and rapid technology cycles of products and goods, all ultimately hamper high-quality processing and recovery. Additional factors are demographic changes, changes in the needs of a mobile, fast-moving, digital and ageing society and the associated regional and temporal differences in construction, rehabilitation and dismantling requirements.

"Urban Mining" has been on everyone's lips for some years, being the quasi-mining of raw materials in urban areas both in cities and communities. Strictly speaking, however, only concepts of an extended municipal waste management industry have been developed so far. But in contrast to municipal waste management with its rather short and thus easily understandable and predictable material cycle times, an intergenerational task such as Urban Mining, requires more and better guidelines and a far-sighted strategy for material flow management. For such large amounts of material that take a significant time to reach the industry, a management concept including a prospective knowledge and decision base for the secondary raw material industry and for local governments is needed. For example, we need database-driven, dynamic and district-specific forecasting models in order to be ready for the contribution that Urban Mining can make to resource conservation in a sustainable circular economy.

Through this brochure, the German Environment Agency wishes to convey a common understanding of Urban Mining and to encourage its steady progress by using this strategic approach. I wish you a stimulating read.

Maria Krautzberger
President of the German Environment Agency



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INTRODUCTION

Before this car is delivered, it already has 15 tonnes of raw material input.

Urban Mining: buzzword or added value?

Raw materials are an essential pillar of today's life and prosperity. In order to meet demands, Germany must increasingly rely on imports: more than a third of the materials required nationwide, around 600 million tonnes, are now imported annually. In fact, 1.7 billion tonnes of primary raw materials have to be extracted and harvested worldwide for these imports, i.e. they are directly removed from nature [1]. The reason being that we not only import raw materials, but often rather highly processed products that require far more raw materials along their life cycle than their actual weight suggests. For example, approx. 15 tonnes of raw materials are needed for an imported medium sized car by the time it is delivered from the factory. In addition to the imported raw materials, about 1.1 billion tonnes are annually extracted domestically [2].

Overall, Germany uses domestically about 1.3 billion tonnes of material annually after subtracting exports. This amount of material corresponds to a concrete cube with each edge 800m long, and this huge cube stays within the Federal Republic – year upon year. But what is the destination of this enormous material flow? Obviously, industry continues to grow physically because the annual waste production is less than one third of this amount.

Given the enormous demand for raw materials and scarce natural resources, alternatives are needed. This is why the maxim "Urban Mining" has become popular in recent years. If the anthropogenic, or man-made, stock continues to grow, why not use it as a raw material source? Why dig ever deeper for mineral resources or continue to increase imports from distant countries when the material wealth is literally on our doorstep? Urban Mining regards our immediate habitat as a raw material source. In the widest sense, it is about the extraction of valuable materials from all those sources that have been created by human hands such as buildings, infrastructure, durable consumer and capital goods and much more. Urban mining thus extends the dictum "waste is raw material" found in the classical recycling industry.

Although recognised in science for years, the Urban Mining concept has now quickly become a buzzword under whose guise a gold rush atmosphere is evolving on our own doorstep. It suggests that demolition waste, cell phones or old household appliances conceal real treasures that are just waiting to be recovered. But when terms such as electronic waste, unused and forgotten mobiles, end-of-life car recycling, recycling bin or landfill treasure map are mentioned in the same breath, the impression may seem that the term "Urban Mining" was only invented as a cover for better media impact across the entire waste and raw materials industry. This also then provides well-known answers to some well-known questions and problems of waste management, for instance, selective collection of municipal waste, accepting product responsibility, illegal E-waste export or thermal disposal to discharge pollutants. Nevertheless, a new complexion can be helpful in re-focusing attention on old problems. At the same time, there is a much greater danger that the innovative aspect will be lost, and that Urban Mining becomes a mere slogan that will have different meanings depending on the context. This would be regrettable because Urban Mining contains important new approaches and is important as a strategy on the road towards a resource-efficient circular economy.

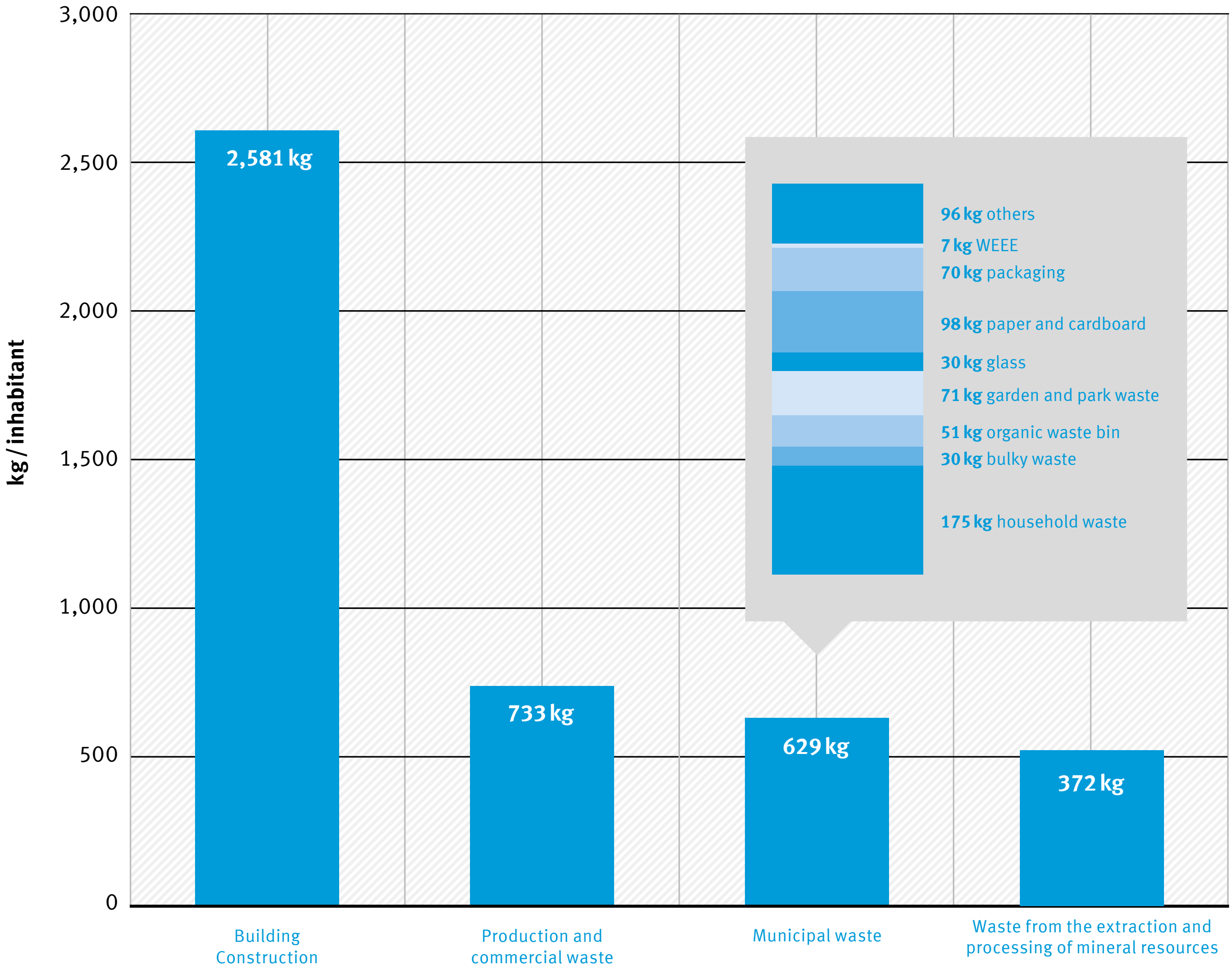
Moving away from the resource-intensive, linear economic model of "take, make, consume and dispose" and towards a resource-efficient circular economy is a declared objective of the EU [3]. To achieve this target, functionality of materials in products must be maintained as far as possible in a material cycle and thus prevent enrichment of pollutants and impurities. A circular economy requires thinking in terms of material flows from a life cycle perspective taking into account the entire global value chain from raw material extraction to waste management. Urban mining provides a strategic approach to material flow management and can use the potential of the circular economy to reconcile different interests [4, 5]. The following six aspects may exemplify this:

1. Reduction of import dependency

Although Germany still has extensive domestic raw material mining, for instance potash and specialty clays, it is 100 percent dependent on imports of ores and metals [105] which is why recycling has such a high priority. For example, 30 percent of semi-finished copper and copper casting production is based on domestic copper scrappage. More than 50 percent of German steel production is already produced from old scrappage and production scrap. Selective recovery can reduce import dependency in the future, even for critical technology metals such as the rare earths neodymium and dysprosium used in generators of wind turbines.

Figure 1

Amounts of per capita net waste in Germany [2014]



Source: [9]

2. Managing resource scarcities

Many future technologies are based on critical technology metals. Their acquisition is not only risky, but they are indispensable. A progressive increase in demand for the elements gold, tin and antimony would exceed the current reserve base i.e. the currently possible mineable deposits, within three to four decades. It is questionable whether sufficient new deposits can be discovered that would expand the reserve base accordingly. Urban Mining may offset the resulting shortages.

3. Economic benefits

Recycling increases domestic added value and contributes to significant cost savings in the manufacturing sector. The German secondary raw material industry produced copper and steel worth €8.6 billion in 2007. This resulted in cost savings of €1.5 billion compared to primary metals [6]. Urban mining will help to further increase domestic added value through recycling. With their €29.1 billion turnover and 3.5 percent annual growth in 2014, recycling activities constitute the undisputed core of the overall market of a circular economy (41 percent) [7].

4. Contribution to global justice of distribution

At around 16 tonnes per capita per year, direct domestic material usage in Germany is three to four times higher than in threshold countries such as India and about twice as high as in China [8]. And is that because or although we have such a large anthropogenic stock?

Urban mining can help reduce primary raw material demand and thus help other countries to have access to raw materials and facilitate their development.

5. Managing waste

In 2014, net waste generated in Germany amounted to about 350 million tonnes; equivalent to about 4.3 tonnes of waste per person [9] (see Figure 1). Only one seventh of this is so-called municipal waste such as household waste, packaging, paper and glass, which mainly comes from non-durable goods. However, this relatively small part gets the greatest attention in public debate, for example the overall recycling ordinance. By contrast, the amendment to the more persuasive Commercial Waste Ordinance was passed with hardly any objections. Urban mining directs the attention to the question of what happens to the remaining 3.7 tonnes and the durable goods.

6. Environmental protection

Recycling copper, steel and aluminium alone saves 406 petajoules of primary energy in Germany, almost three percent of Germany's annual primary energy consumption. This corresponds to the annual fuel consumption of two large lignite-fired power plants. In addition, global raw material savings of 181 million tonnes per annum are associated with recycling, along with other environmental impacts resulting from their refining and further processing (2007) [6]. A strategic expansion of secondary raw material production by Urban Mining could considerably increase these savings.

Metal recycling contributes significantly to the conservation of natural resources.

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Recycling mixed building and demolition waste poses a major challenge. Therefore, selective collection must be improved in the future.

To prevent Urban Mining from becoming a meaningless buzzword, and to exploit the possibilities mentioned above, it is necessary for the term to be understood in a uniform manner and to clarify its content.

Urban mining should not just subsume the entire established municipal waste management system. Rather, it should focus on the total stock of durable goods and their intelligent management in the anthroposphere, i.e. the habitat and sphere of influence made by man. Given the dwell times, secondary raw materials can be extracted from durable goods if Urban Mining manages to monitor when, what type and the amounts of materials that are released from the anthropogenic stock.

In the context of global raw material extraction, the Urban Mining approach can stand for a future paradigm shift: material flow management and the management concept of durable goods as a contribution to the conservation of natural resources. A glance at the anthroposphere itself and its interactions with the ecosphere can help understand the fundamental changes.

Transformation processes in the Anthropocene

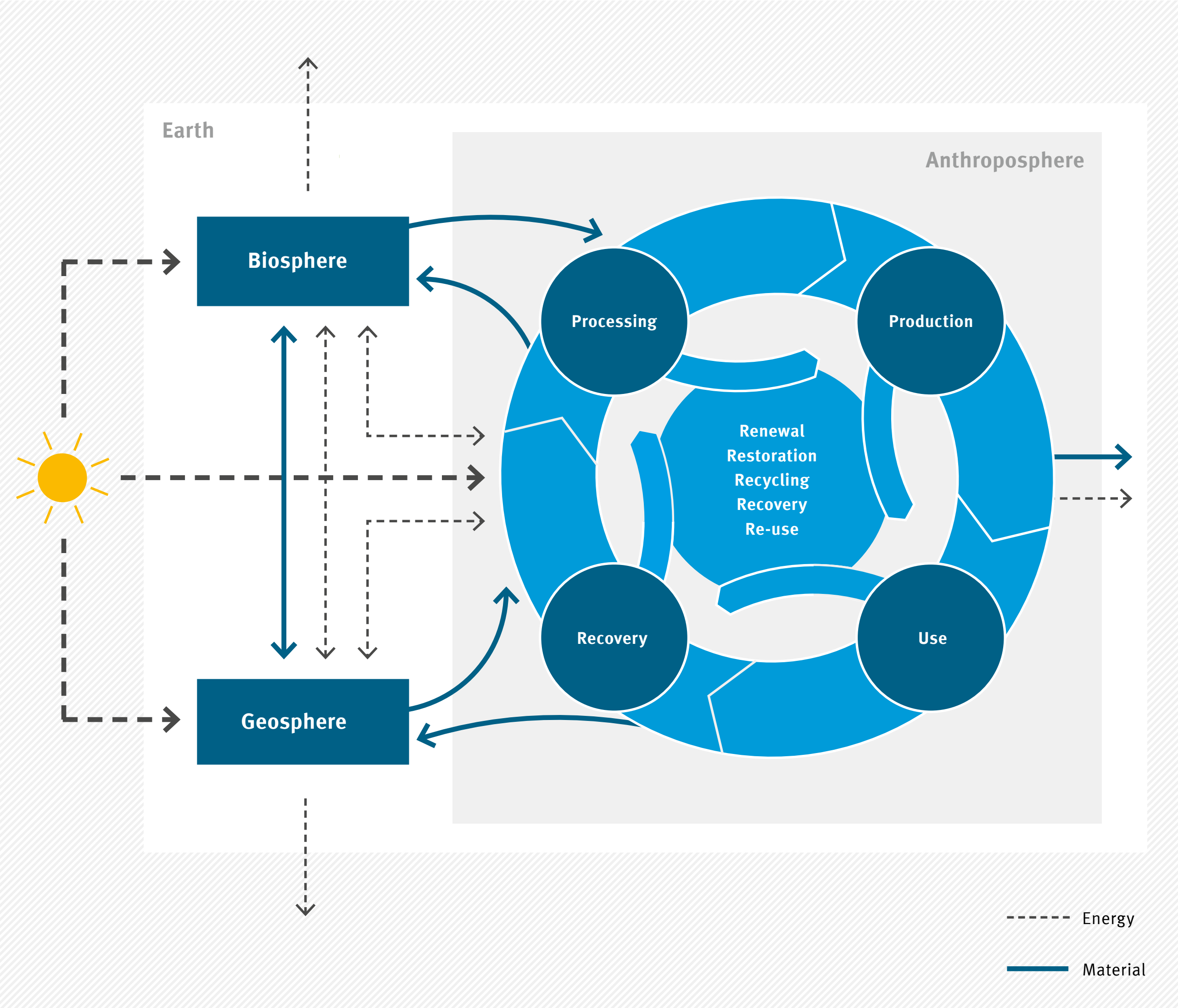
The reuse and recycling concept behind Urban Mining is by no means new. The extraction of secondary raw materials from disused goods is not a modern invention. Before the industrial revolution, many mineral materials such as dressed granite stones or iron fittings were used up to the end of their usefulness and reused because they were too valuable or their production too expensive to dispose of them prematurely. Also, the model that describes the interaction between the human habitat, i.e. the anthroposphere, the biosphere and geosphere, is still valid as the different spheres are part of a virtually closed system that is driven by the constant energy supply from the Sun.

What is new is the extent of the interactions between the human sphere and the other spheres as well as the rapid increase in society's global hunger for raw materials over the last decades. A closer look at the anthroposphere provides the key to understanding why Urban Mining will be so important in the future (see Figure 2).

The anthroposphere is humans' societal, technological and cultural sphere of action in which they live, work, communicate and manage their businesses. Humans extract raw materials from their natural environment and utilise other

Figure 2

Anthropogenic metabolism with the natural environment



UBA's illustration according to [10]

natural resources as well. By doing so they transfer them into the anthroposphere where their biological and technical processes have been established and operated and their activities take place.

The extracted raw materials are transformed into infrastructure, residential and non-residential buildings as well as everyday goods and form the so-called anthropogenic stocks. These stocks accommodate the mass of all materials that remain in a material system at the end of a balance period. The stock of a store equals the sum of the initial stock and the balance of inflows and outflows. Depending on whether a stock is growing or shrinking, it can be a source or a sink of materials [10, 11].

The anthroposphere is characterised by an extensive transformation process. All human activities produce waste and emissions when materials are used or transformed. Wastes are deposited in landfills, sometimes purposefully, sometimes unintentionally, discharged into waters or emitted into the atmosphere. The anthroposphere can be understood as an independent metabolism that maintains metabolic relationships with its environment. For some time, experts have been talking about an anthropogenic or, synonymously, about a socioeconomic, industrial or technical metabolism [12, 13]. Parts of the environment such as the geosphere, the hydrosphere and the atmosphere are not only colonised by raw material extraction but also by the output of the anthropogenic metabolism. The boundaries of the spheres are blurred and permanently shifted by dynamic metabolic relationships.

Anthropogenic metabolism had no existential impact on the natural environment at a global level in human history for a long time, and the environment's sink capacity remained in a stable state of equilibrium due to intermeshing biological and geological material cycles. It was only the revolutionary industrial change-driven by the exploitation of fossil fuels – which caused not only a massive intervention in geological material cycles, but also an extensive decoupling of an increasingly industrialised agriculture from natural nutrient cycles [14]. Since then, anthropogenic metabolism has intensified enormously, both in terms of quality and quantity, so that a new geological epoch can now be spoken of as the Anthropocene, the age of man [15, 16]. An important indication that the geological era of the Anthropocene has begun is the man-made phenomena of climate change, acidification of oceans, desertification, erosion, heavy metal pollution, radioactive contamination and loss of biodiversity [17].

Using biophysical methods and models, it is possible to define a global "safe operating space" whose ecological limits guarantee a secure and sustainable life for humankind. However, we have probably already exceeded the thresholds for four out of nine specified Earth system processes [18, 19]. All these are existential manifestations of the disturbed metabolism between the anthroposphere and the other spheres – the "writing on the wall" for an unsustainable way of life and economy.

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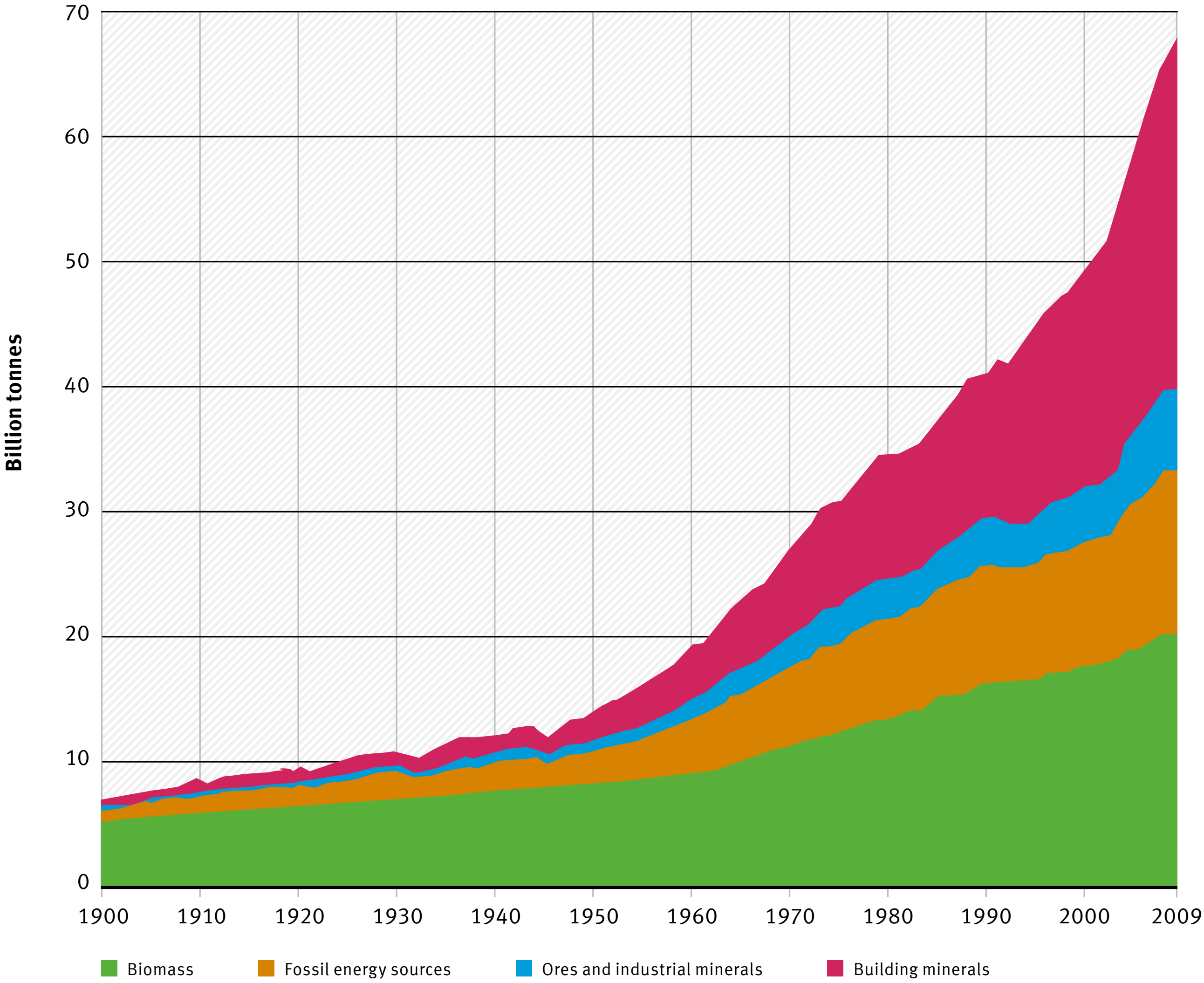
Man as a geo-historical factor: artificial lighting abolishes night.

Figure 3
Global raw material production [1900 – 2009]



Source: [20]

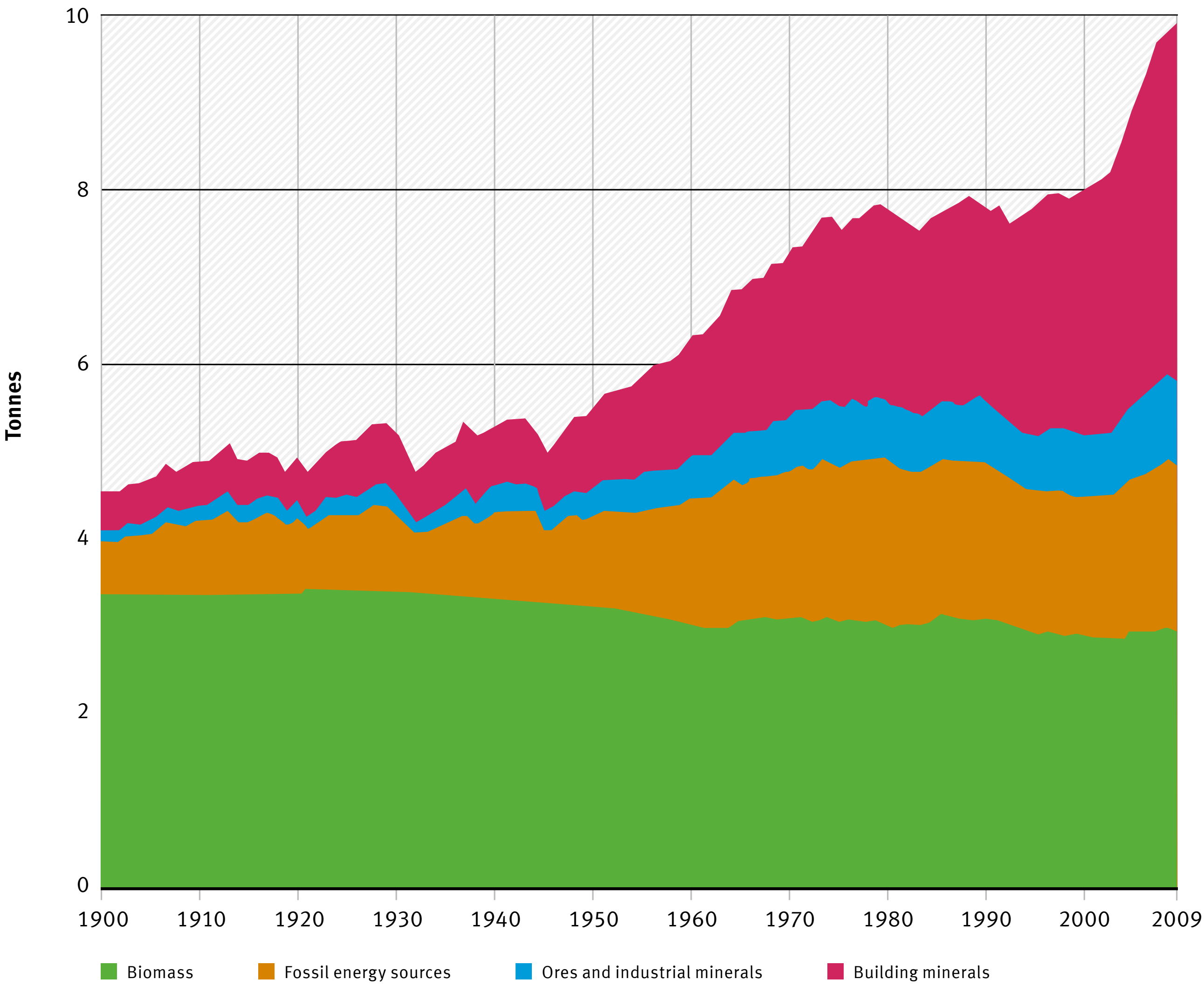
The rise of the anthropogenic material stock

The described intensification of anthropogenic metabolism increased global resource extraction by eightfold in the 20th century (see Figure 3). With a fourfold increase in population, per capita demand for raw materials has doubled while per capita biomass demand has virtually remained unchanged despite an absolute increase (see Figure 4). The use of fossil fuels, whose indirect effects on the anthropogenic climate change are perceived as one of the most obvious "metabolic disorders", has tripled. The extraction and processing of ores, industrial minerals and building minerals has increased by six to eightfold [20] not least due to this energy input.

Anthropogenic material flows of many metals in mining, production and consumption are now on the same scale as natural, geological flows generated by sedimentation, erosion or tectonics [21]. Anthropogenic copper flows (with approx. 15 million tonnes per year) exceed natural ones by a factor of three. This is a rapid development considering that more than 97 percent of an estimated 400 million tonnes of man-made copper was produced in the 20th century [22].

The shift is characterised by the diversity of materials, which has been triggered by developing new technologies among other things. While only 14 chemical elements were used commercially in any form at the beginning of

Figure 4
Global per capita raw material production [1900 – 2009]



Source: [20]

the 18th century, by 1900 this number increased to 32 of the 83 elements known at that time. In 2000, all 80 natural stable elements of the periodic table and seven other radioactive elements were used commercially [23]. Today's PC boards are a very good example: they incorporate 44 different elements [24] (see Figure 5, p. 14).

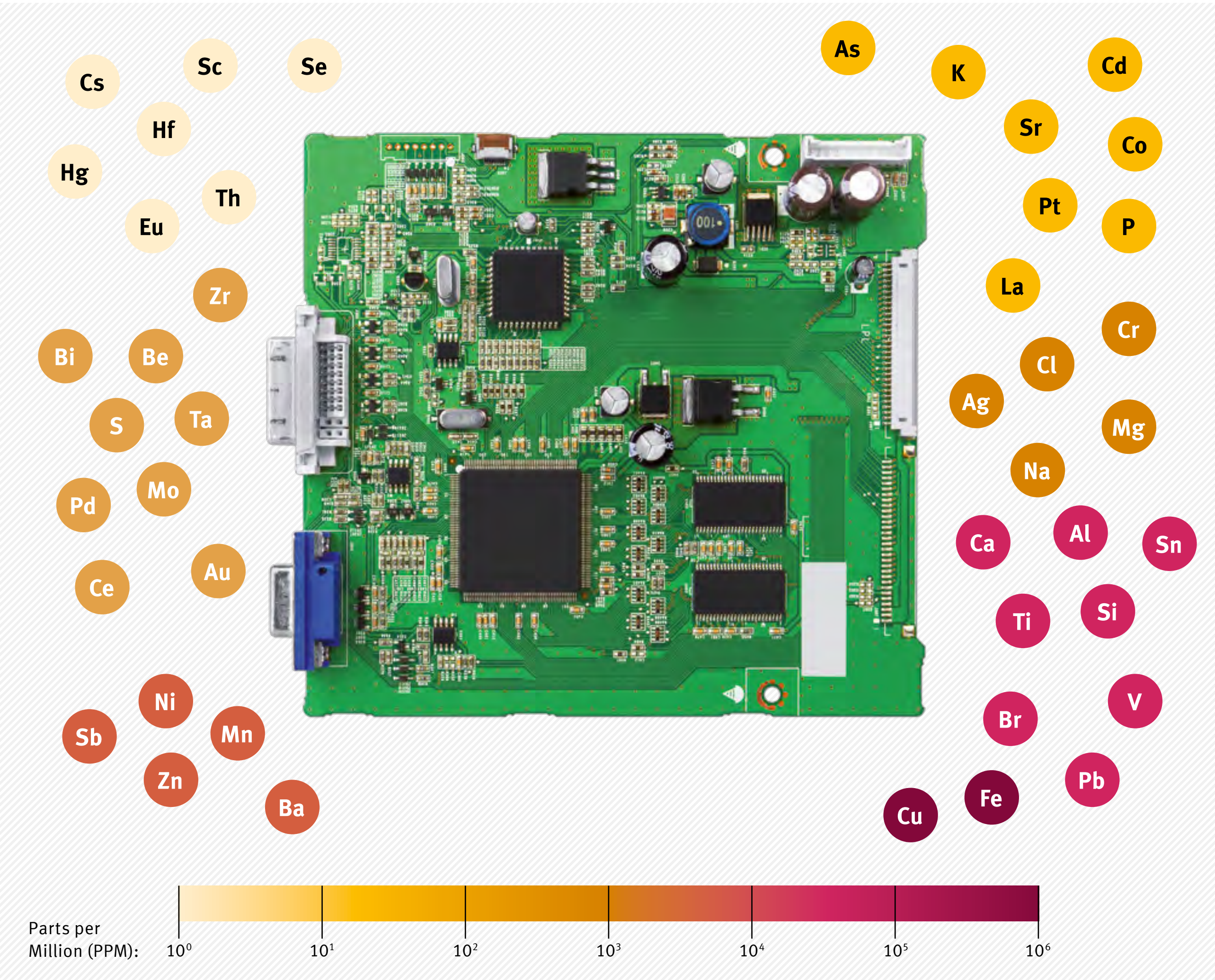
Only a few generations in human history were necessary for a large number of metals and minerals to be systematically and extensively shifted and transformed from the geosphere to the anthroposphere [25]. All this development has taken place in the industrialised countries accounting for only 15 percent of the population but about one third of global raw material consumption. Translating this figure to Germany shows that around one percent of the world's population uses four percent of the raw materials.

Global economic output rose by a factor of 24 in the past century driven by an enormous raw material consumption and population growth. National economies have also significantly increased in physical material terms, above all due to the accumulation of metals and building minerals. For the most part, in contrast to biotic and fossil materials that are mainly consumed as food or feed or used as fuel, they will still be present in the anthroposphere for many decades and form an enormous reservoir of materials.

The bulk of metals and building minerals are converted into long-term capital goods for highly networked urban settlements, which function as cultural and economic centres thanks to complex infrastructure and logistics systems. Ongoing urbanisation has created urban cultural landscapes since the mid-20th century, where about 55 percent of the world's population lived in 2015 [26] – and the trend is rising. Typical urban areas with growing populations strongly attract raw materials. More than 80 percent of the incoming goods flows remain in these areas and form deposits for an indefinite period [27]. The importance of cities and settlements as raw material stocks also depends on the structural processes of renewal and change that they are subjected to. Density, size and age distribution of their populations vary, demographic development and migration trends creates a dependency path that determines the fate of cities and settlements. Population growth or shrinkage determines the way in which certain cities and settlements continue to experience strong physical growth or their material budgets stagnate. Actual shrinkage has only been observed in exceptional cases, but it will occur more frequently in the future. Two development lines can be identified, which indicate very different views [28]:

Figure 5

Variety of elements on a PC board



UBA's illustration according to [24]

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About 32 million tonnes of materials are tied up in German railway stations alone over the long term.

1. Anthropogenic stocks as raw material sources
Anthropogenic material stocks, accumulated throughout the entire national economy within the last century, are still growing significantly and may have a significant positive influence on future availability of raw materials by enabling the extraction of large quantities of secondary raw materials.

2. Anthropogenic stocks as a "waste burden"
The more the anthroposphere grows, the more waste and emission potentials are shifted from raw material extraction and processing to the consumer sector and consumer goods. A widespread dictum states: "waste is matter in the wrong place". If this is not considered properly, very large regional waste flows may soon appear in the wrong places with all the economic and ecological consequences.

Which attitude will dominate the social consciousness, whether the anthropogenic stocks are perceived as wealth or burden, is less well determined in the global metabolism between the anthroposphere and the ecosphere. Instead, metabolism within our anthropogenic world will be the decisive factor. Urban Mining as a strategy and mindset can make a significant contribution to this issue.

Urban Mining is an
active, creative strategy.

02

URBAN MINING AS A MANAGEMENT CONCEPT

What is Urban Mining?

The German Environment Agency considers Urban Mining as integral management of the anthropogenic stock with the aim of obtaining secondary raw materials from durable products, buildings, infrastructures and deposits. All goods that remain in use for an average of one year or more and are of sufficient relevance, are designated as durable. Although Urban Mining means “mining within urban areas,” it is not just about the inner-city deposits that are important but rather all the goods mentioned above. Whether goods are still being used actively and will be released in the foreseeable future, as in the case of industrial and municipal buildings and domestic appliances or are no longer in use such as closed railway lines, landfills and dumps – is all irrelevant. It also does not matter whether the goods are static (e.g. wind turbines) or mobile (e.g. vehicles), they all need to be considered.

The strategic direction is long-term. It is geared to the lifetimes and storage dynamics of the durable goods being considered and attempts to establish high-quality material cycles. Urban Mining aims for a material flow management system ranging from prospection, exploration, development and exploitation of anthropogenic deposits to the processing of recovered secondary raw materials.

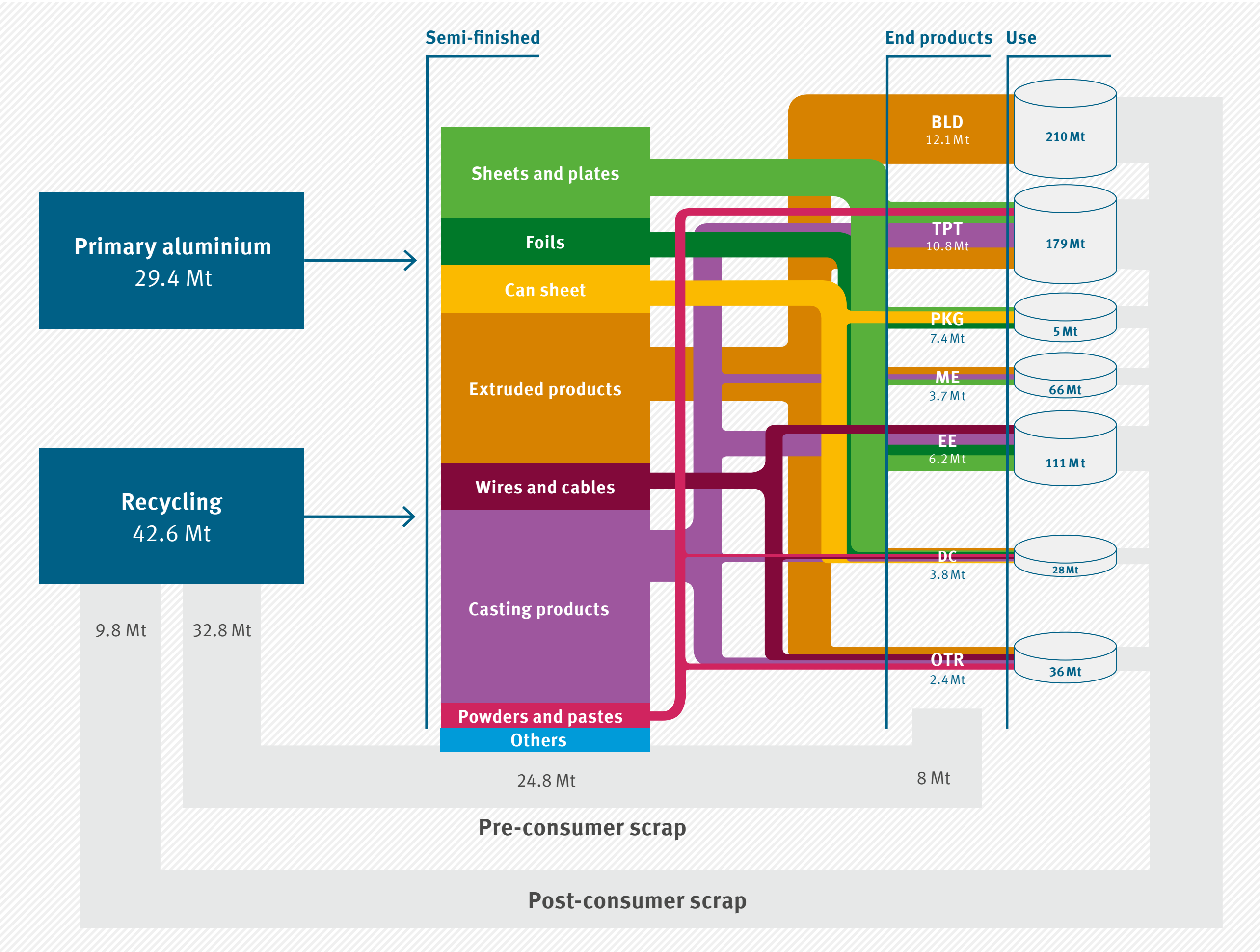
Urban Mining is not an approach that is completely detached from waste management. Neither does it replace regulated waste management areas such as the recycling of end-of-life vehicles or the reduction in the increasing amount of electronic waste from electrical and electronic equipment. Rather, it supplements and supports this methodically and conceptually.

What distinguishes Urban Mining from waste management are the system boundaries under consideration. In essence, waste management deals with the volume of waste itself, its quantity, composition and the best possible and harmless return of materials into the material cycle. By contrast, Urban Mining refers to the entire stock of durable goods where the overall amount is more difficult to assess in order to forecast future material flows as early as possible and establish the best possible recycling routes even before the waste materials are produced.

Informational and prognostic instruments are already in place when products are placed on the market. This creates links to the production and consumption sectors. In the overwhelming majority of cases – in the German Environment Agency’s view – active municipal waste management that deals with short-term consumer goods (organic waste, light packaging, waste glass, household waste), is not considered to be part of Urban Mining.

Figure 6

Global aluminium flows and stocks [2009]



BLD: Building
TPT: Transport
PKG: Packaging
ME: Mechanical engineering
EE: Electrical engineering
DC: Durable commodities
OTR: Others

UBA's illustration according to [29]

Stocks of durable goods

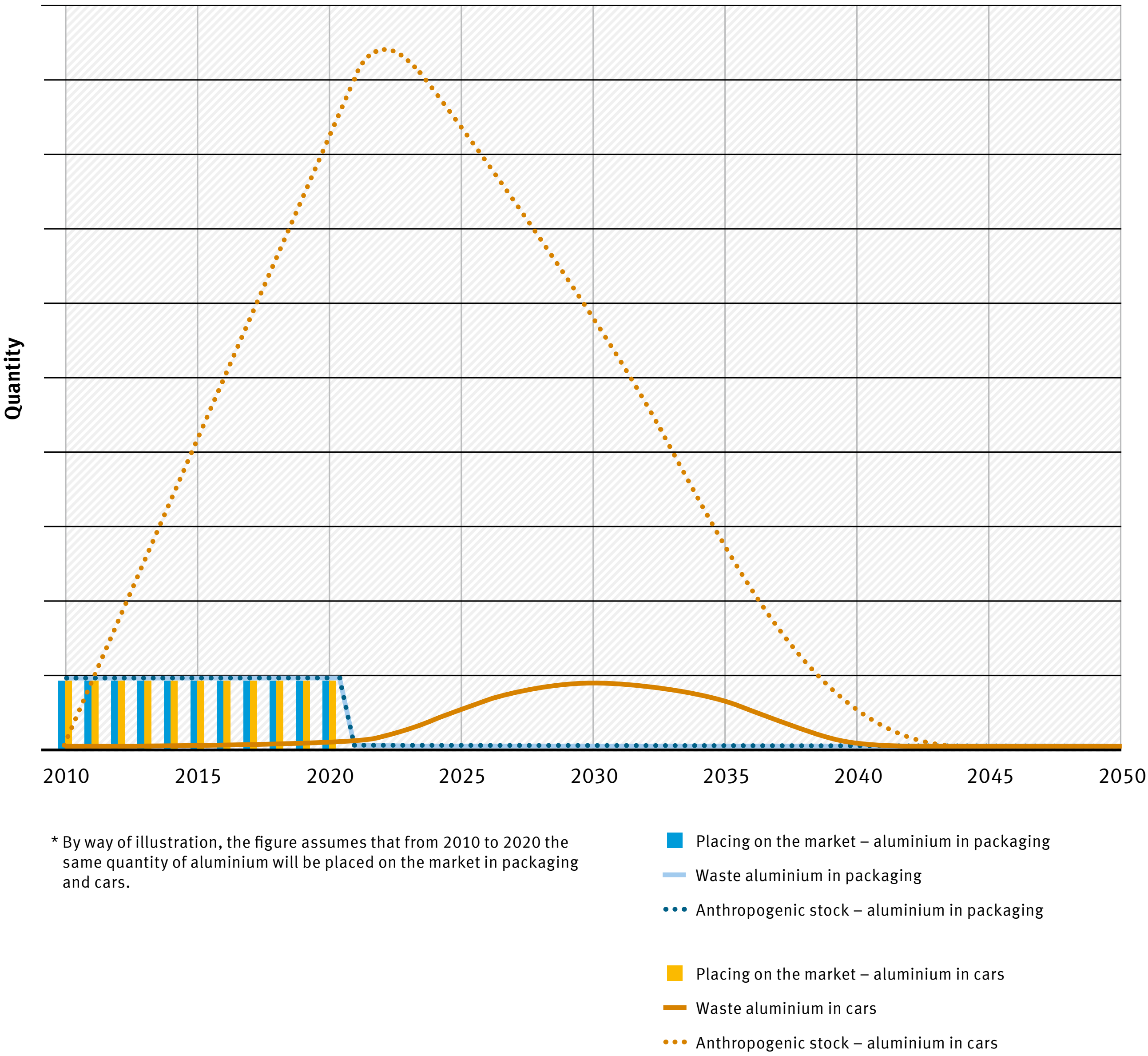
Within Urban Mining a focus on long-term durable goods is necessary because their behaviour is noticeably different to that of short-term consumer goods. In addition, the material deposits they form are significantly more extensive. This problem becomes clear with the global use of aluminium (see Figure 6). Only a sixth is used in short-term consumer goods, mainly in packaging. While around 80 percent of the aluminium used in packaging worldwide is collected as waste and recycled, it is currently only ten to 25 percent in buildings, machinery and industrial plants [29]. Aluminium stored in packaging materials in the consumer sector makes up a low plateau of five million tonnes. By contrast, the aluminium content of all long-term applications is already around 600 million tonnes.

A similar picture emerges for plastics. In Germany about 150 kilograms of plastics are processed per inhabitant per year. Of these, about a third are found in short-term consumer goods such as packaging. On the waste side, the conditions are quite different: for plastics, the recycling rate is lower than for aluminium.

Of the roughly 60 kilograms of consumer plastic waste per inhabitant per year is 60 percent of plastic packaging waste [30, 31]. Although

Figure 7

Stock dynamics of short-term and durable goods using the example of aluminium in packaging and cars *



* By way of illustration, the figure assumes that from 2010 to 2020 the same quantity of aluminium will be placed on the market in packaging and cars.

UBA's illustration

It may take up to 30 years for these aluminium rims to be released from the anthropogenic stock.

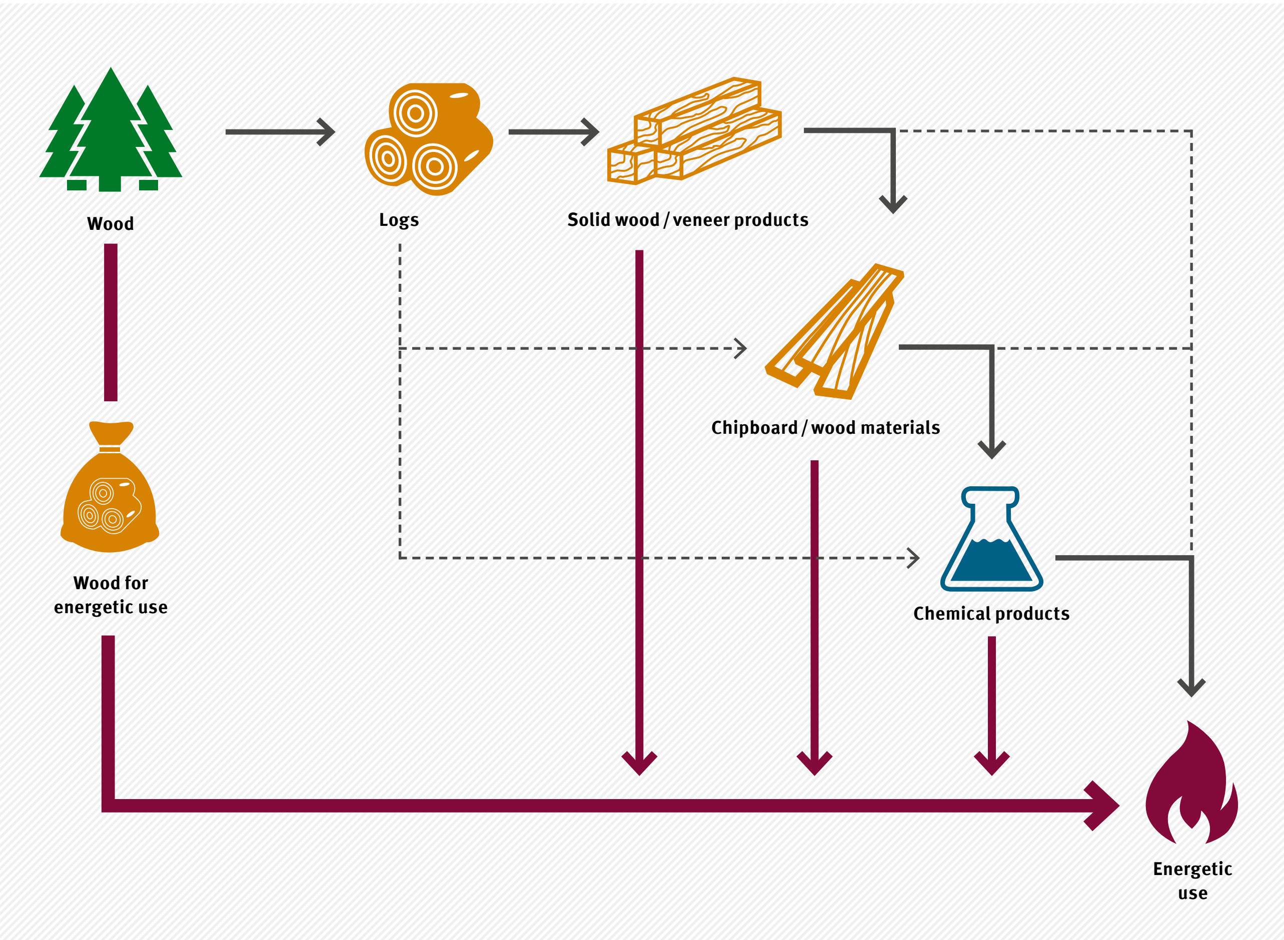
packaging plastics seem to be the most relevant in terms of waste management, they are only of minor importance in the anthropogenic stock that is estimated as three tonnes per inhabitant for plastics.

As the two examples of aluminium and plastics show, short-term goods represent material flows that are relevant in terms of their volume but they usually reach stable saturation in circulation. For example, food, cosmetics or cleaning products are mainly produced and purchased at the same level at which they are used or disposed of. If technological innovations are introduced, for example with regard to the selection of materials in packaging, then previous plateaus will quickly break down and new ones will be established on the basis of the changed product qualities. The total active storage in households does not increase appreciably and remains at relatively low plateau levels. Thus it is not only production volumes that can be planned but also the waste generated by households and commerce – which is an advantage. This is an essential factor for the scope of municipal waste management measures.

Such reliable planning is not readily available in the case of durable goods. It takes much longer before material plateaus develop. The longer the expected duration in use and the less specific the service lifespan of the goods, the more dynamic the stock development becomes. This can be seen in so-called logistic growth curves with a large temporal lag between input and output flows (see Figure 7). Mobile goods and components of immobile goods can migrate through a variety of stocks in the consumer sphere.

Figure 8

Model showing cascade use for wood



UBA's illustration

As long as they are actively used, this is also desirable in terms of cascade use (see Figure 8). Cascade use is the multiple use of products and their components before they are sent for final energetic use or disposal. For example, wood that was used as high-quality solid wood in the building sector, can be either reused as such after the end of its useful life or processed into chipboard, which theoretically can also be recycled several times. Another stage within a cascade could be a (bio-) chemical digestion or gasification to syngas (hydrogen and carbon monoxide) to make it into more complex platform chemicals, e.g. for plastic production. The final stage is energy recovery, where potentially the remaining ash can at least be used as fertiliser additive.

But for many groups of goods, the pathway is lost. And not only in the case of a technical-material dissipation, i.e. a production- or use-related distribution of materials, for example as a result of corrosion or abrasion-related wear. Often, this pathway does not re-emerge until the goods are recovered as waste several years or decades later. Although timing and quantity cannot be predicted accurately, as long as the total material stock grows it is foreseeable that in the long-term output will also increase, predominantly in the form of waste that has to be treated.

Before it is used for energy, wood can be used as material over several stages.

Comparison of Urban and Conventional Mining

Although the extraction of secondary raw materials is not commonly associated with conventional mining, it is worth comparing the two methods. Conventional mining, according to the Federal Mining Act, is dedicated to securing a supply of raw materials through prospection, extraction and processing of mineral resources. Basically, this description also fits the extraction of secondary raw materials in the context of Urban Mining.

As with conventional mining, Urban Mining also differentiates between deposits and occurrences. This differentiation seems important, as anthropogenic stocks or geological resources are only partially mineable at a given time. A (natural) accumulation of usable minerals and rocks is referred to as a “deposit” when commercial extraction is considered and as an “occurrence” when mining is not commercially worthwhile. The total quantity of raw materials contained in the deposits in a region make up the reserves; the aggregated raw material quantities of all deposits and occurrences form the geological or anthropogenic resources.

Despite obvious differences, there are many similarities between conventional and Urban Mining and both have their strengths and weaknesses, depending on the group of raw materials or commodities in the following ten categories (see Table 1):

A look at the *size of the deposits* reveals that, especially at national level, the anthropogenic stocks are in some cases significantly larger than the geological resources for some important raw materials. In Japan, for example, the anthropogenic stock of gold and silver is estimated at 16 percent and 24 percent of world reserves, while the country has no geological resources of these two metals [32, 33]. The worldwide anthropogenic resources of copper are estimated to be 400 million tonnes, almost 60 percent of the current geological copper reserves or just under 20 percent of the current copper resources [34, 35]. While the known geological deposits are currently shrinking due to the extraction of raw materials, those in the anthroposphere continue to increase significantly. As and when new geological deposits are not discovered consecutively, the relative share of anthropogenic resources will increase. However, if a global comparison is made of the geological resources of individual materials from which future reserves can develop, they have a much greater extent than stocks in the anthroposphere.

There is also some evidence for Urban Mining in terms of *prospecting efforts*: In addition to remote

Table 1

Comparison of conventional mining with Urban Mining

	Conventional Mining	Urban Mining
1. Size of deposits	0	0
2. Prospecting efforts		+
3. Degree of exploration	+	
4. Material content		+
5. Transport distance		+
6. Demand orientation	+	
7. Processing costs	+	
8. Environmental impact		+
9. Social license to operate		+
10. Restoration		+

+ beneficial **0** balanced

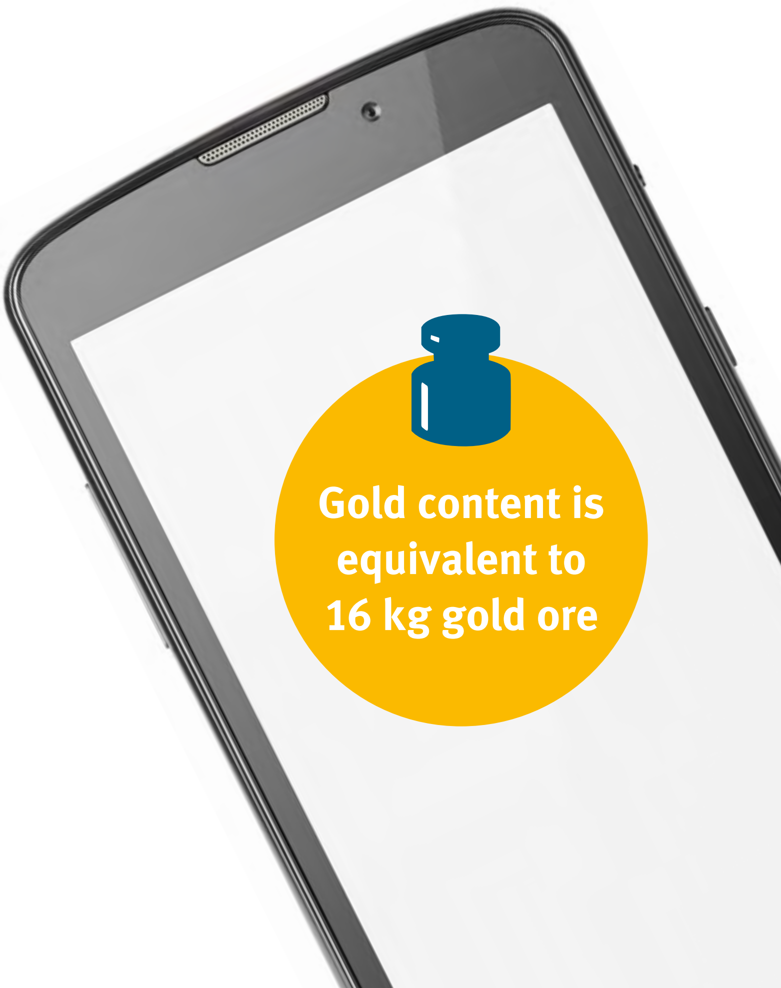
sensing, locating geological deposits also involves many ground geophysical methods (including magnetics, seismics, geoelectrics and gravimetry). These take place locally and already demand considerable financial expenditures. By contrast, anthropogenic stocks can be determined "from a desktop study" by evaluating development plans and statistics from satellite data, cadastres, standards and production, waste and foreign trade.

However, the *degree of exploration* in conventional mining is much higher. Geological deposits are well documented compared to anthropogenic ones driven by economic interests. This is also due to the fact that the development of natural deposits is not only immensely capital-intensive and risky – only two per cent of the exploration activity leads to mining production – but a lead time of about five years from the initial planning stage is required. In 2012, $22.5 billion was invested globally in the exploration of non-ferrous metal deposits [36]. By contrast, the targeted exploration of anthropogenic stocks that are no longer used is still a rare field of study.

As far as the *material content* of the deposits is concerned, Urban Mining is doing well; many metals are found in natural ore deposits in low concentrations. For non-ferrous metals such as nickel, copper and lead, these amount to between 0.3 and 10 percent. By contrast, the same substances are present in anthropogenic deposits such as components, cast elements or machines, predominantly in pure form or high-alloyed. One meter of copper cable from the information and communication sector contains as much metal as 2.5 tonnes of ore [37]. The gold content of an average mobile phone is equivalent to 16 kilograms of gold ore.

Another important point is *transport distance* from the deposits, which determines marketing effort. Geological deposits are often located far from the economic centres where those extracted materials are in demand and are processed into higher-quality products. In addition, many geological occurrences lie in areas with extreme climatic conditions or inadequate or non-existent infrastructure. In contrast, urban mines are in close proximity. This also applies to so-called mass raw materials: For example, secondary aggregates from the dismantling of buildings are usually located in inner-city areas, whereas primary gravel comes from quarries that can sometimes be more than 30 to 50 kilometres away.

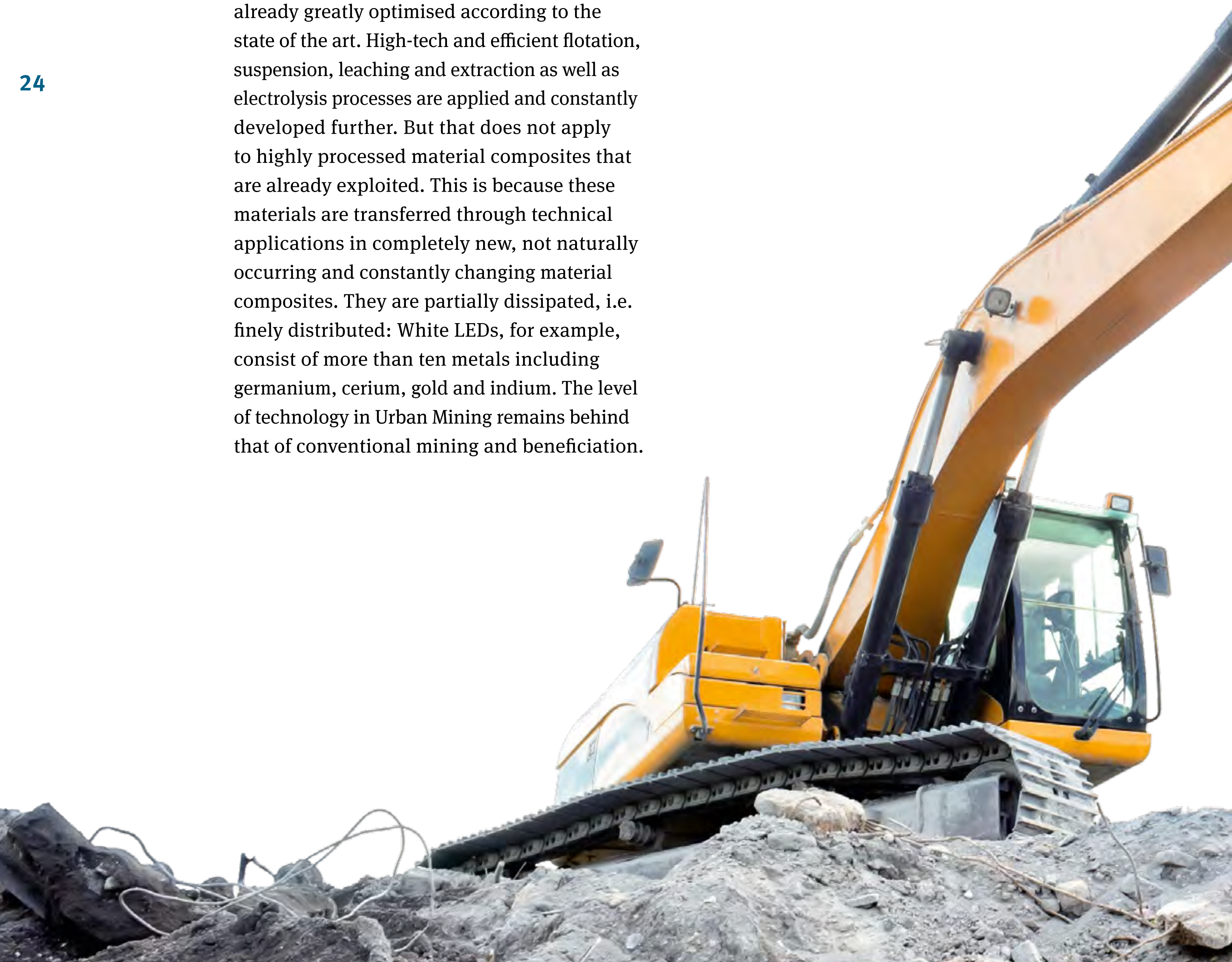
Demand orientation is proving difficult in Urban Mining. Once the reserves have been explored and economic conditions considered, primary production of raw materials can be adjusted to a certain degree to meet increased demand – be it by expanding production or improving efficiency of processing. Driven by the boom in demand for electrode material in high performance batteries, worldwide cobalt production increased 61 percent from 2009 to 2010 [38].



This was despite the fact that cobalt is 80 to 90 percent co-produced in nickel and copper mining [39]. In Urban Mining, however, it is possible to foresee a supply of particular secondary raw materials, but the quantity is not flexibly adjustable.

More problematic in Urban Mining when comparing it to conventional mining, is the extraction of raw materials from composite materials, i.e. the *processing costs*. Certainly, in conventional mining there is also a large amount of joint production. 38 out of 62 metals and semi-metals are more than 50 percent co-produced with other metals [39]. And the processing costs in conventional mining tend to increase as more complex deposits are tapped, due to sharply rising demand and a high level of exploration [40]. However, the accumulation of certain materials, the so-called paragenesis in geological formations and minerals by geochemical-physical models, is quite well researched. The processing technologies are already greatly optimised according to the state of the art. High-tech and efficient flotation, suspension, leaching and extraction as well as electrolysis processes are applied and constantly developed further. But that does not apply to highly processed material composites that are already exploited. This is because these materials are transferred through technical applications in completely new, not naturally occurring and constantly changing material composites. They are partially dissipated, i.e. finely distributed: White LEDs, for example, consist of more than ten metals including germanium, cerium, gold and indium. The level of technology in Urban Mining remains behind that of conventional mining and beneficiation.

With regard to respective *environmental impacts*, the extraction of primary raw materials involves sensitive interventions in ecosystems, sometimes even the release of toxic substances. The processing of ores requires a lot of energy and water. In addition, metals must generally be converted into their reduced, economically most important form through smelting and refining requiring high energy and process engineering inputs. In contrast, the development and provision of secondary raw materials largely has clear advantages. For example, scrap aluminium production, taking the collection into account, requires only eleven to twelve percent of the primary raw material and energy required for primary aluminium production from bauxite smelting. Greenhouse gas effects, acidification, ground-level ozone formation and eutrophication effects are 90 to 95 percent lower [41, 42]. In addition, the recycling processes in highly industrialised countries such as Germany are subject to significantly higher immission control regulations, which are also legislated and can



be adapted to guarantee the highest possible level of protection for people and the environment. In contrast, enforcing acceptable environmental standards in the primary production countries often escapes the economic, legal and political spheres of influence.

The extraction of raw materials often leads to competition for natural resources such as water and land. In the absence of local community involvement, environmental impacts and competition often lead to violent conflicts [43]. Social acceptance, the so-called *social license to operate,* is considered one of the most important business risks in the mining sector [44].

Urban Mining offers advantages here. Since it serves more to conserve natural resources and can defuse conflicts of use, broad public acceptance can be expected.

If a primary raw material deposit is completely exploited, the mining area must be *restored* and in the case of contamination, rehabilitated if necessary. A basic requirement for successful aftercare is effective legislation but above all effective law enforcement, which is unfortunately not the case in many raw material producing countries. It is not uncommon for mining companies to leave areas that are permanently contaminated and unrecoverable. In contrast, if anthropogenic deposits are exploited, aftercare can directly handle them. This is because alongside the production of secondary raw materials, pollutants are captured and harmlessly disposed of even before they are unintentionally released from goods into the natural environment. In addition, this allows for built-up areas to be recovered for other types of use.

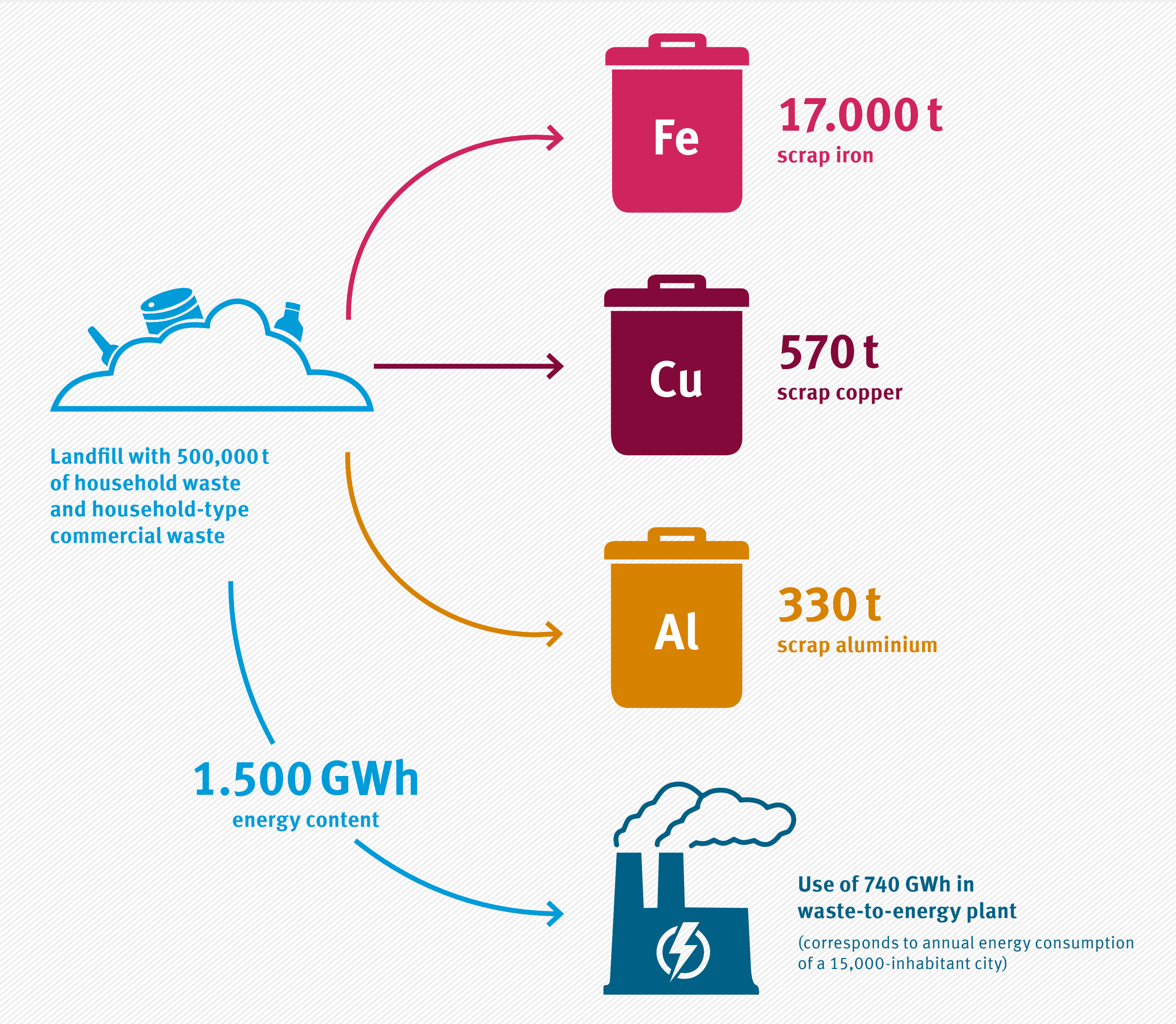
Urban Mining offers many advantages compared to the extraction of primary raw materials in mining.

Raw material potential from old landfills

Applying landfill mining to a medium landfill for domestic household waste and similar household-type commercial waste, an estimated 500,000 tonnes of landfill is expected to yield 17,000 tonnes of scrap iron, 570 tonnes of scrap copper and 330 tonnes of scrap aluminium. In addition, such a landfill has an estimated energy content of 1,500 gigawatt-hours. From this, 740 gigawatt-hours can be generated in a waste-to-energy plant, which corresponds to the annual energy consumption of a city with 15,000 inhabitants [46].

Figure 9

Raw material potential from domestic landfill



UBA's illustration according to [46]

Practical experience has been gained with slag landfills where the waste generated by waste incineration is deposited. These have a high potential for secondary raw material extraction, as non-ferrous metals have only recently been separated. The mining of such a landfill in Switzerland in 2005, for example, provided around 4,270 tonnes of iron, aluminium, copper and brass from the 200,000 tonnes of material extracted [45].

Landfill Mining

A special discipline of Urban Mining is the so-called landfill mining – the targeted material extraction from disused landfills and the recovery of recyclables from these and from dumps. Against the backdrop of highly volatile and increasing raw material prices in the longer term, secondary raw material extraction is becoming more important. However, the secondary raw material potentials are much smaller than in active stocks.

According to estimates, around 2.5 billion tonnes of municipal, building and industrial waste have been disposed of in Germany since 1975. Amongst other things, alternative fuels, metals and minerals make landfill mining in existing landfills worth considering. Since there were hardly any managed landfills before 1972 and the widespread recycling of waste in Germany has only occurred since 1986, many interesting materials can be found especially in old landfills. According to conservative estimates based on waste and materials analyses from landfill mining projects, the following quantities of recyclable materials were landfilled between 1975 and 2005 [45]:

- 250 million tonnes of paper, plastics, textiles and wood. The resulting calorific value corresponds to an estimated material value of 60 billion euros.
- 26 million tonnes of scrap iron, 1.2 million tonnes of scrap copper, 0.5 million tonnes of scrap aluminium and 0.65 million tonnes of phosphorus with a value of around 14 billion euros.

In addition to secondary raw material extraction, there are other reasons for mining landfills. While the emphasis on landfill mining in Germany in the 1980s was on landfill volume recovery and landfill rehabilitation, today the reduction in environmental impact and aftercare costs plus freeing up site space, play an increasingly important role. The latter is especially important for landfills on the edge of conurbations where landfill sites become more attractive as building land due to the growth of housing estates. In Germany there are about 100,000 registered disused landfills. For the period from 1995 to 2009, space made available solely from the closure of municipal landfills is about 15,000 hectares [47].

^
Test drillings are used to examine the recyclable content of a disused landfill.

Disused landfills usually require costly aftercare as they represent a considerable environmental hazard potential, for example in the form of harmful emissions (e.g. methane) or contaminated leachate. The aftercare can take up to 200 years. The cost of closure and aftercare alone is estimated at between 17 and 36 billion euros, based on the 400 landfills closed before 2009 alone [47]. Provisions for liabilities are supposed to cover the follow-up costs but this will not always be the case. Landfill mining can help relieve future municipal budgets. As a result of an interdisciplinary project involving companies, research institutes and administration, a guideline was published in 2016 which provides a multi-faceted treatment of economic, legal, technical and ecological aspects of landfill mining to inform decision makers [48].

Despite the considerations of landfill mining, landfills will continue to be part of a functioning circular economy in order to dispose of pre-treated waste in an environmentally sound manner. It is not always possible to ensure proper and harmless recovery of waste – as required by law as a basic duty for recycling) – as this needs to be technically feasible and economically viable. In this case, landfills can also be considered as long-term deposits for waste – for example, ashes from mono sludge incineration plants with the goal of later phosphorus recovery.

03

RAW MATERIAL POTENTIAL IN THE ANTHROPOGENIC STOCK

From an average old building with ten residential units, approximately 1,500 tonnes of material can be recovered from demolition, including 70 tonnes of metals and 30 tonnes of plastics, bitumen and wood.

How well do we know the anthropogenic stock? What quantities of materials have actually been accumulated in Germany's anthropogenic stock and how much of them will be released in the future? How well can the overall economic metabolism be understood? Exploring this is a demanding task, for which the German Environment Agency has initiated a specific series of research projects- the mapping of the anthropogenic stock (KartAL –"*Kartierung des Anthropogenen Lagers*"). The first step is to record stocks as well as the annual input and output flows. Only on this basis can prognostic instruments be applied which are indispensable for the establishment of Urban Mining.

The total stock

The total amount of materials in Germany's anthropogenic stock can only be determined indirectly. The environmental economic accounts of the Federal Statistical Office are the basis for this. Material flows at the boundaries of the economic system -such as domestic extractions, imports, exports and releases to the environment- are well analysed in economy-wide material flow accounting. However, the materials remaining within the economic system only appear as balance sheet residues [1]. These so-called net additions to stock (NAS) can roughly be interpreted as an increase in the supply of durable goods. In contrast, changes in the inventories of short-term consumer goods, including fuel and food, are largely reflected in the emissions balance. For 2010, this resulted in a NAS of approx. 820 million tonnes of materials in total or approx. ten tonnes per year per inhabitant. For decades, the annual NAS has hardly changed (see Figure 10, p. 30).

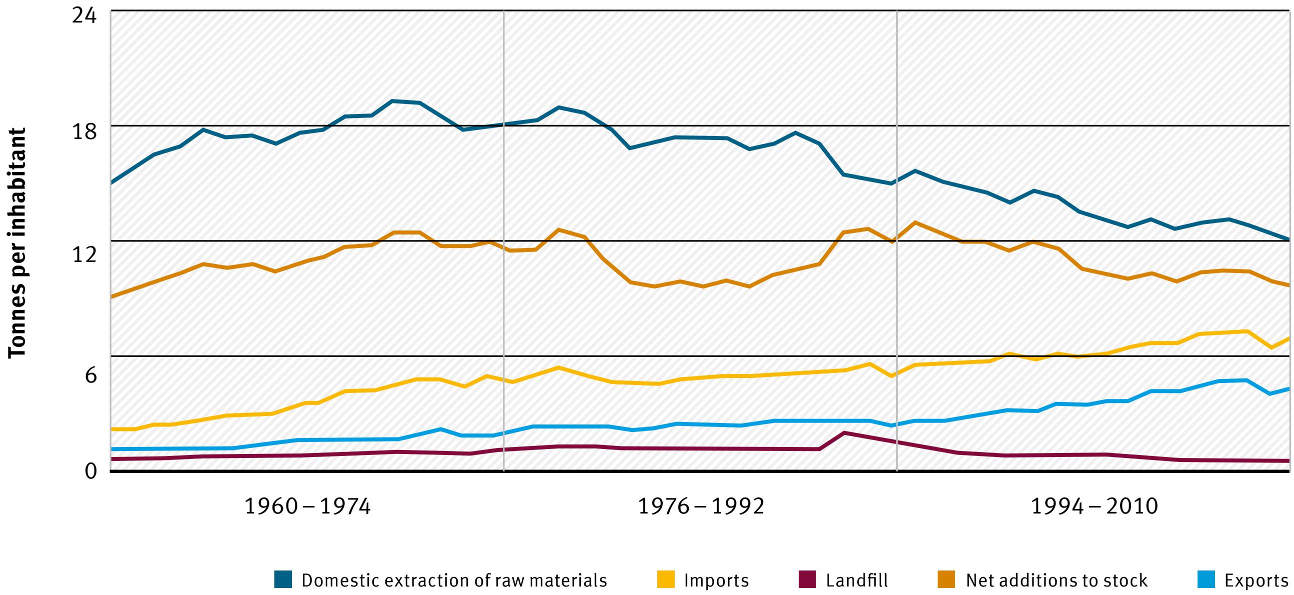
The inflows from imports and domestically extracted raw materials, in particular construction minerals such as gravel, sand, natural stones and limestone, thus largely exceed the outflows from exports, emissions and depositions in the long-term trend. While domestic extractions of raw materials dropped significantly, imports and exports grew at a similar rate. The total stock in the Germany's anthropogenic stock can be estimated for 2010 as 51.7 billion tonnes of materials of which more than 80 percent, or 42 billion tonnes, have been accumulated in the 50 years since 1960 [31]. To illustrate the order of magnitude, this equates roughly to the total of raw materials extracted worldwide in 2000.

Not everything in this overall stock can be classified into groups of known goods. Not all of this will ever be relevant to the secondary raw materials economy e.g. materials that go into landscaping earthworks. To further specify the annual flow of goods into the anthropogenic stock and the containing materials, statistics about macroeconomic production, foreign trade, waste and non-official corporate statistics can be evaluated (see Figure 13, p. 33). For example, in 2010 around 666 million tonnes of materials entered building structures as well as durable consumer and capital goods. Of these, about 20 percent came from secondary materials, mainly from construction waste but also from industrial waste and by-products such as ashes, slags and REA gypsum. 29 million tonnes were deposited, of which more than half (16 million tonnes) were landfilled, the rest went to backfilling measures (13 million tonnes) [31].

Material flows in the anthropogenic stock are determined by a top-down model. Such models give a macroeconomic picture. From an economic and ecological point of view, however, a much more detailed structuring of the goods and materials is necessary. This requires a change of perspective. A so-called bottom-up

Figure 10

Economic material flows in Germany [1960 to 2010]



UBA's illustration according to [31]

analysis is used for stocks and flows by means of extrapolations for individual goods and groups of goods. A major challenge is to estimate the most important categories of goods as comprehensively as possible, determine their number, length, area etc. and then integrate them into calculations using representative material coefficients. Such extrapolations cannot always be conducted, nor can they cover all goods. It occurs that bottom-up analyses largely give lower results than top-down analyses [49]. For 2010, a study about buildings and building technology, grid-bound infrastructures, and long-term capital and consumer goods found at least 28 billion tonnes of materials tied up in these goods. These numbers are more than 20 billion tonnes lower than the numbers from the top-down modelling.

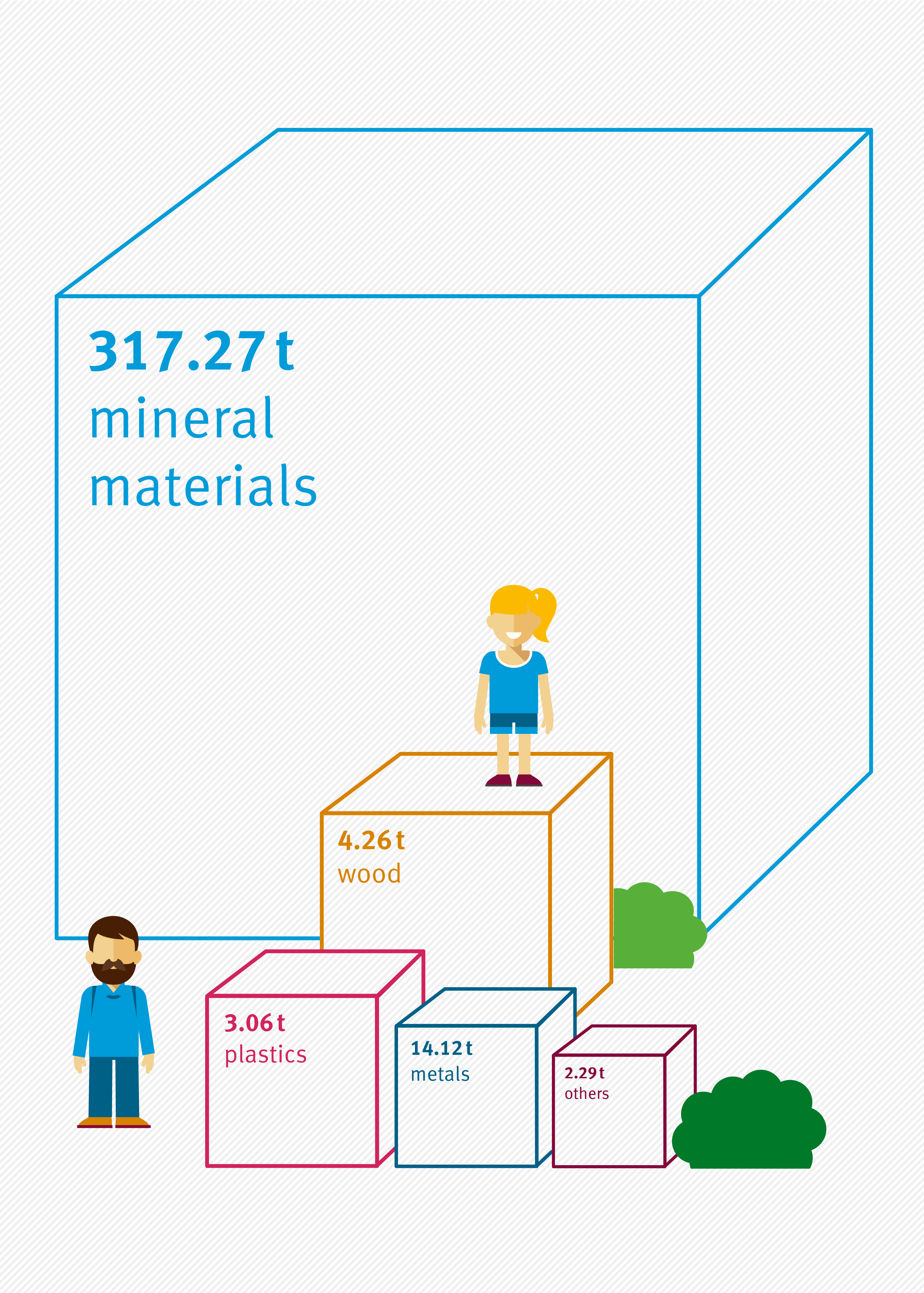
The stock for the above five groups of goods consists of a massive 341 tonnes of materials per capita (see Figure 11, p. 31), including 317 million tonnes of mineral materials, mainly loose rocks and sands, concrete and bricks. This is followed by metals with 14 tonnes, primarily steel but also almost 100 kilograms of copper*.

Furthermore, the stock amounts to four tonnes of wood, three tonnes of plastics and another two tonnes of other materials that cannot be clearly assigned. By far the largest part of the stock lies in the construction sector (see Figure 12, p. 32), 55 percent alone in residential buildings and bound to non-residential structures. Civil engineering, which includes transport infrastructures, drinking water, wastewater, energy

* The total share of non-ferrous metals was estimated at 212 kilograms per capita. However, in a study commissioned by Metals for Climate, a corporate initiative in WVMetalle, 950 kilograms of non-ferrous metals were determined per inhabitant (2014) [107]. The significant differences can be explained because the first case is based on a bottom-up, goods-based methodology which is not complete per se and depends on the assumed material coefficients being representative, while in the second case a material flow balance based on production quantities is used which follows more of a top-down logic.

Figure 11

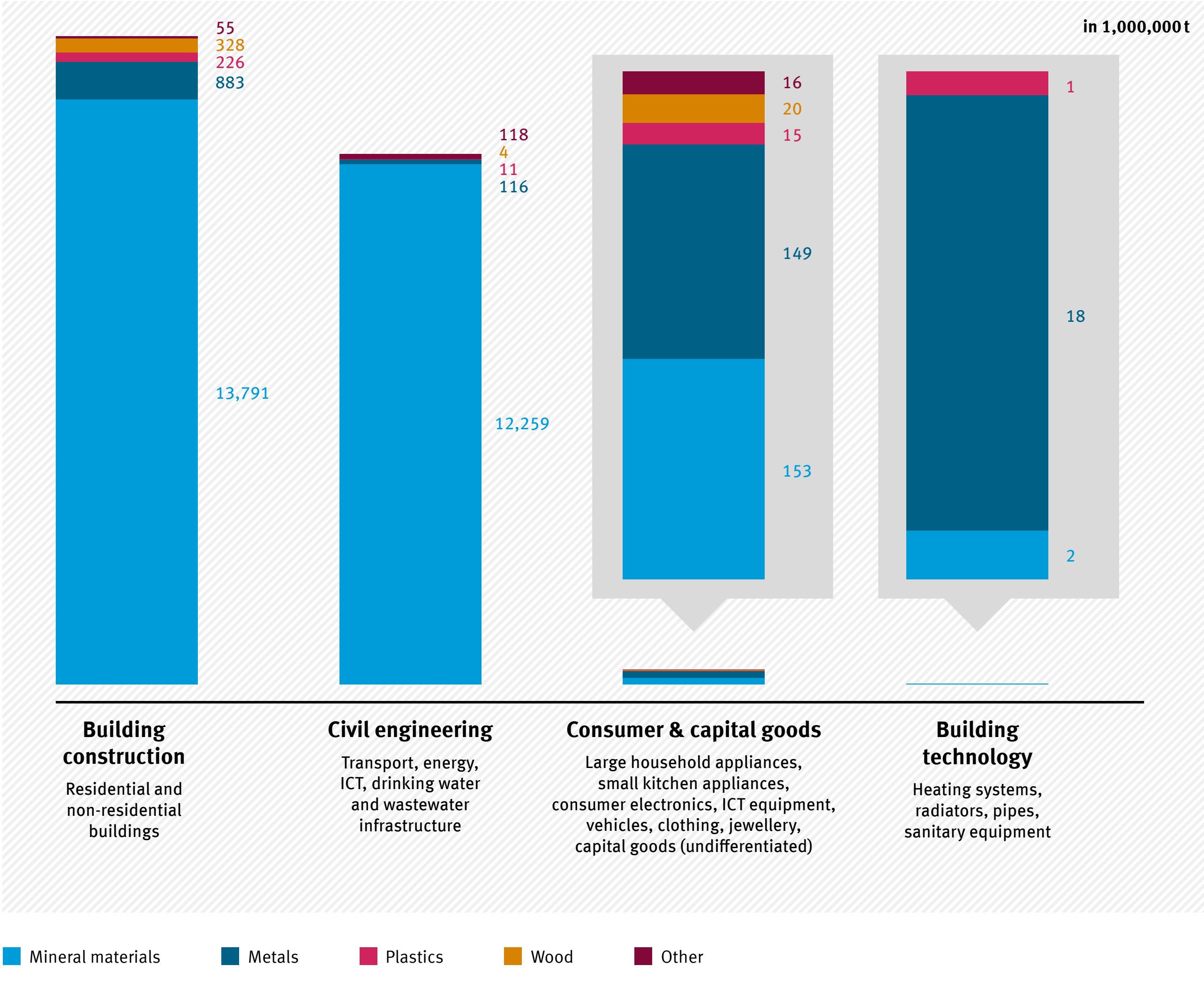
Known material stocks percapita in Germany [2010]



UBA's own illustration according to [49]

Figure 12

Anthropogenic material stock by groups of goods and materials in Germany [2010]



Source: [31]

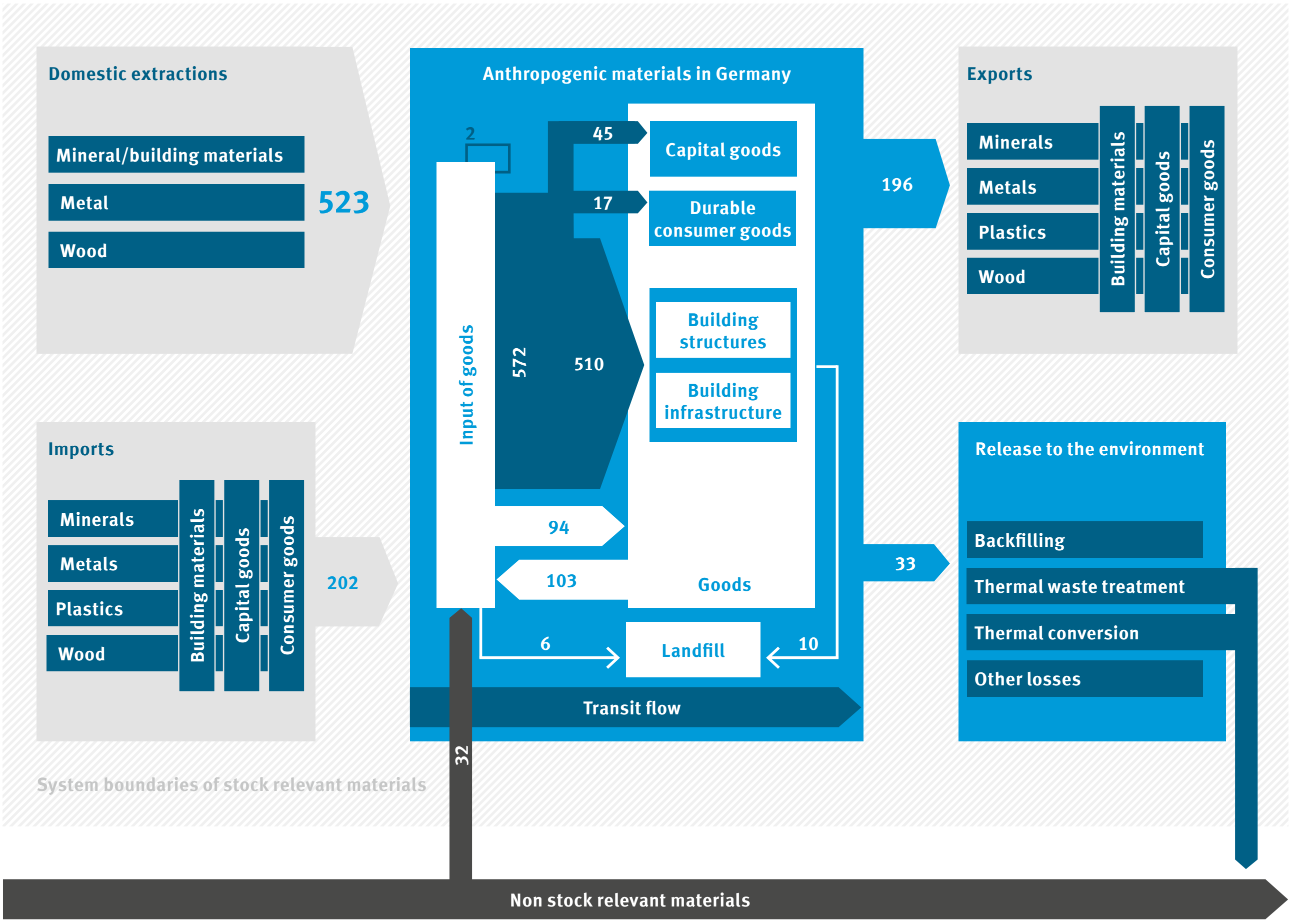
The material value of the metals in the German anthropogenic stock can be estimated at around 650 billion euros.

and information and communication networks, covers 44 percent. The material amount tied up in building technology such as pipes and heating systems as well as durable consumer goods and capital goods, is significantly smaller with less than one percent of the total material stock.

However, the materials of these groups of goods are of particular interest. While mineral materials dominate the building stock, metallic materials share a much larger part in building technology and in capital and consumer goods. This ranges from just under 40 percent in capital goods, to over 60 percent in consumer goods up to almost 90 percent in building technology. These are mainly ferrous metals and to a lesser degree non-ferrous metals such as copper and aluminium and in smaller quantities precious and special metals, the recovery of which is of particular environmental and economic interest (see Box, p 34). The importance of these quantitatively smaller fractions in the stock is also evident when looking at the raw material values associated with them: the sheer material value of the anthropogenic stock amounts to an estimated € 1,300 billion without the actual, much higher current goods values – the fixed assets – being taken into account. Of this total, € 650 billion alone is attributable to metals, around € 150 billion each to plastics and wood, and € 350 billion to minerals and other materials.

Figure 13

Flows in the anthropogenic materials stock in Germany in million tonnes [2010]



Source: [31]

Precious and Special Metals

Metals that are particularly resistant to corrosion are called precious metals, not least because of their high value. These include in particular, gold and silver as well as the platinum metals.

Unlike the bulk metals used such as aluminium, iron and copper, there are metals that are incorporated and added in much smaller quantities to products whose relative recovery and supply risk are sometimes much higher. These are subsumed under the term special metals, for example indium, gallium, tantalum, neodymium or cobalt.

Among the precious and special metals are also so-called conflict minerals such as tantalum, gold, tin and tungsten. The sovereignty over their mines in Central Africa and Latin America is not only the target of armed conflict. The proceeds of extraction and trade are also used to finance militant rebel groups responsible for serious human rights violations. In order to stop supporting this as a customer in the future, following the US, the European Commission is now seeking legal regulation for transparent and certified trade of these raw materials [51]. Their recovery from the anthropogenic stock also represents an important avoidance strategy.

Dynamic stocks

At around 28 billion tonnes, the total amount of the anthropogenic stock for the identified product groups is approximately equal to 75 times the figure of that which is newly spent for those goods every year (about 372 million tonnes). The annual new flows of materials into the designated product groups do not necessarily develop proportionally to the existing stocks.

New goods' groups are growing rapidly, others are disappearing slowly or relatively quickly. The reason for this is technological developments and politically motivated trends, for example for energy savings through increased building insulation, but also in contrast, changed consumption patterns, consumer preferences and functional obsolescence. In addition, the materials contained are subject to constant change both qualitatively and quantitatively. Specific dynamics develop for groups of materials and goods, as the civil engineering example shows.

In civil engineering, a relatively large increase is apparent: In contrast to the overall stocks, the annual use of mineral materials in civil engineering is about twice as high as in building construction. While only about one-tenth of the metals found in structures is found in civil engineering infrastructures, it now accounts for one-third of the quantity annually used in the building industry as a whole [31]. A key driving force for this is the "Energiewende" (energy transition). In 2010, nearly 30 percent of the materials used to build and repair power generation and distribution infrastructure went into the construction of new wind, biogas and photovoltaic plants. In the overall material inventory of all energy infrastructures, however, these represent only five percent so far. This will change fundamentally in the coming decades in view of the enormous growth momentum.

Installed materials decide about future recovery: in addition to the bulk metals such as steel, aluminium and copper, relevant quantities of fibre-reinforced plastics and strategically important special and precious metals such as silver, tin, neodymium and gallium will be enriched in these infrastructures. In other areas, such as the transport infrastructure, growth is relatively low as the stock seems to be close to saturation. About 80 percent of annual material demands are already accounted for by maintenance, upgrading and refurbishment. The situation is similar in the building stock and associated building technology.

Special attention for Critical Raw Materials

At the beginning of the 21st century, leading geoscientific institutions postulated that the supply of raw materials was safe and there was no reason to fear any serious limitation of growth due to resource scarcities [52, 53]. This was also a reaction to the still widespread misunderstanding of interpreting so-called static lifetimes of raw materials as availability lifetimes (see box).

Nonetheless, raw material shortages, especially raw material criticality, have become a much discussed topic in raw material politics and economics in recent years. Not least due to experiences of extraordinary price shocks and high price volatilities, it was increasingly recognised that limited availability in future will be a result of a greater variety of supply risks. These range from geological, technical and structural to geopolitical, socioeconomic and ecological criteria. The demand side also came into focus. This is because the extent to which a scarcity of raw materials exists, depends not only on supply but also on how strong the buyer, for example, a state, region, or corporation relies on a stable supply. For this purpose, consideration is given to the importance and adaptability (vulnerability) in the case of a supply interruption.

On the lists of critical raw materials for Germany and the EU there are mainly so-called technology materials [55]. New, somewhat disruptive, innovative technologies have developed over the past few years or decades, which – although mostly in very small quantities – are functionally dependent on a large number of elements that previously often had only minor economic significance. Due to their interesting chemical and physical properties, these technology materials – predominantly precious and special metals – are hard to substitute in a variety of applications such as environmental technologies or information and communication technologies (see Figure 14, p. 36). They have experienced a rapid demand surge within a very short time, not only in Germany but worldwide.

More than two-thirds of the global production of platinum group metals (e.g. in catalysts, alloys) but also of indium and gallium (e.g. in electronics, optoelectronics, photovoltaics), tantalum (e.g. in electronics, capacitors) and rare earths (e.g. in permanent magnets, optoelectronics, electrochemical storage) took place after 1988 [57]. Apart from politically unstable producer countries, their availability is limited due to high market concentrations, restrictive export and trade policies and structural co-production, as well as occasionally very low recycling rates from end-of-life products. While functioning recycling systems are established for the large material flows of ferrous and non-ferrous metals as well as precious metals, recycling for many other technology metals does not yet take place or only to a marginal extent [58] (see Figure 15, p. 37).

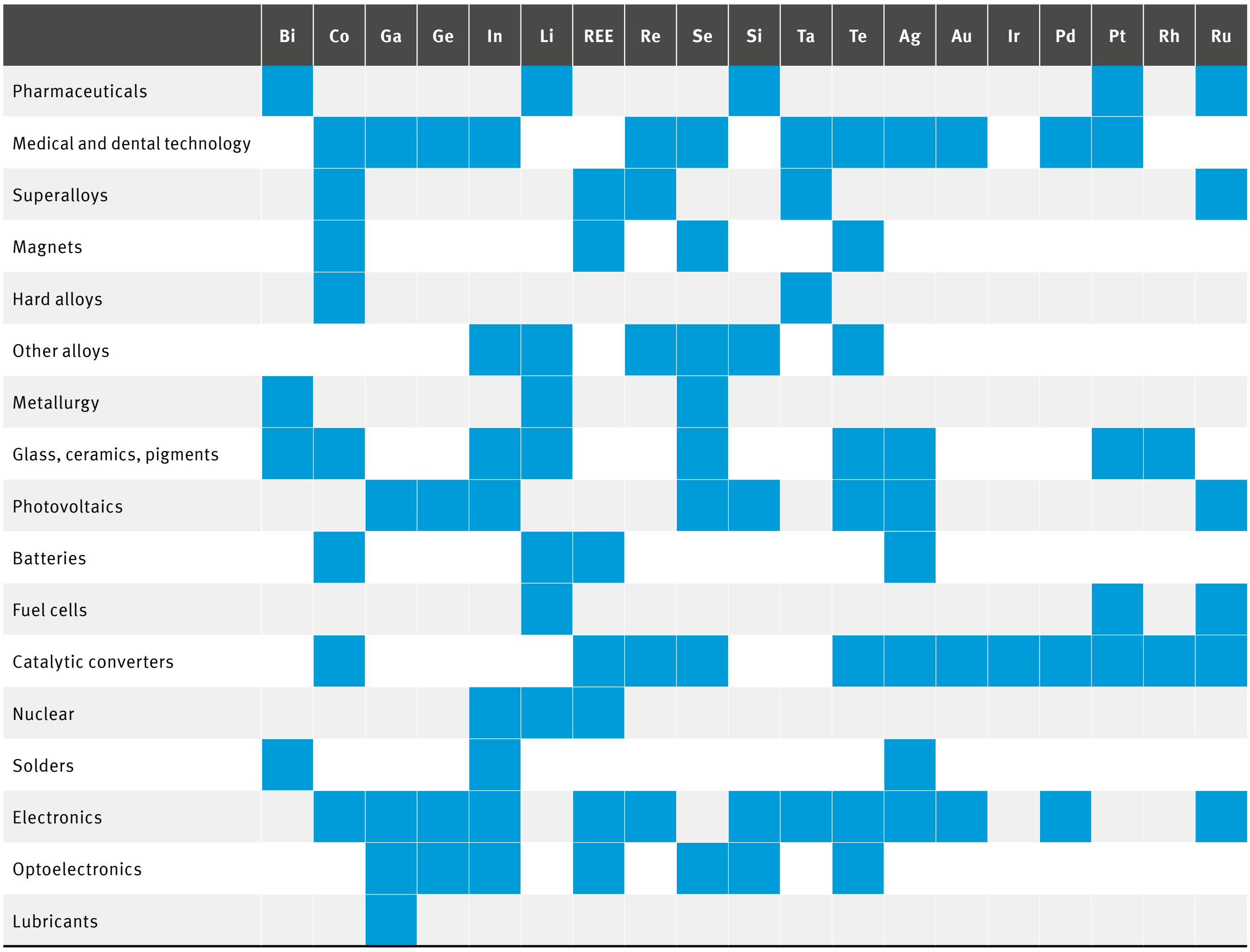
Especially in recent times, anthropogenic stocks have been enriched with a great variety and large volumes of very significant substances. The amount of highly valuable platinum group metals

"Static lifetimes" are not scarcity measures

Static lifetimes represent the ratio of available reserves or resources of a raw material to the current annual worldwide production and are thus known as reserves-to production-ratios. In retrospect, it can be seen that static lifetimes of both fossil energy resources and ores have remained virtually constant, or even increased, despite an eminently higher consumption trend in the second half of the 20th century. Technological progress and economic conditions enabled a significant exploration increase and thus expanded reserves [54]. Static lifetimes tend to say more about the characteristics of mining exploration cycles rather than the physical availability of raw materials.

Figure 14

Technology metals by application fields



Source: [56]

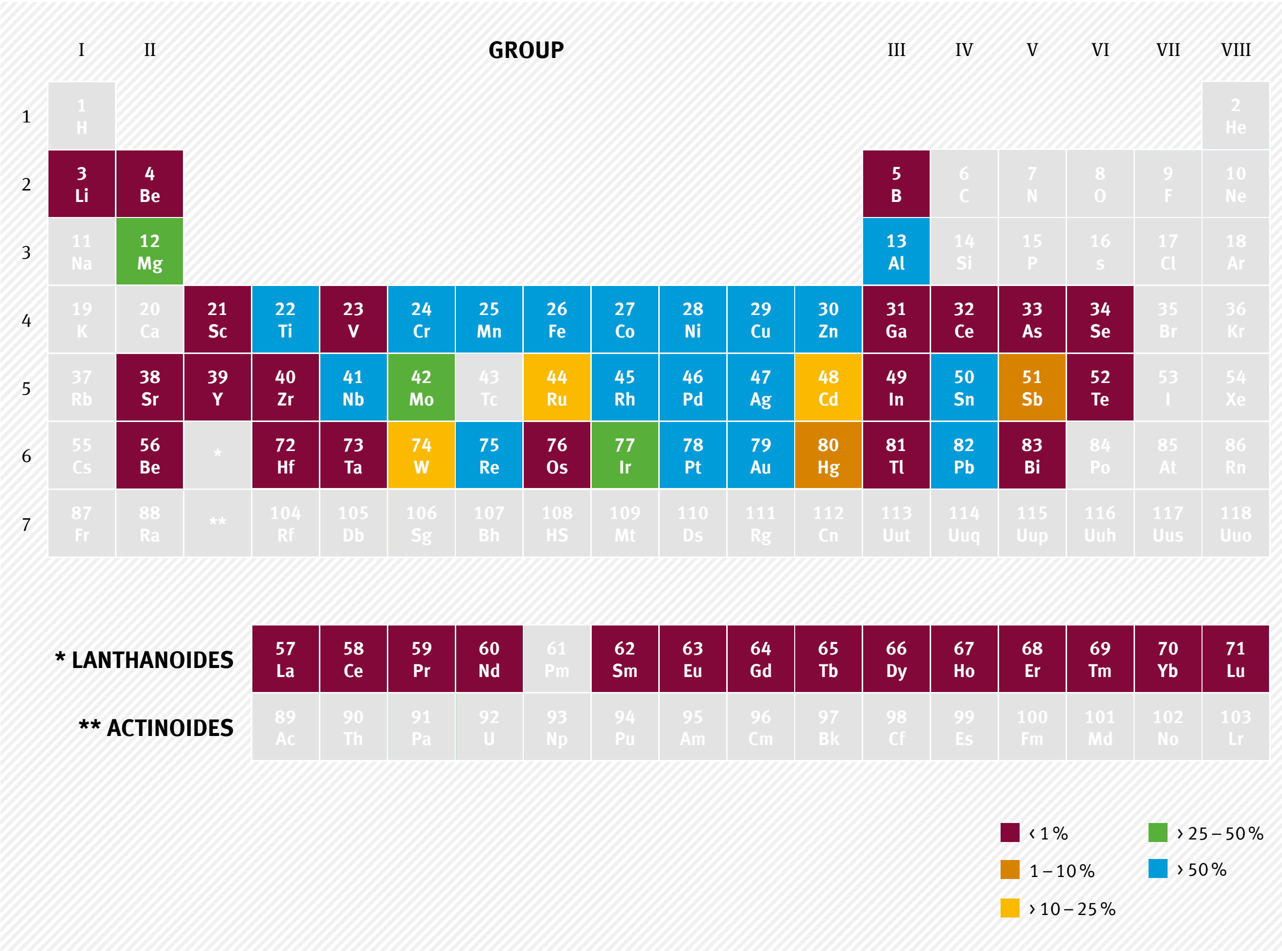
recoverable from used products in Germany in 2020 alone is estimated to be between four and twelve percent of the current annual world production of these metals [59, 60]. These projections do not yet include the quantities of end-of-life vehicles and household electrical and electronic equipment that are expected to increase the total recoverable amount of these metals by another third.

The raw material criticality for many currently critically classified raw materials in Germany and the EU will foreseeably increase in the future. This is because high-growth key technologies alone such as microcapacitors, batteries and fuel cells are predicted to double or even quadruple the demand for raw materials (e.g. tantalum, heavy rare earths and rhenium), in the next 20 years [61]. As a result, these substances are of immense economic strategic recovery interest. In the medium to long term, the raw material base can be expanded through recycling systems, thus mitigating the raw material criticality of many such important raw materials. However, due to the sometimes very low utilisation concentrations of technology metals, there is the danger of a dissipative (i.e. irrecoverable) loss through dispersion in large material flows or the environment.

Even if larger quantities of end-of-life wastes are generated, the recovery and the required concentration, especially of the elements that are currently critical, represent an extraordinary challenge. The recovery of precious and special metals requires new collection and

Figure 15

End-of-life recycling rates on a global average



Source: [58]

logistics concepts as well as treatment processes for the relevant used products. “Pooling” (merging of sector-specific separate waste flows with similar recyclable material contents) must be comprehensively expanded in order to overcome this obstacle. This is another task for Urban Mining in addition to many mass materials from very complex material composites.

^
Systematic knowledge management and targeted planning principles are indispensable.

Potential: from resources to reserves

The management of the anthropogenic stock for the recovery of secondary raw materials from durable products, buildings, infrastructure and depositions can be supported by evaluation methods routinely used in primary mining and other industries. To systematise urban mines, evaluation schemes must be established and backed up with data. The first methodological and exemplary proposals are already available [62, 63].

In primary mining, classifications such as the McKelvey scheme have been developed to link resources and reserves [64]. This scheme also illustrates that availability is not absolute. Both the absolute magnitudes of the geological potential of resources and reserves, as well as their relationships with each other are changing. Increasing exploration activities – driven by future profit expectations – are transforming previously unrecognised geopotentials into resources and reserves. Technological progress also plays a role.

If we consider the Earth's entire crust as the geological potential, then the geological resources are the raw material volumes of all occurrences of economic interest which are demonstrably present or which can be assumed for geological reasons. By contrast, reserves are only those raw material volumes in deposits, i.e. the stocks that are economically recoverable at the current time, at current prices and using existing technologies.

The term "cut-off grade" indicates what the minimum content of recyclable materials must be. The reserve base is currently not yet economically viable but is conceivable in the long-term [65].

An analogy for anthropogenic stocks is obvious. Anthropogenic stocks are also not conclusively determinable. They are by no means all equally explored and, due to different deposit conditions, are not equally well suited for the recovery of materials.

Exploring anthropogenic stocks

Some deposits and occurrences are proven and clearly documented by statistics or cadastres. Others can at least be derived, for example, by extrapolations and projections. Suspected deposits and occurrences may be identified by indirect, more advanced modelling and analogies, for example, using sectoral top-down data on the production of product groups suggesting relevant deposit sizes. After all, part of them cannot be further determined and counted among the unknown stocks derived as balancing items from material flow calculations for example.

Condition and economic viability

From the perspective of a raw material economy, the state of the art in technology and the economic and logistical conditions are decisive for the evaluation of the deposits. The contents of individual substances and their purity and integration into other materials have a significant influence. As a rule, the recovery cost increases with growing dissipation (fine dispersion). For example, the field of application can differentiate whether metals occur in pure form (e.g. precious metals), in alloys (e.g. brass, stainless steel), in complex material composites (e.g. electronic components, circuit boards) and dissipative applications (e.g. pigments in paints) [66]. Although wood and plastics are used much more often in pure form, they involve the use of additives such as flame retardants, biocides and plasticisers, which pose special challenges for recovery.

In evaluating whether the development of the stock is worthwhile, the range extends from the current economic viability to the technical impossibility often present in dissipative uses. In between, there are interesting grey scales: marginally economical and technically feasible, but sub-economic mining. The former – a marginal economic viability – is given if it can be achieved through minor price changes and slight adjustment measures of the framework conditions. The second implies a technically demonstrated feasibility based on ongoing research activities, and still awaits a market-oriented implementation.

Types of anthropogenic stocks

The nature and conditions of the anthropogenic stocks are also of great importance. Essentially, three forms can be distinguished [67]. Most goods of the anthropogenic stock are in use, i.e.

in used deposits and occurrences. A licensed passenger car is just as much part of the used stock as a habitable residential building, furniture, large electrical appliances or a power plant, as long as there is an intention of it being used. It does not matter whether it is the first, multiple or cascade use and the intensity of use is also of no concern.

Unused anthropogenic stocks are to be distinguished. These include goods that are no longer intended to be used, but have not yet been disposed of and, if appropriate, recycled. In most cases, there is no intention of disposing of these goods, which would convert them into waste. Unused anthropogenic stocks include, for example, closed-down railway lines, brownfield sites, underground cable lines and canals that are no longer connected to a network. Stocks of discarded and defective electrical appliances that accumulate in private households – including the widely discussed old "unused and forgotten" mobile phones – can also be considered as a borderline case. However, this allocation is heavily dependent on the value attitude of the owner and the conceivable theoretical reuse.

A third category is anthropogenic depositions. These typically include all above-ground and underground landfill classes – which are relevant for landfill mining. This category also includes mining and smelter heaps, particularly from before high-tech processing, as well as other depositions of industrial waste such as phosphogypsum heaps and red mud lakes from aluminium production.

Classification

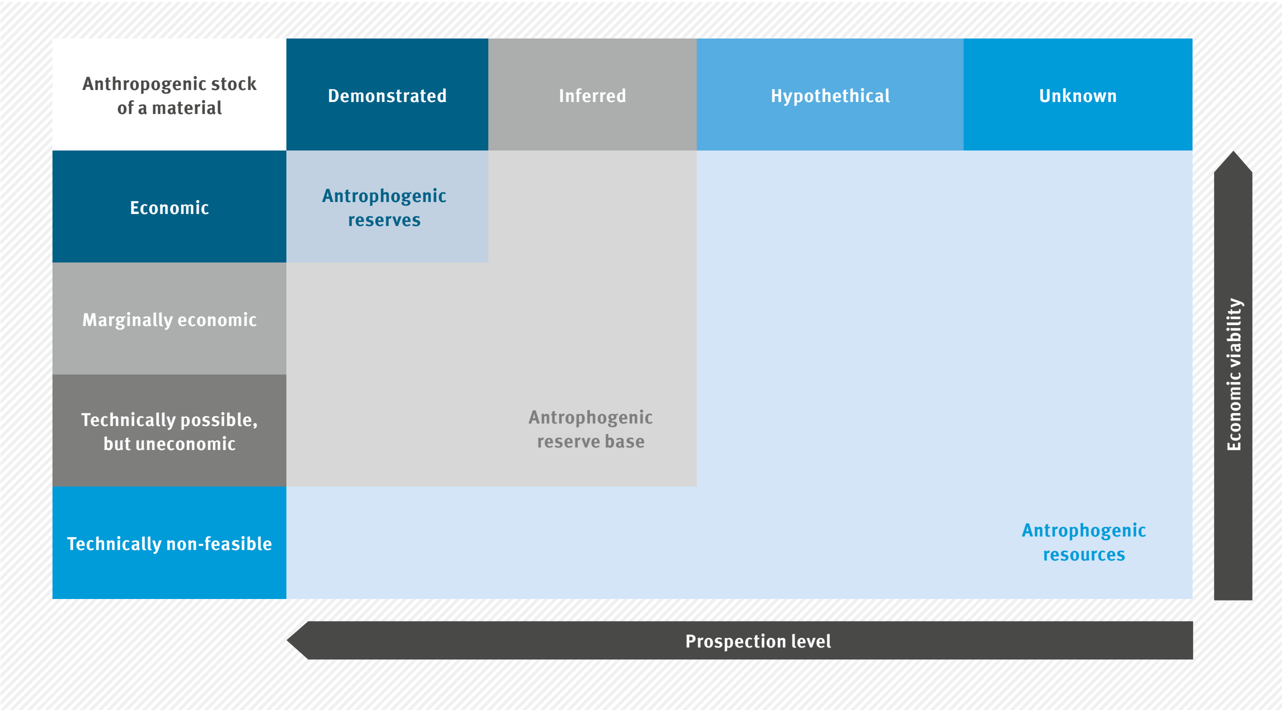
Combining all this information shows the current anthropogenic reserves, the medium- and long-term reserve base as well as the anthropogenic resources at a material level for individual materials in high density (see Figures 16 and 17). Such an illustration shows not only their quantitative ratio with each other, but also compares them to primary deposits, which can be very important for resource strategies.

Behind the classification into the various segments there is an anthropogenic cut-off grade too, which provides information on the required minimum substance concentration in order to recover a substance under given technical possibilities and to concentrate it to form the usable raw material.

Theoretically, however, an ecological cut-off grade can also be identified, which points out which recovery efforts would still be justified in relation to primary mining so as not to generate any additional negative environmental impacts and thus conserve natural resources [69]. The room for manoeuvre is enormous, as shown by the example of aluminium (see p.24). However, the absence of downcycling is a prerequisite. This is because downcycling necessitates the subsequent use of additional primary materials, which clearly worsens this straightforward balance.

Figure 16

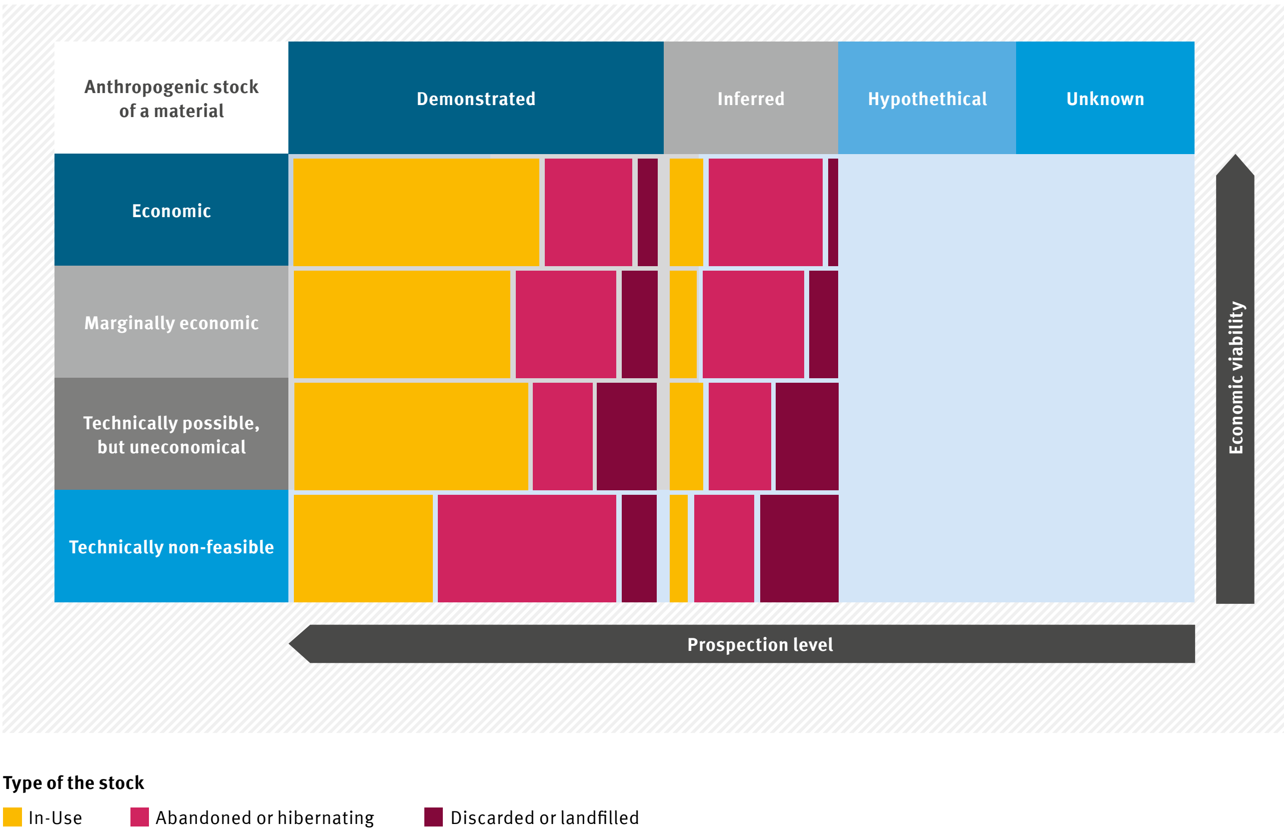
Classification of anthropogenic stocks



UBA's own representation

Figure 17

Classification of anthropogenic stocks by their type



UBA's own representation

Case study – secondary zinc materials in Germany

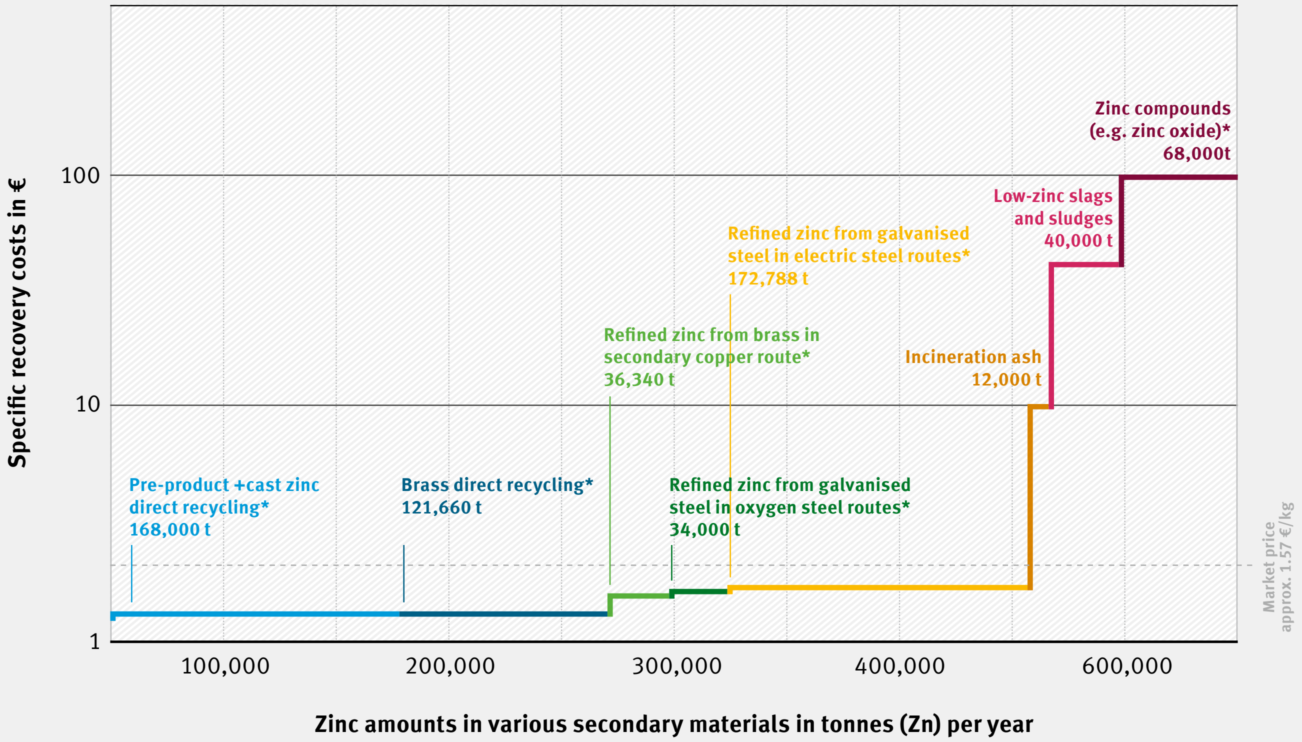
Germany has various secondary materials containing zinc, which can be processed and recycled in different processes. These occur in both used and unused stocks, as well as in anthropogenic depositions. Depending on the technical, logistical and energetic effort, there are different costs for the recovery of the metallic zinc. Figure 18 provides a schematic overview of the quantities of zinc found in Germany in selected secondary materials as well as the respective specific processing costs for the recovery of metallic zinc. Goods made of zinc, brass and galvanised steel products as well as some zinc-rich residues can be classified as anthropogenic reserves.

Direct re-melting of metallic zinc or brass scrap is the least expensive. Part of the occurring brass scrap is recycled through the secondary copper route because of its high copper content of over 55 percent where zinc is first oxidised. Further processing usually occurs in hydrometallurgical zinc refining, which uses an electrolytic process that produces fine zinc. Although this processing is more expensive than direct re-melting, it nevertheless enables the separate recovery of both copper and zinc.

Recycling of zinc from galvanised steel is as expensive as the recycling of zinc in the secondary copper route. In steel recycling, zinc is separated in oxidised form in steelworks dusts. Subsequently, it is upgraded pyrometallurgically and later electrolytically reduced to refined zinc in the hydrometallurgical route.

Figure 18

Zinc amounts in selected secondary materials occurring in Germany and their average production costs



Amounts marked with * are based on the main consumption in Germany in 2014

UBA's own representation according to [68, 106]

Some zinc-containing residues such as ash and sludge with higher zinc contents can also be directly processed pyro- or hydrometallurgically into zinc compounds.

Regardless of the chosen process route, the cost of recycling zinc and brass scrap and zinc-containing steelwork dusts is below the market price for zinc of approximately 1.57 euros per kilogramme[a], which enables the economical processing of these secondary materials.

On the other hand, low zinc ashes, slags and sludges[b] are attributable to parts of the reserve base and above all to anthropogenic resources. Although these have a high prospection level – the zinc contents are predominantly known or can be reliably derived – technical and economic restrictions on recovery do not allow recycling in most cases.

While it is technically possible to extract zinc from incinerator ash (e.g. FLUREC process [68]), it is currently not economically viable due to the high processing costs.

The recycling of metallic zinc from zinc compounds such as zinc oxide is in many cases uneconomic for energetic reasons or due to the dissipative distribution (e.g. in cosmetics, pigments, etc.). In addition, there is a lower prospection level, which means that these are also relatively undetermined anthropogenic resources. Zinc contents are not only far below an economic cut-off grade – recycling also lacks an ecological motivation to conserve resources since the required upgrading and reduction requires a disproportionate amount of energy.

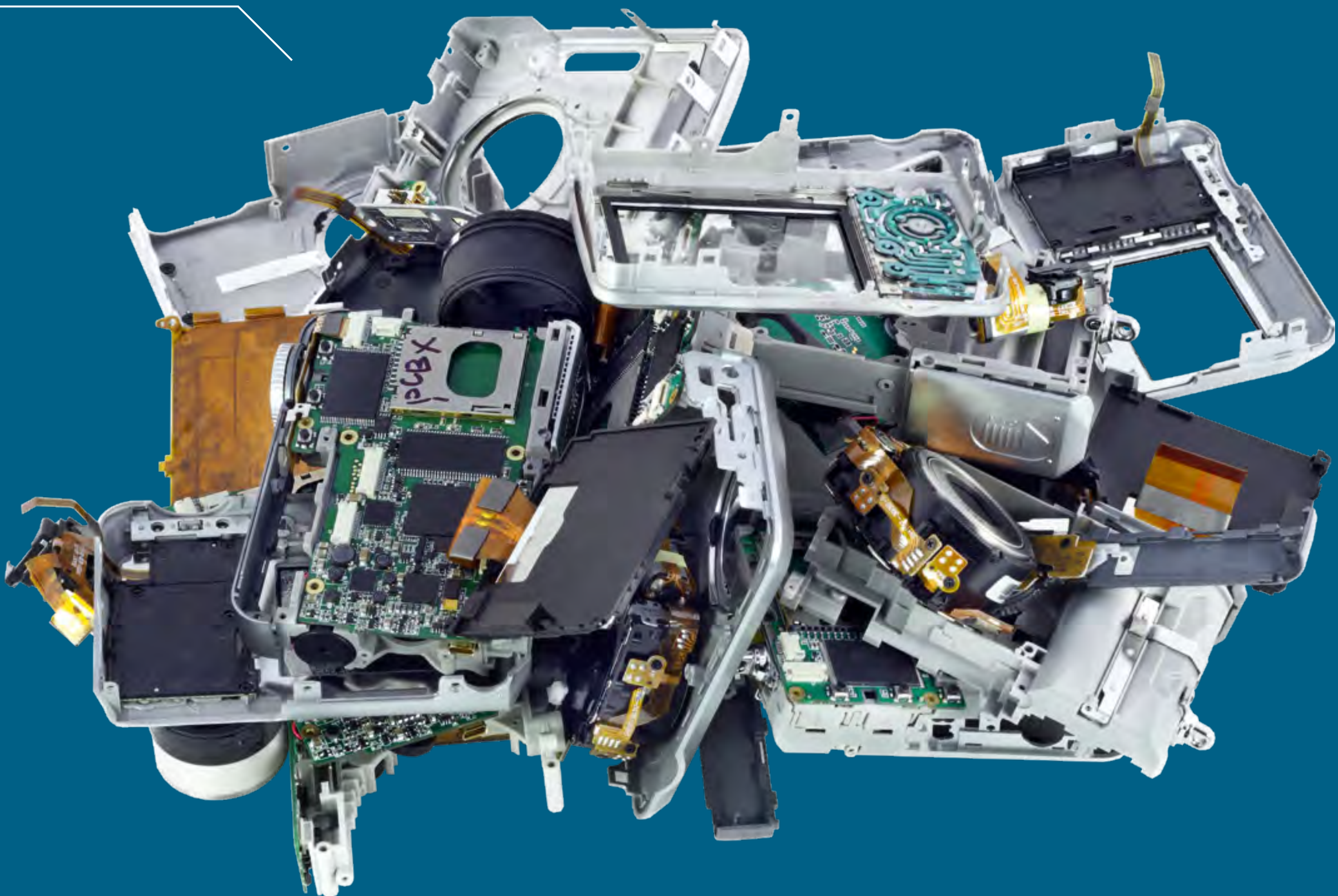
Galvanised steel sheets provide good corrosion protection. In recycling, zinc must be separated and concentrated. Innovative hydrometallurgical processes lead to improved yields.

a 2011 – 2016 average (http://www.finanzen.net/rohstoffe/zinkpreis)
b e.g. residues from hydrometallurgical zinc refining, residues from the processing of zinc-containing steelwork dusts

04

KEY QUESTIONS

How can recycling this electronic scrap also recover non-precious critical raw materials in the future?



The comparison between Urban Mining and conventional mining has already highlighted the strengths of Urban Mining in extracting secondary raw materials and in conserving primary resources. It has also become clear that a multitude of requirements have to be fulfilled so that Urban Mining can meet the challenges of a sustainable, resource-saving development. In order to strategically develop the potential of Urban Mining, five key questions need to be answered:

1. **Where are the stocks?**
2. **Which goods and materials are contained and in what amount?**
3. **When do the stocks become available for raw material extraction?**
4. **Who participates in the extraction?**
5. **How can material cycles be closed effectively?**

Where?

The first question is aimed at prospecting, meaning finding and identifying durable goods and their stocks. Some of these stocks and goods are universally visible, but they are rarely collected systematically. In buildings, infrastructure, mobile goods and heaps, it is necessary to subdivide and differentiate the partial stocks into used and unused stocks and depositions. Systematic collection methods must now be developed for this purpose since our goods are being collected vicariously through financial flows as long as they have a positive market value. For Urban Mining, however, goods become particularly significant when their utility value in the consumption sphere trends to zero. However, at this point their trace has mostly been lost in the stock, which is why they are inventoried very poorly and their whereabouts are unknown.

How much?

Even if the stocks have been identified, their exact condition is still unknown. Many of our goods have been processed to a high degree and have undergone a multitude of refinement, processing and transformation processes. There are also technological developments that lead to the introduction of new materials within a short time.

The information about the amounts and type of recyclable materials and pollutants in certain goods are lost in many cases during production and are thus hard to identify. So far, the content of this “Black Box” had to be painstakingly reconstructed from the end of the value chain, when the goods become waste after several years of use. This is why it is important to establish a material flow management from the moment materials are used. The market value of goods as an indicator is only of limited use. While a high market value goes hand in hand with a better inventory, it does not reveal much about the specific material quality or even the material value, which are very important for Urban Mining. For example, a desktop computer from the late ’90s is no longer being used, but it has a much higher material value than one from 2018.

When?

The question of when urban stocks are available as secondary raw material sources is far more difficult to answer for durable goods than for non-durable ones but is nevertheless of great interest to the raw materials industry.

The average lifetime and service life vary between a few years for electrical appliances, ten to fifteen years for automobiles and 30 to 80 years

^
Change of perspective: looking at the image, do you still see Frankfurt am Main or do you classify the stocks with the eyes of an urban miner and determine material stocks and retention times?

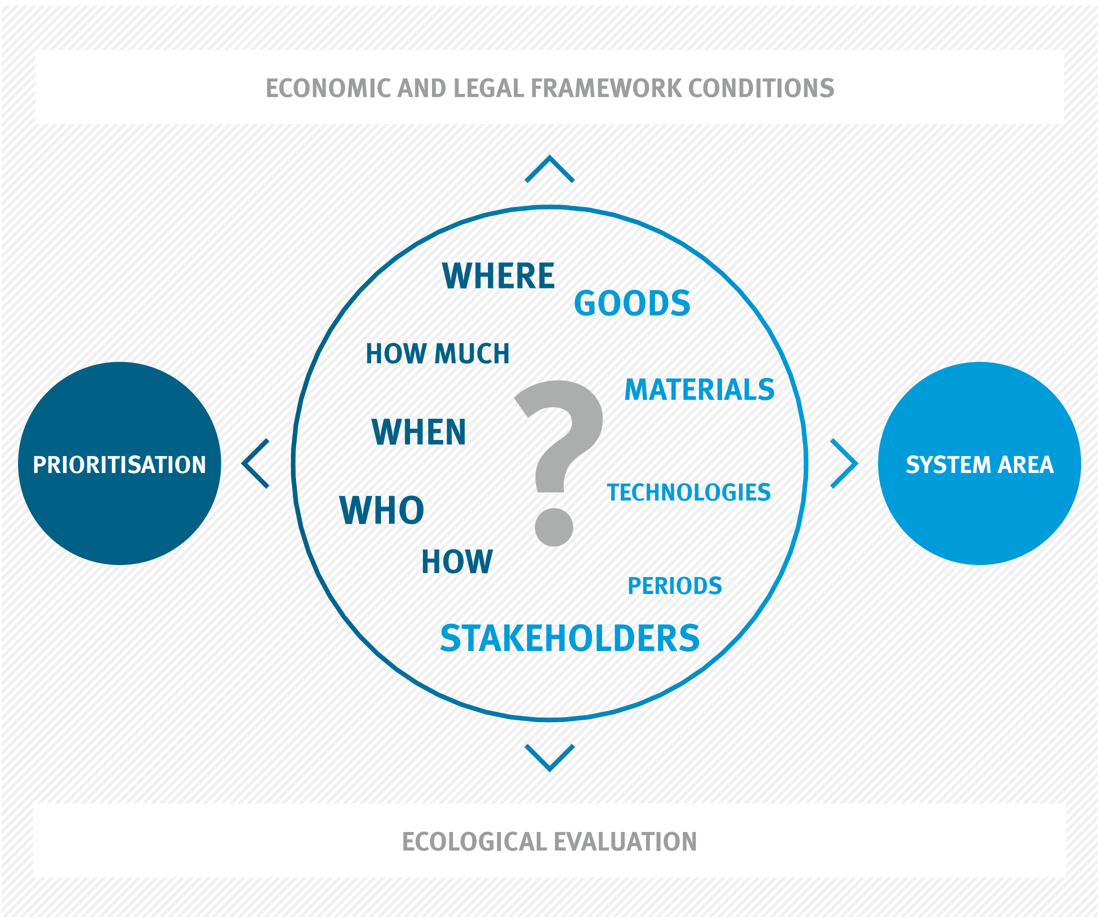
for buildings. There are also very different retention time distributions due to different forms of use, such as a cascade use. The challenge is to capture and understand these dynamics, both in terms of current stocks and their prospective growth.

Who?

Exploiting urban stocks with the aim of high-quality functional recycling with the lowest possible quality constraints requires systemic thinking. This must involve a large number of stakeholders. The question of who owns a stock's goods and who owned them in the course of cascade uses or at the end of the life cycle is important. Stakeholders involved along the chain (e.g. waste producers, collectors, traders, recyclers, processors, producers) are rarely vertically integrated and have very different interests and incentives that help them make their decisions.

How?

Achieving a spatial, material and temporal forecast accuracy of secondary raw material sources is necessary, but not sufficient, to close material cycles. The recovery of raw materials must maintain the materials in their existing functionality as far as possible in a material cycle – drainage into other material cycles and waste discharge should be reduced. In order to ultimately fulfil the potential of Urban Mining, the technical, logistical and organisational prerequisites must be met. Are there adequate processing technologies available for concentrating recyclable materials and removal of contaminants? Have quality requirements been regulated in a binding manner and have political framework conditions been created for high-quality, ecological recycling solutions? Has the demand side been sensitised? This is a key to the market-driven procurement of secondary raw materials whose transaction requires a high level of reliability in terms of quantity, quality, location and timing.


ECONOMIC AND LEGAL FRAMEWORK CONDITIONS
WHERE
GOODS
HOW MUCH
MATERIALS
WHEN
?
TECHNOLOGIES
WHO
HOW
PERIODS
STAKEHOLDERS
PRIORITISATION
SYSTEM AREA
ECOLOGICAL EVALUATION

05

A success factor in Urban Mining: the right separation, extraction and processing of different material fractions.

PAVING THE WAY – ACTIVITIES AND MEASURES

The first steps have already been taken at various levels to answer the five key questions. A conceptual example is the mapping of the entire anthropogenic stock in detail for individual groups of goods and materials. A variety of initiatives have been launched to expand the knowledge of the anthropogenic stock and to create bases for action, from research projects to regional and sectoral Urban Mining concepts and economically viable business models.

These individual initiatives and the methods developed as part of them can have a beacon effect and act as a model for the exploitation of other materials in the anthropogenic stock. Urban Mining e. V. already provides an active platform for the exchange of experience in Germany [70]. Paving the way for Urban Mining requires tools and measures from very different disciplines, which must be further developed and put into context.

Research – setting the right emphasis

The research focuses on mass flows. The funding initiative of the Federal Ministry for Education and Research – "'r3' Innovative Technologies for Resource Efficiency -Strategic Metals and Minerals" – has sponsored a variety of projects focusing on the recycling and the recovery of critical metals in the Urban Mining thematic cluster. Among them were several projects (SMSB, REStrateGIS, ROBEHA) for exploration of mining and smeltery heaps [71]. According to estimates, the Harz Mountains alone, as one of the major ore reserves in Germany for non-ferrous and precious metals, host more than 1,000 heaps. With the help of remote sensing data, on-site sampling and geochemical analysis, heap cadastres are being developed and the recyclable materials determined. In addition to economic viability considerations of recycling the deposited waste rock, slags, dusts, sludges or even refractory materials and overburden heaps for their metal content in hydro- and pyrometallurgical processes, the legal framework conditions for the approval of such explorations are also examined.

Prospecting in settlement areas was also advanced. The recycling potential of brownfield sites and commercial buildings was determined headed by the Technical University of Darmstadt with financial aid from the "r3" funding measure (PRRIG). The initiative involved the empirical recording of raw material inventories and parameters in the Rhine-Main area and the elaboration of raw material cadastres. Methodological foundations and tools were also developed which enable the targeted recovery of metals from the demolition of industrial and commercial buildings in the future [71].

Similar activities are taking place for the city of Vienna. The Christian Doppler Laboratory for Anthropogenic Resources (hosted by TU Wien) prospects the materials of the Viennese building stock in order to evaluate its future resource potential [72]. Therefore the composition of single buildings prior their demolition is determined. Besides onsite investigations, wrecking companies data as well as construction plans are collected and evaluated. The material data is subsequently combined with remote sensing techniques in order to assess the current generation rate of construction and demolition waste and its respective resource potential.

However, the focus does not lie solely on the large mass flows. Improving the recycling of special metals from electrical and electronic equipment (EEE) was the goal of the r3-Project UPgrade, carried out under the direction of the Berlin Institute of Technology, with the participation of the Münster University of Applied Sciences and many other project partners.

The process carried out experimental material flow analyses of selected processing and treatment processes along the recycling chain [71]. This aims to be the foundation for the development of new purification processes that target the up to now insufficiently recovered metals such as germanium, tantalum, antimony or rare earths. Similar objectives were pursued in the UFOPLAN research projects ReStra [59] and RePro [60]. A project-specific procedure for electrical appliances and other industrial goods was used in these projects to investigate the quantities of selected critical metals that are expected to become waste in 2020. This helped illustrate how product stewardship can be improved through the collection, processing and recovery of waste flows.

The large European research project ProSUM was primarily focused on data preparation and provision. A centralised database of all available data and information on arisings, stocks, flows and treatment of waste electrical and electronic equipment, end-of-life vehicles, batteries and mining wastes was developed. The project also provided data for improving the management of these wastes and enhancing the resource efficiency of collection, treatment and recycling. The developed Urban Mining Knowledge Platform will be continued via the new integrated project ORAMA [108].

The systematic research series for mapping the entire anthropogenic stock – carried out on behalf of the German Environment Agency – (see box) and the Project Mining the European Anthroposphere (MINEA) have a conceptual nature [73]. MINEA is a pan-European expert network with members from more than 30 countries [73]. MINEA cooperates closely with the United Nations Economic Commission for Europe (UNECE) and will publish a global standard for the classification of resources that arise from anthropogenic sources such as mine tailings, incineration residues, buildings and consumer goods. This new standard enables effective management of material recovery projects, from the exploration to the production phase, and was released in 2018.

In focus – exploiting and processing construction waste

Construction waste is a particular focus of Urban Mining. Construction waste accounts for around 60 percent of the total volume at an annual volume of approximately 200 million tonnes in Germany and is the largest waste fraction. It mainly includes demolition waste, road construction waste, construction site waste as well as soil and stones. At around 90 percent, the recovery rates for all of this waste are currently very high. Only a very small proportion is landfilled, the majority is processed and used in other ways. However, a closer look at the recovery routes shows that actual recycling is barely practiced. Of the approximately 52 million tonnes of annual demolition waste, predominantly from building construction, only a fraction is processed into high-quality concrete aggregates and other building materials that are re-used in building construction. However, about 30 million tonnes are used in road construction in the form of recyclate, but not predominantly in narrowly defined applications such as frost layer and base course. Most of the aggregate obtained from demolition waste is used for low-quality close-to-ground purposes, for example in landscape and path construction or as a balancing material. In addition, a significant proportion of demolition waste enters the backfilling and reclamation of quarries, gravel pits, disused opencast mines and spoil heaps [78]. There are two reasons why this is problematic for the future.

1. *Construction waste will increase significantly.* In light of the demographic development, persistent migration and shrinkage in many East German and in some West German municipalities, and a foreseeable change in the housing needs of the German population, demolition and rehabilitation will lead to significantly higher quantities of demolition waste. Great changes will take place in the building sector. At present, three tonnes of material used in building construction generate only one tonne of waste. It is estimated that by 2050, the amount of demolition waste that will flow from the residential building stock throughout Germany will be far greater (approximately one and a half times

“Mapping the anthropogenic stock”

The research series “Mapping the anthropogenic stock” commissioned by the German Environment Agency pursues the goal of systematically improving the knowledge and decision-making basis for the secondary raw material industry in order to establish Urban Mining from durable goods. These are the key questions:

- **What proportions of the newly introduced materials and stock as a whole will be available as secondary raw material sources in the future?**
- **When and in what spatial distribution is this likely to occur?**
- **Are the technical, logistical and legal framework conditions adequate for high-quality recovery and is there a sufficiently high demand in the intended areas of application?**

A modular approach was chosen, which ranges from condition assessment – the status quo – to forecasting future developments and the possibilities of active material flow management. So far, the approach has made a systematic estimation of the size and composition of the current anthropogenic raw material stock as well as an analysis of data sources and parameters to capture the dynamics [31, 49, 74]. This formed the foundation for developing an updatable stock model for the entire Federal Republic of Germany. A system called DyMAS (Dynamic Modelling of Anthropogenic Stocks) was programmed for this purpose, which is used for material and commodity level scenario analysis and forecasting to determine what fraction of the annually newly introduced materials and stock will be available as a secondary raw material source in the future [75, 76]. Through the connected database and a standardised data exchange format, the system serves as a knowledge store for goods, materials, inventories, lifetimes etc.

Above all, Urban Mining requires integrative knowledge and information management and the involvement of practitioners and relevant stakeholders. For this reason, another project of the research series makes use of the DyMAS system and addresses the existing technical, informational, logistical, organisational and legal barriers to mineral construction and demolition waste as well as base and special metals, which currently hamper a qualitative closure of material cycles [77]. The requirements raised from producers’ standpoints for secondary materials and for the removal of contaminants and impurities from them are discussed in the course of dialogue forums with all stakeholders involved in the recycling chain. Also, quality and purity standards for the respective secondary building materials and secondary metals/alloys are developed.

In addition, the most recent project of the research series introduces a material passport for buildings and a building cadastre concept for regionally registering the material budget. This creates the planning basis for an effective, regional material flow management which will be validated together with practical partners.

more) than the amount being newly used in them [79]. In the long term, the building stock will become a net raw material source.

2. *The possible recovery paths will change.*
It can be assumed that the current preferred recovery routes will be saturated in a regional manner, for example in landfills and road and path construction. Their reception capacity will become a limiting factor. The high installation for upgrading roads outside the cities that has been hitherto practiced due to cost reasons has physical and technological limits, which means that demolition waste masses resulting from civil engineering will also increase. In addition, there are increased ecological quality requirements nationwide for replacement building materials. The Umbrella Ordinance (see Box, p. 52) closes a previous legal gap and provides better regulation for the protection of soil and groundwater in the areas of use, for example, in landscaping and earthworks as well as in fillings. In this context, the German Building Industry Association has already detected disposal bottlenecks and the need for additional landfill space [80]. In order to recover the secondary raw materials extracted from construction waste masses in the future and to thus protect primary raw materials and landfill space, further areas of high-quality application, particularly in building construction, must be developed. This will very likely lead to a slight reduction in the current high recovery rates, since quality assurance requires the removal of large quantities of pollutants and fine-grained fractions that have not been separated in previous recovery practices.

Urban Mining will have to face the two challenges of managing the increasing construction waste mass and establishing new, resource-efficient recovery routes. Approaches to quality assurance, to the discharge of pollutants and to material passports can make important contributions towards overcoming these issues and will be discussed in more detail below.

Umbrella Ordinance

The Umbrella Ordinance (MantelV) provides for a harmonisation of material standards for water, soil protection and waste legislation. It combines an amended Groundwater Ordinance (GrwV), an amended Federal Soil Protection and Contaminated Sites Ordinance (BBodSchV), an amended Landfill Ordinance (DepV) and a new Substitute Building Materials Ordinance (EBV). The Umbrella Ordinance enables a nationwide uniform regulation of the requirements for the production and harmless use of mineral substitute building materials as well as the application and incorporation of soil material in accordance with the requirements of soil and groundwater protection. The aim is to facilitate the conservation of natural resources through the highest possible recovery rates for mineral substitute building materials in the sense of a circular economy, and to create legal certainty through nationwide uniform requirements for the introduction of substances into groundwater, the construction of technical structures and backfilling. The following premise applies: humans and the environment, particularly soil and groundwater, should be protected against pollutants as a precaution when using mineral substitute building materials.

The regulation of quality standards and installation classes in the Umbrella Ordinance has considerable effects on Urban Mining and the framework conditions for material flow management. Regarding the five key strategic questions mentioned above, the Umbrella Ordinance is one of the economic and legal framework conditions.

Quality assured recycled building materials

In principle, high-quality recycling aggregates can be extracted from demolition waste and can be re-used as a concrete aggregate in building and civil engineering. Such aggregates have analogous structural properties to gravels and crushed stone from their natural sources and can protect these valuable raw material occurrences. By 2020, high-quality recycling of mineral demolition waste in Germany could directly substitute a quarter of the total aggregates for in-situ concrete, precast concrete and concrete products in building construction (eleven million tonnes) [81]. Moreover, this estimate already takes into account regional disparities, meaning shortage and surplus regions. Building material supply chains for mass building materials – whether from primary or secondary materials – are viable only economically within narrow spatial limits. By the year 2050, construction activity will likely decrease throughout Germany and it would be possible to increase the maximum technical aggregate potential for new construction and renovation from demolition waste by means of suitable collection, processing and pollutant removal.

Recycled concrete is still seldom used in Germany, although standardisation works such as DIN 10945/EN 206-1 and DIN 4226-100/EN 12610 regulate all constructional requirements for an increased use of recycled materials in concrete. The number of successful pilot projects is steadily rising, especially in Rhineland-Palatinate, Baden-Württemberg and Berlin, scientifically supported in some cases by the Brandenburg Technical University of Cottbus [82]. The Canton of Zurich is a model region where pilot projects have been successful. However, the situation is different in construction practice. The processing of mineral construction waste according to its technical and physical suitability for high-quality applications widely lacks acceptance and thus demand from clients. Consequently, the logistical and technical efforts are made in a very low-budget manner, and the produced recycling building materials are only primarily approved for simple applications [78]. The public sector can undoubtedly increase demand at all levels because it is the largest client in Germany. The German Environment Agency is striving to live up to its role in the field of sustainable construction. For example, UBA's extension building at the Dessau-Roßlau headquarters, which is scheduled to be completed in 2019 intends to use recycled concrete in addition to other environmentally friendly building materials. A first step was taken with the adaptation of the procurement criteria for official buildings [83]. Finally, a neutral tendering practice and a non-discrimination principle for the use of mineral recyclates at state (Länder) and municipal levels must be established and practiced.

However, producing quality-assured mineral recyclates to a far greater extent than thus far requires an early start. This can be supported by the consistent separate collection of demolition waste. In this context, UBA advocated the inclusion of a mandatory separate collection of construction and demolition waste, for example for insulation materials, gypsum-containing waste, ceramics and bricks, in the Commercial Waste Ordinance (GewAbfV) as part of its last amendment in 2017. In order to adequately eliminate impurities and pollutants, particularly sulphates from gypsum-containing interior structures, it is necessary to start with selective dismantling as directly as possible during demolition measures. Model projects demonstrated that an elimination of prior pollutants through selective on-site measures can reduce the environmental impacts of the recovery of recycled aggregates from old concrete. This not only minimises energy-intensive and possibly high wastewater usage subsequent sorting processes, but also fulfils the highest quality criteria [84].

In the meantime, processing reveals completely new technological possibilities for detection and utilization, which become very important for Urban Mining. The selective separation, sorting and homogenisation of the individual demolition waste fractions such as concretes, bricks, sand-lime bricks or aerated concrete are technologically very demanding, despite selective dismantling and require processes such as near-infrared technology for detection – previously used mainly in plastics and paper recycling. However, material recycling

Materials for new, high-quality recycled products: lightweight granulates can be produced from difficult-to-process masonry fractions for numerous new applications.

does not have to be the only recovery strategy. Another promising option is the raw material use of the demolition material, which creates completely new materials suited for high-quality applications. Thanks to many years of research at the Bauhaus University of Weimar, versatile light granules can be produced from masonry rubble [85]. Around ten million tonnes of masonry rubble occur in Germany per year. However, it is considered to be difficult to recover because of its heterogeneity and the high proportion of fines in the processing. The new recycling product builds on the chemical-physical, highly diverse composition of masonry rubble. This is classified, ground and thermally hardened with a blowing agent. The light granules produced can be used in the same characteristics as expanded clay from primary raw materials and thus contribute directly to resource conservation. They can be used in high-quality steel and lightweight construction concrete as well as for lightweight concrete blocks [86].

Remove pollutants

An intelligent combination of selective dismantling, separation of construction waste and modern processing technologies is indispensable for achieving high-quality recycled Urban Mining

products. Extraction of valuable substances and removal of pollutants are equally important to avoid risks to human health and the environment.

Professional pollutant analysis in buildings can help remove pollutant-containing fractions during demolition and subsequently dispose of them properly. This can prevent an accumulation of pollutants in recyclates as much as possible.

Pollutants can be found in many building products, e.g. in floor coverings, plasters, sealing membranes, wood panels, piping, thermal insulation or paints (see Table 2, p. 57). In most cases, these products or additives met the legal standards in the past but are now prohibited or at least no longer used. For instance, lead pipes in drinking water networks, roofing membranes heavily contaminated with polycyclic aromatic hydrocarbons (PAH) from coal-tar oils, PCB-containing sealants, brominated flame retardants, asbestos in floor tiles, panels, plasters and fillings, arsenic and cadmium as rust protection or as pigments or stabilisers in paints, lacquers and plastics, heavy metal-containing slags in concrete, carcinogenic short-fibre artificial mineral fibres in thermal insulation, PCP- and/or lindane (HCH)-containing insecticides as wood preservatives, plasticizers like phthalates in floor coverings [87]. In nearly all cases these substances were used intentionally.

Since the harmful risks were recognised, the following limiting values and substance prohibitions slowed down or even stopped further accumulation in the anthropogenic building stock. However, the majority of the pollutants still remain in the building stock due to the long service life of buildings.

Contaminated materials from demolition must sometimes be classified as hazardous waste and therefore subjected to special documentation, transport and treatment requirements pursuant to the German Circular Economy Act (KrWG). Contaminated sites are therefore also part of the anthropogenic stock's legacy to be handled very carefully in the future.

However, there are also new material problems such as biocides and persistent organic pollutants. Substances such as biocides are still deliberately used on a large scale against biodegradation, damage by gnawing, plant cover or weathering. Unfortunately, risks to humans and the environment can often only be detected after several years of using these substances. The European regulation for biocidal products (No. 528/2012) has been introduced to achieve improvement in this respect.

Persistent organic pollutants are also assumed to cause or to be likely to cause harmful impacts. Intensive energy restoration measures have taken place in existing buildings for nearly 40 years to save energy in the building sector. Among insulating materials, mineral oil-based insulating materials have experienced a significant increase. Almost 300,000 tonnes of polystyrene-based insulating materials (XPS and EPS) are installed annually. The flame retardant HBCD (hexabromocyclododecane) has been used for decades in PS-based insulating materials to meet the high flame protection requirements on façades and roofs. Since 2013, this substance has been declared in the Stockholm Convention, an international agreement to end or restrict the production, use and release of organic pollutants, as a persistent, i.e. environmentally hard to degrade, and bioaccumulating organic pollutant (POP). Because of these characteristics, HBCD is also classified as a “substance of very high concern” according to European Chemicals Regulation REACH criteria. As a result, more environmentally friendly flame retardants have been introduced since March 2016 [88] when the HBCD prohibition entered into force, with some exceptions for certain EPS insulating materials until February 2018. For the recovery of insulating materials, which will only emerge in large quantities in the coming decades, this means that HBCD must be removed in any case. Conventionally, this is only possible using thermal treatment, e.g. incineration, where HBCD is completely decomposed and the bromine content is precipitated in a form of less problematic salts.

But recycling is not entirely ruled out for the future. The so-called “CreaSolv” process uses a solvent to liquefy polystyrenes. Subsequently, additives such as flame retardants can be separated from the polystyrene, which can then be used again to produce composite thermal insulation systems [89].

^
Composite thermal insulation systems can effectively reduce heating costs and thus emissions of greenhouse gases. However, special requirements apply to their harmless disposal.

HBCD removal includes styrene-based insulation materials installed prior to 2015. However, a separate analysis needed to distinguish them from newer thermal insulation systems and a separate collection is logistically difficult. There are similar recycling barriers for other insulating materials such as artificial mineral fibres and many other building products such as treated timber: wastes of certain building age classes or installation types may contain contaminants. Since no information is usually available about the exact origin and formulations in demolition practice, energetic recovery or disposal is the obvious choice for these high-calorific waste flows [90].

Material passports as a future-proof source of information

In order to support high-quality recycling in the future, the necessary data and information on structures must be available before any rebuilding, dismantling or demolition is due. A material passport for buildings, which, in addition to the energy performance certificate, also contains a material inventory, can be a suitable instrument for individual objects.

It is necessary to have a building documentation that records the material inventory in a structured way throughout the building's life cycle. The quantities, qualities and the location of construction materials in the building, are very useful data. Documentation of the installation methods is just as important to make the building more suitable for recycling. Ideally, this should also include separation and selective dismantling techniques, for example for bolted composite thermal insulation systems, as well as state-of-the-art recycling requirements from the time of installation. The extent that materials can be recycled decades later should be determined during the planning and building stages. However, there is a problem since conventional building planning makes creating a full record of the materials used a labour-intensive thus expensive task. Integral planning may offer a remedy by collecting information from the individual parties (client, planner, construction company, etc.) [87].

However, buildings can significantly change during their useful life due to renovations, extensions and rebuilding as well as refurbishing building services. An update of the material passport is an important requirement to ensure continuity even for ownership changes during the building life cycle.

The idea of a material passport is by no means new. Material passports for buildings have served to record the stock of federal buildings in Germany for about 15 years. They contain concise building parameters and operating instructions as well as records of the building history – key information for rebuilding and dismantling [91]. Such recording incentives have scarcely existed for private and commercial clients and owners so far [92]. Subsequent mapping of existing buildings is accompanied by a considerable effort and site inspections taking place at the time of a rebuilding or necessary demolition.

Nationwide application of material passports can generate systemic benefits over the long term. If all new buildings were recorded using material passports from now on, almost a quarter of all residential buildings would be mapped by 2050. Applying material passports to engineering structures and infrastructures, entire settlements could be mapped in material cadastres. Electronic management would enable an evaluation of very differentiated building and structure typologies as well as their building

Table 2

Pollutants in building materials

Pollutant	Occurrence
Formaldehyde	Chipboard, furniture, windows, lacquers, wallpaper and adhesives
Pentachlorophenol (PCP), Lindane	Wood preservatives, sealants, trowelling and sealing compounds, paints and cleaners
Asbestos	Fire, thermal, heat, sound and moisture protection (mainly in buildings from 1950 – 1980)
Synthetic mineral fibres (SMF)	Thermal insulation, footfall sound insulation on floors, sound absorbers on walls, fillers in plaster, doors, heating and installation pipes, lightweight walls
Polychlorinated biphenyls (PCB)	Elastic sealants, cable sheathings, sealing compounds, lacquers, paints, cooling insulating liquid in transformers, capacitors, fluorescent lamps
Polycyclic aromatic hydrocarbons (PAH)	Coal tar, pitch and tar oil, floor tiles and adhesives, gaskets, roofing membranes, sealing and trowelling compounds, lacquers
Heavy metals Zinc, lead, nickel, cadmium, copper etc.	Depositions in industrial plants, in the soil and discharge into groundwater

age classes. Dismantling experiences and practices as well as new recycling technologies for material groups contained could also be linked. Dismantling and secondary raw material management may generate new economies of scale and learning curve effects. The amounts of reusable components and the potential of recycled building materials could be attributed to the building industry, municipalities and traders in a regionalised fashion.

Last but not least, electronic material passports may significantly improve the ecological performance assessment of buildings. Of course, it would be possible to record resource use for all building products used – including rebuilding and rehabilitation cycles. Alternatively, realistic recovery scenarios may complement recovery effects that are only partly mapped in building product life cycle assessments.

Increase recycling efficiency – prevent downcycling

The success of the circular economy can be measured by the ability to reduce the outflows from a material cycle into other material cycles and to reduce the separation of materials as waste in final sinks or partly dissipative emissions [50].

As a strategic approach to material flow management, Urban Mining can contribute to unlocking the resource saving potential of the circular economy using intelligent logistics and technology. Base metals such as steel, copper and aluminium are a group of materials where urban mining should not expect major initial challenges. As they are predominantly used in their metallic form, their material can theoretically be recycled in melting processes without any limits or quality loss. This makes them significantly different to materials used in their molecular form such as plastics, paper and wood-based materials. Most plastics age due to the influence of light and chemicals during their use phase. They are sensitive to contamination and mixing during recycling. Even heating thermoplastics to re-melt them can be a problem for material recycling when quality is expected to be maintained. Plant fibres in paper and textiles, for instance, experience a reduction of fibre lengths when recycled, which leads to loss of functionality. Mineral and ceramic materials as well as wood are difficult to recycle at the same level of quality because they are form-bound and non-formable [93]. Technical recovery therefore changes them considerably since they usually go through a cascade use accompanied by downcycling.

High market value of metals is a beneficial property. The incentive to regain that as fully as possible, is accordingly sizeable. So large that criminals sometimes pre-empt Urban Mining. Metal theft, not just from junkyards but from goods still being used, is a serious problem. Thieves are especially keen to get hold of copper – whether pure or as brass and bronze. Their "victims" include signalling and catenary cables in railways, telephone lines, heating and sanitary facilities in partially empty residential buildings, rainwater pipes on buildings as well as art objects and commemorative plaques.

Metal scrap is usually effectively collected, sorted, processed and re-used in proper waste management chains. Scrap recycling rates of iron, copper and aluminium at 50 to 90 percent on a global average are among the highest of all metals [58]. Scrap recycling rates can be calculated as the product of collection, pre-treatment, sorting and processing efficiencies. Thus, losses at the beginning of this chain propagate until the end. Although overall recycling efficiencies in some product groups such as end-of-life vehicles and electronic waste could be significantly increased – deficits lie in collection and treatment in particular [94] – however, no primarily quantitative recovery problems are expected for these metals.

The actual challenge is of a qualitative nature (see Figure 19) as metals are rarely used in their pure form – they are usually alloyed. The addition of certain alloying elements can specifically change the properties of its later field of application. About 100 types of aluminium are in common use.

Thanks to modern near-infrared processing technology, high-quality material recycling of plastics is possible.

For steel, this number exceeds 2,000. In addition to alloys, surface coatings are applied to various metals. Tin, zinc, nickel, chromium and copper coatings are used for corrosion protection in particular.

At the end of product life cycles, scrap metals emerge in the same form and diversity. In order to regain all functional properties of the metals contained, alloys should be specially sorted and processed by types. Coated metal composites, however, should be separated again in high purity.

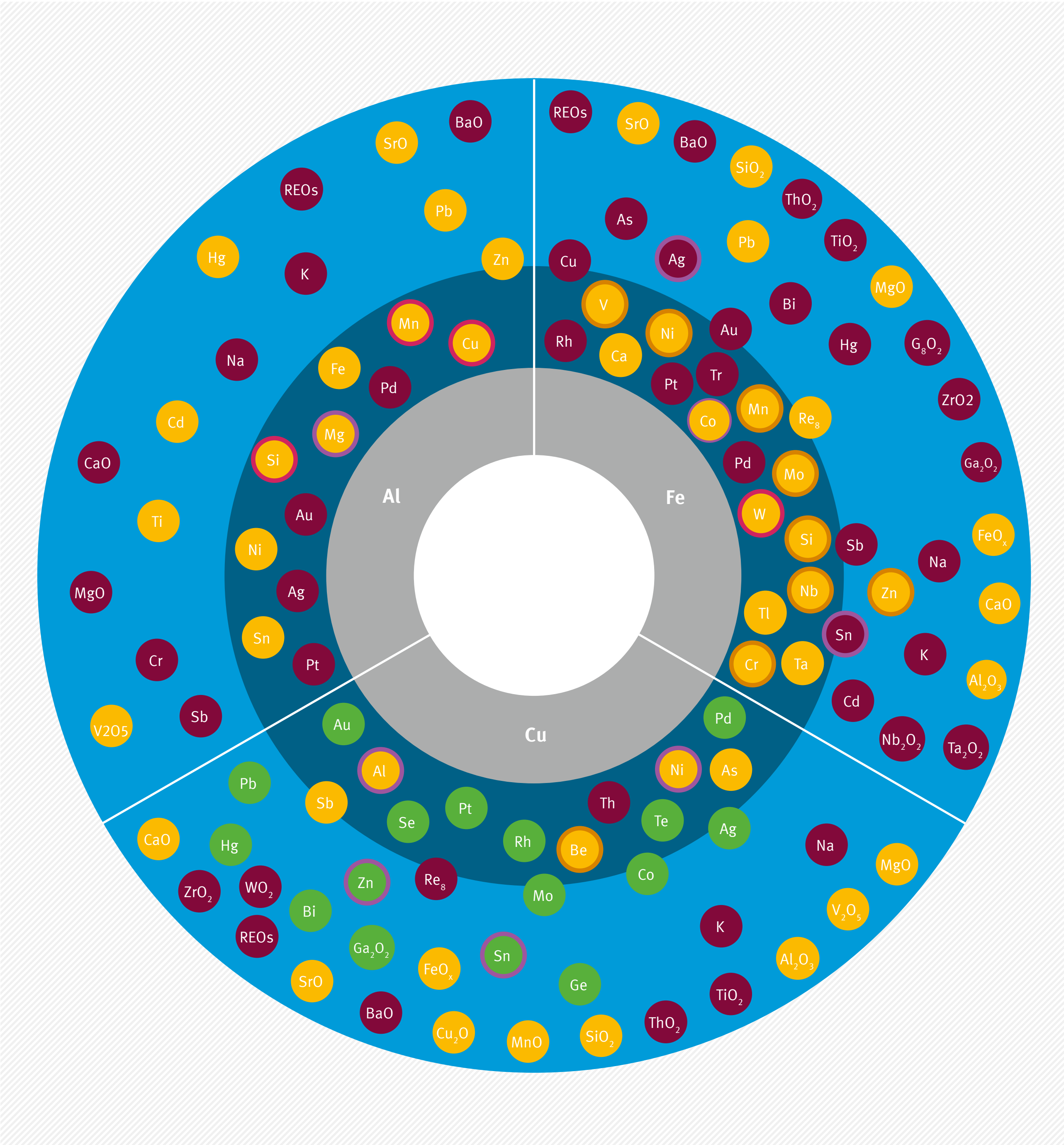
Independently of the economic conditions, the effort in separating processes is proportional to the physical and chemical properties of the metals. The more similar they are to desired or tolerated and unwanted accompanying substances, the more complex and energy-intensive the separation. The resource conservation effects are correspondingly lower or may even switch to the opposite. One also speaks of thermodynamic limits in this context [97, 98].

Last but not least, this is reflected in the cost-effectiveness of the procedures. Due to its relatively low melting temperature, aluminium is recycled using relatively unselective melting processes, while copper recycling achieves a purity of a minimum 99.99 percent up to high-purity cathode copper using electrolytic processes.

Depending on the process management, metallurgical recycling processes transfer non-precious, reactive metals such as zinc, magnesium, rare earths, titanium and chromium into slags, sludges or exhaust dusts. This works well in steel recycling in electric arc and oxygen blast furnaces. However, feasible recovery of the metals from slags, dusts or sludges is economically limited in the first place. Even if state-of-the-art recovery processes are used, significant fractions of the metals remain in the slags where they are contaminants and restrict the slags' use as a substitute construction material. The metals contained are functionally lost regardless of whether the slags are used as materials or landfilled. For example, only 84 percent (ideally 95 percent) of the zinc content can be recovered from zinc-containing waste even in highly specialised recycling-Waelz processes [99].

Figure 19

Downcycling – a challenge in metallurgy



Alloying elements in products made of aluminium, iron and copper

- Main alloying element (more than 50 % of the world production of metals is alloyed in the respective carrier metal)
- Frequent alloying element (10 – 50 % of the world production of the metals are alloyed in the respective carrier metal)
- Rare alloying element (less than 10 % of the world production of metals are alloyed in the respective carrier metal)

Metallurgy in aluminium, iron and copper recycling plants

- Lost
- Recovered in alloy or oxide products
- Recovered in elementary form
- Main recycling product (carrier metal)
- Dissolved in metal phase of the carrier metal
- In slags, sludges, dusts

UBA's illustration according to [95, 96]

^
Object of desire: due to their high market value copper wires disappear even from stocks being used.

Other metals, however, cannot be separated from melts in large-scale processes. In the case of steel and aluminium, for example, no economically and industrially viable technology is currently established which could remove copper and tin impurities from the melt [93]. This has the consequence that, although they are kept in a material cycle, they lose their original functionality. One peaks here of downcycling or quality-reducing recycling. Two aspects are problematic here.

1. Loss of secondary raw materials

If the contents of particularly resource-intensive alloying elements such as nickel, cobalt and molybdenum are lost in low-alloy steel melts, primary materials must be increasingly used for high-alloyed stainless steels. In addition to the metals copper and tin, precious metals such as gold from electronic waste are irretrievably lost once they have entered the large steel pool [100].

2. Contamination

Metals introduced can enrich over several material cycles to such an extent that they impair the properties and quality of the main carrier metal. In order to prevent this, primary raw materials are added during recycling to achieve a sufficient dilution effect.

In the past decades of strong growth, global metal demand has far exceeded scrap supplies. Only 20 to 50 percent of iron and non-ferrous metals are currently recovered from scrappage on a global average. More than half of them often come from new scrap and return material, i.e. material that emerges directly from production processes, so that the actual proportion of scrap is even lower [58]. Due to the strong demand for moderate quality structural steels and alloyed cast aluminium, which are particularly needed for vehicles and engines in the transport industry, awareness of a creeping quality degradation problem in the supply of recycled materials is still low at a global scale. At present, low-alloy steel grades and those with special requirements for alloy content continue to be produced chiefly from primary raw materials. Or, as in aluminium recycling, they are diluted by primary materials to such

Type and quality of recovery determines the contribution of metal recycling to resource conservation. For example, one tonne of high-purity copper from extraction to finishing, refining and electrolysis requires approximately 196 tonnes of primary raw materials extracted from nature – including copper ore, silica, limestone and crude oil. If copper scrap is recycled into a copper raw material that can replace this high-purity copper, this only requires nine tonnes of new raw materials, especially for energy sources for scrap collection, sorting, processing and smelting. Ideally, recycling one tonne of copper scrap saves 187 tonnes of primary raw materials. However, if a copper flow is absorbed by steel recycling via shredder fractions for example, not only does copper loose its functional, physical properties, but as a contaminant also impairs the quality of the electrical steel. Also, the effect achieved for primary raw material substitution is much lower in this so-called downcycling because the production of one tonne of blast furnace steel as a comparative product requires only 6.7 tonnes of primary raw materials.

an extent that high quality wrought alloy standards can be achieved.

The practice of downcycling can cause significant negative ecological feedback in the future. Situations can be expected where oversupply of low-quality scrappage will dominate due to saturation effects on growth markets and an increased amount of scrap from the anthropogenic stock. Scrappage supply will then exceed demand taking into account the necessary dilution with primary material. This situation can already be expected for alloyed cast aluminium scrappage from the transport sector from 2018 onwards. The surplus may increase up to an annual 18 million tonnes worldwide by 2050. Lost electricity savings from the functional recycling of this cast aluminium scrappage may then amount to an annual 240 terawatt-hours, which would correspond to about 40 percent of the 2013 German electricity demand. Given the current global electricity mix, this would result in approx. 170 million tonnes of CO_2 equivalents, which could be avoided [101]. Even if similar surplus scenarios for steel scrap due to copper and tin contaminants do not show over the short term, a lost resource conservation effect can still be measured. Energy consumption and greenhouse gas emissions caused by steels used in the automobile industry is about one third greater due to the addition of primary material needed qualitatively than theoretically required [102].

Such scenarios and simulations make it clear that a veritable quantitative problem can arise from the qualitative problem of downcycling of metals. For the future, this means that suitable techniques must be developed above all and incentives created to limit the further entry of alloying elements into the large “metal pools”. Old scrap extracted from the anthropogenic stock must be collected, sorted and processed as accurately as possible by alloys and applications. At the same time, technologies must be further developed to facilitate efficient processing and high-quality recycling of separated accompanying substances such as zinc.

This is a logistical, organisational and economic challenge, and also a serious engineering one. In recent years, various novel metal sorting techniques such as X-ray transmission (XRT), X-ray fluorescence (XRF) and laser-induced plasma spectroscopy (LIBS) have been developed and optimised [103]. They must now be integrated into the market. The successful large-scale deployment of an optimised X-ray transmission facility was demonstrated in 2014 within a project funded by the German Environmental Innovation Programme [104].

This makes it possible to effectively detect and retrieve non-alloyed and very low-alloy aluminium particles in shredded material. These can be used again e. g. in high-quality wrought alloys for window profiles without the addition of primary aluminium. But it is also conceivable that many other applications such as aluminium beverage cans and automobile panels may benefit from this technology to achieve virtually closed material cycles. The value of recyclates can increase considerably solely due to separating associated substances. The enormous economic potential for the future has been quickly recognised. Meanwhile, one of the world’s largest aluminium companies is implementing the technology. Competitors are exhaustively searching for comparable solutions.

SUMMARY AND OUTLOOK

The integral management of the anthropogenic stock for the extraction of secondary raw materials from durable products, buildings, infrastructure and deposits will gain great significance in the Anthropocene. Urban Mining can provide the necessary systematic, interdisciplinary framework for material flow management in order to integrate growth and shrinkage dynamics in the anthropogenic stock into a resource-efficient circular economy policy. The aim is to keep the materials contained in our built environment in their existing functionality over the long term in the same material cycles and so prevent accumulation of pollutants and impurities – even and especially when the amount of released materials from the stock increases significantly. Achieving this in an economic world that has expanded under other circumstances, i.e. an affordable primary raw material supply and freely available sinks for waste and emissions at the expense of non-internalised environmental impacts, poses major challenges for environmental policy and economy.

With great difficulty, we must retrospectively map the anthropogenic stock that has so far developed and analyse the materials contained in our waste. Five key strategic questions on the location, condition and release of stocks, the stakeholders involved, and the technical, logistical and organisational prerequisites must be answered and put into context at an early stage. Neither are the extensive investigations and research associated with the existing stock trivial for the current developments. Technological development is progressing so fast that even the distribution of materials into groups of goods such as electrical appliances or vehicles can only be tracked with great uncertainty. Nevertheless, we now have the opportunity to create the knowledge and decision-making basis that will enable us to be more effective over the coming years and decades. We can be more effective in collecting and recycling small, significant material flows alongside large main material flows. Being more effective means safely removing and disposing of pollutants. We can also be more effective in starting a material flow management at the materials use point – and not just at the waste generated point.

The key to forecasting future potential in the anthropogenic stock is recognising qualitative and quantitative changes in the stock of goods. Relying solely on the substances that are most valuable under current market conditions and on recycling methods that mainly induce downcycling will be just as inadequate for harnessing the immense resource conservation potential of our built environment as alignment towards non-material-specific volume recovery rates, such as those used in the past for construction waste. The management of the anthropogenic stock can also be understood in terms of combined production as is the case in primary mining. Even if individual material loads yield proceeds, others – such as special metals – can also be removed and separated. Further concentrating these materials and directing mass flows to highly specialised recovery installations can be groundbreaking.

Whether the achieved benefits justify the level of expenditure should be determined in the future much more by the resource utilisation and environmental impacts of the primary raw materials industry. Compared to the immense costs required to extract and refine raw materials from the natural environment using high-tech processes, the processes used for secondary raw materials do not appear to be fully developed. From this point of view, the level of organisation and technology in the circular economy could be significantly increased.

The German Environment Agency is committed to a strategic and interdisciplinary orientation of Urban Mining, which includes both urban prospecting, exploration, development and exploitation of anthropogenic stocks as well as the processing of recovered secondary raw materials. Many of these functions require completely new methodological approaches, developments and tools or the integration of existing ones. These include

- indicators, models and assessment schemes for urban mines,
- digital cadastres, databases, material passports for buildings and goods to strengthen the prospective knowledge base,
- the prudent development of sorting, separating and recycling technologies for complex material composites and their distribution,
- foresighted design of logistical and legal framework conditions for extraction, collection and processing,
- the initiation of market-driven stakeholder constellations to strengthen the demand for quality assured secondary raw materials.

All of this can be merged in a successful Urban Mining strategy which will give a big boost to the circular economy.

In the long run, a double dividend could be due. This is because the information base developed for Urban Mining will provide important incentives for product and building design – for a recycling-oriented construction.

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