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Toward circular and socially just urban mining in global societies and cities: Present state and future perspectives

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This study evaluates the perspectives of urban mining in the framework of the circular economy (CE) and starts with a brief analysis of the size of global and urban metabolism and the role that plays materials and waste streams such as construction and demolition waste (C&DW) and waste from electronic and electrical equipment (WEEE). These can be considered as temporary stocks or deposits to be mined in the future, thus shedding light on the concept of recycling potential, end-of-life functional recycling, and material concentration. The recycling potential could be very variable as in the case of metals. The average concentration of some metals (e.g., gold) in WEEE shows that it is higher per ton of electronic product compared to the amount in mining ores. This explains the importance of the concept of urban mining in the circular economy (CE) transition, given that the CE concept was born to address the challenges of high resources consumption rates and worsening environmental problems. The urban mining phenomenon becomes timely and extremely important for cities as they are relevant hubs of materials and energy consumption and source of environmental and social impacts in external areas due to mining and extraction activities. This study points to the need for creating and establishing strong synergies between the concept of CE and urban mining and the role of cities as innovators in finding circular solutions by incorporating more socially just urban mining activities to improve urban resource management, land use, and local and global wellbeing.

KEYWORDS

circular economy, construction and demolition waste, waste electrical and electronic equipment, urban mining, circular urban mining, just urban mining

Introduction

Construction and demolition waste (C&DW) and waste from electrical and electronic equipment (WEEE) are the two most relevant waste streams available in large and increasing quantities in our societies and cities at the global level (Krausmann et al., 2018; Shittu et al., 2021; Wiedenhofer et al., 2021). The European Union identified C&DW and WEEE within the priority product value chains in the Circular Economy Action Plan. The latter pointed out the challenges coming from key value chains, evidencing the need for "*urgent, comprehensive*, *and coordinated actions*" capable of addressing their proper management (European Commission, 2020). This shows that there is the political awareness pertaining to the negative environmental and social impacts associated with these waste streams in their life cycle, and, on the other hand, on their potential environmental, energetic and socioeconomic value (Borthakur and Govind, 2017; Shittu et al., 2021).

However, such potential value is still not fully perceived by the stakeholders in the construction industry (Silva et al., 2017; Ghisellini et al., 2021a), resulting in dumping, landfilling or illegal abandonment of these potentially reusable/recyclable materials, which could be an alternative to their natural substitutes (Silva et al., 2017). The recycling rates are still low, as less than one third of C&DW is recovered at the global level (World Economic Forum, 2021). Similarly, about 20% of global Electronic and Electrical Equipment (EEE) is properly managed according to sound environmental criteria (Forti et al., 2020). In 2019, in the European Union (EU), where the WEEE regulation is recognized among the best in the world, about 50% of the electronic waste generated remains uncollected (EUROSTAT, 2022). Moreover, high social justice concerns arise from unprocessed WEEE that often ends up in landfills and dumpsites in developing countries, causing serious harm to the surrounding eco-systems and human populations, with bad and child labor conditions and many toxins entering the local groundwater system (Awasthi and Li, 2017).

C&DW and WEEE streams could be among the main contributors to the urban mining phenomenon (Koutamanis et al., 2018; Gidarakos and Akcil, 2020; Ottoni et al., 2020). In fact, they are stocked in large quantities in our societies and cities and, still, lack adequate and effective planning for their recovery (Di Giacomo, 2021) thus preventing the exploitation of their ores locally e.g., at the city level as alternative ones to those extracted in natural mining (Graedel, 2011).

Against this background, this study focuses on the concept of "urban mining" as an important circular economy strategy and a process (encompassing the operations of collection, separation, sorting, and processing) Graedel (2011) at city level for waste streams, e.g., C&DW, WEEE, and related materials, products, components for their return into a new production cycle (Ottoni et al., 2020). In the circular economy (CE) model, the exploration of the concept of "urban mining" has a different perspective compared to the case of the recycling economy (Van Buren et al., 2016). Therefore, a central message of this study is that the CE framework is important for optimizing the urban mining process (Borghi et al., 2018) and for widening the attention to the other CE practices for the recovery of products or waste beyond recycling, such as the reuse, repair or refurbishment (Arora et al., 2017; Ghisellini et al., 2019; Ottoni et al., 2020). As evidenced by Stahel (1981), the "reuse" and "recycling" have different effects on the flows of materials and goods of an economy. Reuse leads to a slowdown of the flow of materials from production to recycling. The recycling closes the loops between post-use waste and production and does not affect the speed of the "flows" of materials and good.

It is expected that CE and urban mining as a strategy would be beneficial in reducing the demand of raw materials upstream from cities (Ji et al., 2020) and the associated environmental (Ulgiati et al., 2010) and social impacts (UNEP, 2011; Mancini and Sala, 2018), increasing the awareness of planning for their more long-term sustainability (Ingwersen, 2011). The CE research is currently devoting much more attention to the social and justice aspects of CE practices, and this involves taking into account such aspects in the urban mining concept being part of the CE practical framework (Ottoni et al., 2020).

Understanding global and urban metabolism of C&DW and WEEE in cities

The amount of mined and accumulated materials (defined as anthropogenic resources) from the Industrial Revolution onward is more than 80% of the world natural resources. Aldebei and Dombi (2021) highlight that a large share of the accumulated materials is mainly waste now. It is estimated that 35% of the in-use materials in 2010 will be disposed of as waste by 2030, which is about the same amount of waste generated in the last 110 years (Krausmann et al., 2018).

The anthropogenic stock of gold, silver, lead, and zinc is higher than the known natural deposits, while the anthropogenic stock of copper and iron is equal to known natural deposits Johansson et al., 2013; Krook and Baas, 2013; Cossu and Williams, 2015; Nakamura and Halada, 2015; Zhang et al., 2017).

In this perspective, it is no surprise that the most recent studies evaluating the economy-wide dynamics of materials stocks and flows at the global level (for 14 materials in nine world regions), from 1900 to 2035, have shown that there are no clear signs of material stock saturation and a stabilization of resource material flows, except for the Industrial Old World,

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Abbreviations: C&DW, Construction and demolition waste; CE, Circular Economy; EU, European Union; REE, Rare Earth Elements; WEEE, Waste from Electrical and Electronic Equipment.

Middle East, Northern Africa, Latin America, and Caribbean where the stock *per capita* levels could approach a saturation after 2035 (Wiedenhofer et al., 2021). Figure 1 shows the trends from 1900 to 2015 about material stock *per capita*. This further confirms the previous analysis by Krausmann et al. (2018) and Haas et al. (2015).

Industrialized regions have a high material stock *per capita* and a low growth rate of the material stocks, while, in emerging regions of Asia, the material stock *per capita* is lower, while the growth rate of materials stock is higher. China's material stocks are growing at 7.6% per year (Wiedenhofer et al., 2021). At the urban level, the material flow analysis of mega cities such as Guangzhou shows high material consumption triggered by urban construction activities that represent half of the consumption of non-metallic materials (Cui et al., 2019).

Cities concentrate in their area, the large part of the country's population and economic activities. For this reason, they are characterized by high consumption flows of materials and energy (Graedel, 1999), which are the source of environmental impacts in terms of consumption of natural resources, emissions, and waste at the local and global scales (Niza et al., 2009). Cities can be considered as organisms, and the study of their metabolism represents a good knowledge base in a policy perspective for monitoring its evolution over time and evaluating the effects of changes aimed at promoting a more sustainable management of the material and energy flows (Graedel, 1999).

United Nations Sustainable Development Goals and within such a framework, the Goal 11 (Sustainable cities and communities) (Serranti, 2021), and sub-goals 11.6 draw the attention to the goals of reducing by the year 2030 the environmental impacts of cities, improving air quality and municipal waste management practices. Furthermore, are suggested the strengthening of national and regional development planning to promote positive economic, social and environmental relationships between urban, per-urban and rural areas (11a) and the adoption and implementation of policies and plans "*toward inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters....*" (11b) (United Nations, 2022).

There are many studies in the international literature about the urban metabolism of cities or metropolitan areas (Barles, 2009; Niza et al., 2009; Rosado et al., 2014; Hoekman and Von Blottnitz, 2016; Cui et al., 2019) showing the input and output (products, co-products, and emissions) to and from the investigated urban system. Studies do not always provide the total amount of materials used (Domestic Material Consumption, DMC) by a city or metropolitan area in a disaggregated manner in terms of material categories. However, Rosado et al. (2014) analyze the DMC by material categories and subcategories from the year 2003 to the year 2009 for the Metropolitan area of Lisbon. Their data show that, in the year 2009, the total DMC was 21,455,650 tons. The high share in total DMC was that of nonmetallic minerals (45%), followed by biomass (25%), fossil fuels (18%), metallic minerals (6%).

Stone, cement, and sand are the most significant materials consumed in the non-metallic minerals category, while iron, steel-alloying metals, and ferrous metals have a share by 80% in totally consumed metallic minerals. The same order of relevance can be found also for other indicators of material flow analysis (provided in the study only for the year 2005) such as DMI (domestic extraction of materials plus imports of materials), while, in net addition to stocks, the nonmetallic minerals category is the most relevant (82%), followed by metallic minerals, biomass, fossil fuels, chemical, and others. Finally, in domestic material output, emissions to air have a share by 53% in total Domestic Processed Output (DPO), followed by exports (28%), MSW (9%), C&DW (6%), wastewater (3%) (Rosado et al., 2014).

Infrastructures, buildings, machineries, and vehicles can be considered as temporary stocks of resource materials or deposits that are accumulated in cities and, in the future, could be mined once they have achieved their service life. In differentiated urban solid waste, C&DW, WEEE, and end-of-life vehicles (Modoi and Mihai, 2022) are further resources available in relevant quantities in cities with a good recycling potential (Heckens, 2021). The recycling potential is an indicator of the potential environmental and energy benefits obtainable from a recycled material (Thormark, 2006). By recycling, e.g., some building materials, such as steel and aggregates, it is possible to recover about 29% of the embodied energy used for the manufacturing and transport of such building materials (Thormark, 2006; Blengini, 2009).

The recycling potential depends on different factors, such as the material concentration and composition, product composition, dispersed use, and product contamination (Heckens, 2021), and is strictly related to the functional end-of-life recycling (UNEP, 2011). The latter measures the efficiency in recovering a material in its whole life cycle and, e.g., for some metals (available in WEEE or C&DW streams), can be higher than 50% of the whole value or much lower (UNEP, 2011). Half of the value is, in fact, lost during collection, transport, separation, sorting, and recycling of the metal. In this regard, Graedel (2011) and colleagues (UNEP, 2011) studied the end-of-life functional recycling for sixty metals by constructing the "periodic table of recyclability" (Figure 2). From their evaluation emerges that only some metals used in pure forms (copper, lead, gold, silver, platinum, palladium and rhodium) or in alloys (e.g. aluminum, titanium, chromium, manganese, iron, cobalt) are easy to recycle and the functional end-of-life recycling is higher than 50%. Beyond these metals

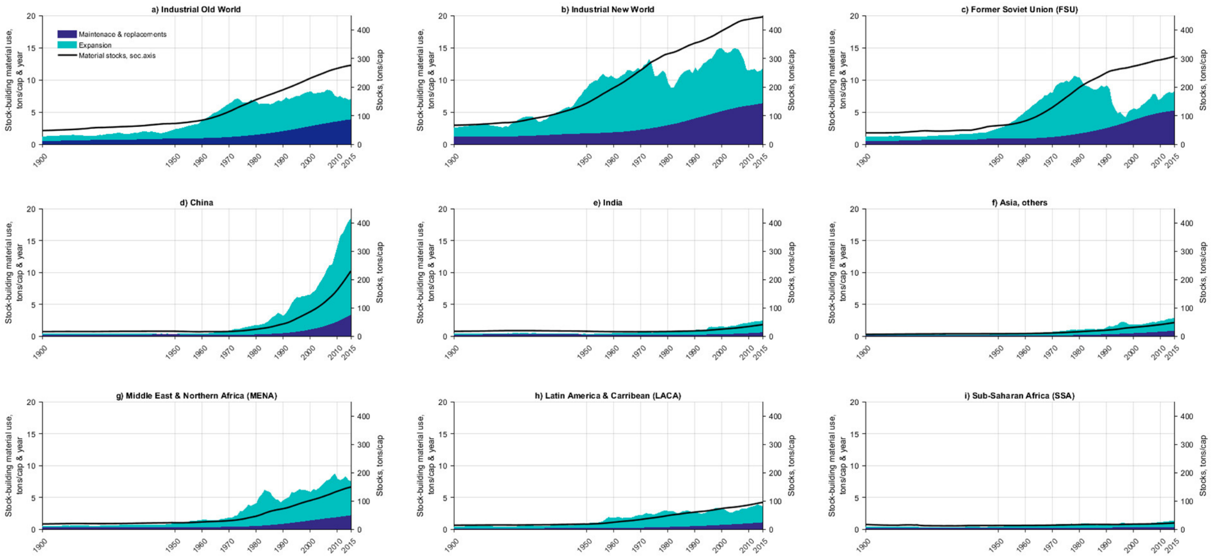

FIGURE 1
Material stocks in nine world regions and their expansion versus maintenance and replacement flows in the period 1900–2015. Source: (Wiedenhofer et al., 2021). Courtesy of Dr. Dominik Wiedenhofer, Institute of Social Ecology Vienna (SEC), Department of Economics and Social Sciences (WiSo), University of Natural Resources and Life Sciences, Vienna (BOKU).

the end-of-life functional recycling is lower as can be seen from Figure 2. The challenge is then to match in product design the features of high performances of materials as well as the need for keeping high their recycling potential (Graedel, 2011).

In the CE model, the Ellen Mac Arthur Foundation since in its early reports suggested the importance of focusing on pure materials[1], with the purpose of taking the full advantages of closing the loops. However, this involves the reorganization and optimization of global production system and the participation in the involved changes by all the stakeholders and industries in the supply chains (World Resource Forum, 2022).

After this, it is also interesting to shed light on the average concentration of precious metals in WEEE reported in Table 1 as it is higher in wastestreams compared to the amount in mining ores. For example, in Ontario mines, gold grades of 18/20 grams gold/ton are extracted. About 30 grams/ton is considered of high grade. However, for underground mining, several ounces of gold per ton are considered to be of high-grade, while 5 grams gold/ton is usually economically viable [2].

1 https://reports.weforum.org/toward-the-circular-economy-accelerating-the-scale-up-across-global-supply-chains/reorganize-and-streamline-pure-materials-flows/

2 https://www.mining.com/web/making-the-grade-understanding-exploration-results/

The concept of urban mining in the CE model

The concept of "urban mining" is the key in the CE model and the parallelism with the traditional mining activities help in understanding why it is so important. Let us remember that the concept of CE emerged in response to the need for reducing the demand of finite natural resources and better use them in the whole life cycle of products, components, and materials (Ghisellini et al., 2016; Geissdoerfer et al., 2017; Kirchherr et al., 2017; Panchal et al., 2021; Oluleye et al., 2022). It is suggested that, under a CE, the global society would live on Earth within the means of its energy and material resources (Deutz, 2020) being conceived as a closed system (Boulding, 1966).

Mining activities are sources of global and local environmental (Nuss and Eckelman, 2014; Fu et al., 2021) and social impacts (Xavier et al., 2021), including primary forest loss (Butsic et al., 2015), conflicts events, and fighting activities to maintain the control of a mining area (Berman et al., 2017), not to mention they contribute to the worsening of climate change (UNEP, 2011; Liu et al., 2020, 2021; Fu et al., 2021). Mancini and Sala (2018) evidence further social impacts such as land use competition of mining activities with those of the local population that encounter land expropriation, displacement, and resettlement, becoming a cause of food insecurity. Environmental and human health negative impacts also arise due to the use of explosives and other chemical substances such as cyanide, which cause toxic and carcinogenic

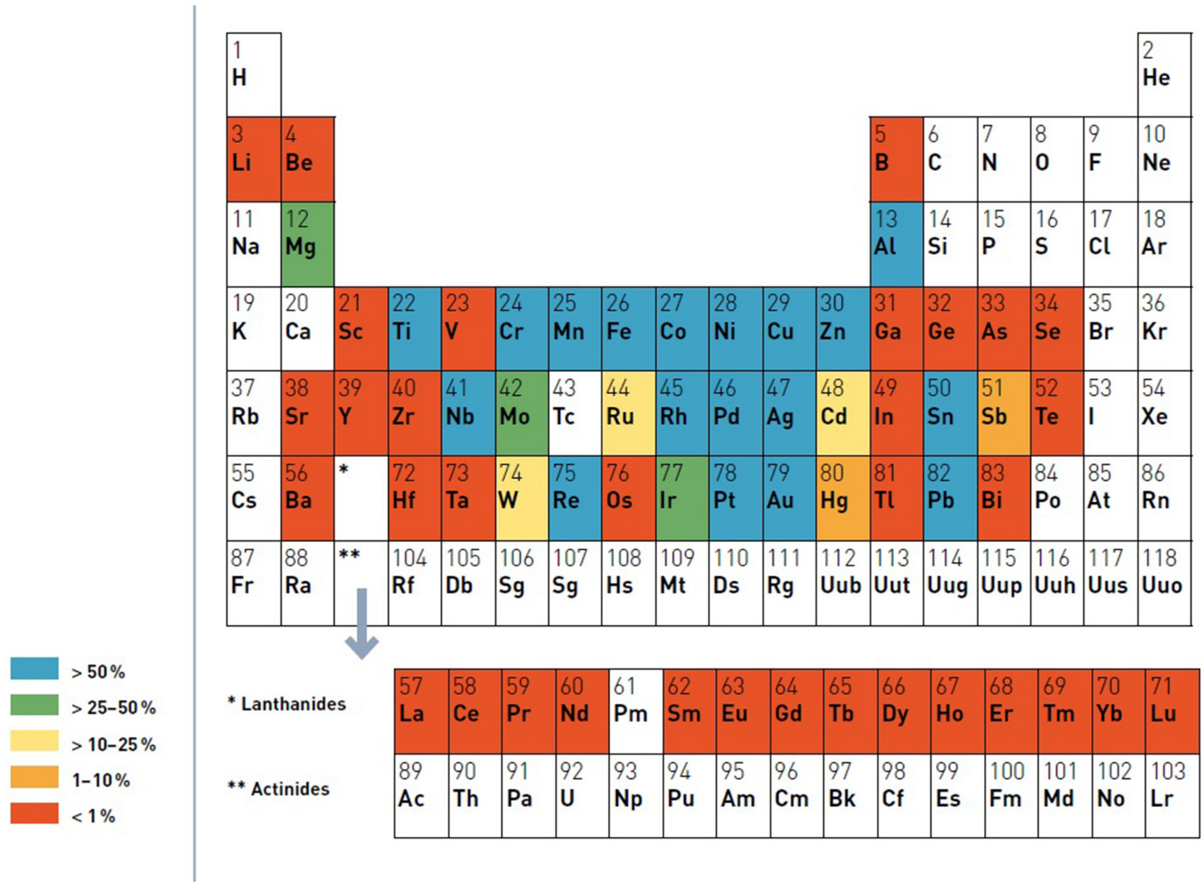

FIGURE 2
The periodic table of global average end-of-life functional recycling for sixty metals. Source: UNEP (2011).

effects. Furthermore, water use competition and contamination can negatively impact local communities and their economic activities, preventing fishery activities that support their livelihoods (Mancini and Sala, 2018).

In the CE perspective, the suggested approach is necessarily "cradle to cradle" in analogy with the natural systems where the concept of waste does not exist as "*nothing that contains available energy or useful material is lost*" (Frosch, 1992). The CE maximizes and prolongs the value of natural and man-made resources over time (Ellen MacArthur Foundation, 2012), preserving their integrity by the most appropriate product design strategies (Stahel, 1981; Bocken et al., 2016). This stresses the importance of the adoption of the concept of "urban mining" and integrates the latter within the practical framework of the CE since the first stages of the life cycle of a product (Serranti, 2021). The recovery of materials is the main driver of the concept of "urban mining" (Chen and Shi, 2020; Serranti, 2021; Xavier et al., 2021), distinguishing it from "landfill mining" where the goal is not the recovery of materials but the solution of the problem at the disposal level "end of pipe treatment" (Aldebei and Dombi, 2021). "Urban mining" is also linked to the economic feasibility of the whole process as in the case of traditional mining (Aldebei and Dombi, 2021). The recovery of C&DW materials such as, in particular, steel is profitable. The same is for e-waste materials even if they depend on market prices (Favot and Massarutto, 2019). Zheng et al. (2021) have calculated that the mean urban mining costs of copper are about 3,000 US$ per ton lower than the virgin mining costs (5,500 US$) and price (7,500 US$). The mean urban mining cost for aluminum is about 1,660 US$, while the virgin mining cost is 2,500 US$, and the price is 2,200 US$.

The implementation of urban mining as a strategy in CE transition should be a goal shared by all the stakeholders, provided the existence of environmental and socioeconomic benefits of urban mining, and these are measured in a scientific manner such as by means of MFA and LCA (as we will show in the next Section Environmental and social benefits of urban mining). In this view, increasing the awareness of all the involved stakeholders that "*urban mining is about sustaining the resources on which all of technology depends, whether or not it is economical*

TABLE 1 Average concentration of precious metals in printed circuit boards from different equipment types.

Reference	Equipment type (origin of the printed circuit board)	Silver (g/t)	Gold (g/t)	Palladium (g/t)	Platinum (g/t)
Angerer et al., 1993	Audio and video equipment	674	31		
Huisman et al., 2007*	Radio set	520	68	8	
Huisman et al., 2007*	DVD player	700	100	21	
Cesaro et al., 2018*	DVD player	413	83	12	
Angerer et al., 1993	Personal computer	905	81		
Hagelüken, 2006	Personal computer	1,000	250	110	
Huisman et al., 2007*	Personal computer	1,000	230	90	
Keller, 2006	Personal computer	775	156	99	
Kramer, 1994	Personal computer	600	300		
Legarth et al., 1995	Personal computer	700	600	100	40
Cesaro et al., 2018*	Personal computer	875	428	95	
Art, 2008	Computer keyboard and mouse	700	70	30	0
Huisman et al., 2007*	Computer CRT Monitor	150	9	3	
Huisman et al., 2007*	Computer LCD Monitor	1,300	490	99	
Hagelücken and Corti, 2016	Computer Monitor	280	20	10	
Huisman et al., 2007*	Printer	350	47	9	
Cesaro et al., 2018*	Printer	40	54	21	
Ernst et al., 2003	Telephone	2,244	50	241	
Ernst et al., 2003	Mobile Telephone	3,573	368	287	
Cesaro et al., 2018*	MobileTelephone	2,171	1,067	137	
Huisman et al., 2007*	Small IT and communicationequipment	5,700	1,300	470	
Hagelüken, 2006	TV set-CRT Monitor	280	17	10	
Huisman et al., 2007*	TV set-CRT Monitor	1,600	110	41	
Huisman et al., 2007*	TV set-CRT Monitor	250	60	19	

Sources: Chancerel et al., 2009; Cesaro et al., 2018. *Combination of data from different sources.

at the present time. Metals are gifts from the stars that were generated over billions of years; we should treat them with awe and respect they deserve and devise ways to recycle them over and over. Only then will sustain ability become a reality" (Graedel, 2011).

Environmental and social benefits of urban mining

The evaluation of the environmental benefits of urban mining for WEEE is rather complex due to the existence of a wide range of products, components, and materials (Biganzoli et al., 2015). A few studies have focused on a macro scale (e.g., nation, region, province scales) perspective (Withanage and Habib, 2021). Biganzoli et al., 2015 assessed the whole life cycle of WEEE from the collection in the Lombardy region (Northern Italy) until their final treatment in secondary plants and consequent material and energy recovery of the treated WEEE. The authors combined the Material Flow Accounting method with the Life Cycle Assessment. In the latter, they also included the accounting of the avoided materials and energy benefits coming from the treatment of 1 ton of collected WEEE. Their results show that the amount of material savings for steel and commercial glass has been the highest compared to the other materials that can be recovered over the five categories of WEEE. In Italy, the latter are R1 (Heaters and Refrigerators), R2 (Large Household Appliances), R3 (TV and monitors), R4 (Small Household Appliances), R5 (Lighting Equipment). The saved amounts for steel resulted in: 471 kg/ton (R1 category), 665 kg/ton (R2 category), 384 kg/ton (R3 category, FPDs), 490 kg/tons (R4 category). Material savings for commercial glass amounting to 800 kg/ton was mainly recovered in the R5 category. Precious materials savings mainly resulted in R3 and R4 categories and, in lower percentages, in R2 categories. R1 and R5 categories do not contain precious materials.

The results for the R4 category (where are included, e.g., mobile phones) show the following precious material savings:

gold (5 g/ton), palladium (10 g/ton), silver (180 g/ton). In the year 2011, 9,849 tons of R4 have been collected in the Lombardy region. As a result, the potential savings of avoided primary precious materials was in the R4 category: 49.24 kg of gold, 98.49 kg of palladium, 1,772.82 kg of silver. The authors concluded that the environmental benefits of the recovery of the whole WEEE collected in the regional system have been higher than the overall impacts due to the recovery activities for most of the environmental categories (except human toxicity-cancer effects and freshwater ecotoxicity).

The recovery of C&DW is also beneficial for the environment. The available literature evaluated the environmental and socioeconomic benefits and costs of the C&DW management systems at the national scale in Finland (Dahlbo et al., 2015) and in some Italian regions: Lombardy in Northern Italy (Borghi et al., 2018) and Iodice et al. (2021) in Campania Region (Sourthern Italy). Moreover, Blengini and Garbarino (2010) considered the provincial scale (Torino in Northern Italy) as well as Ghisellini et al. (2021a) investigated the C&DW management system of the Metropolitan City of Naples. These two provinces shared similar C&DW composition compared to the Lombardy region where a high fraction (80%) of the total amount of C&DW generated consisted of mixed C&DW[3]. Blengini and Garbarino (2010) showed that avoided landfilling and avoided Natural Aggregates (NA) transportation are two relevant factors in determining the environmental sustainability of Recycle Aggregates from C&DW compared to NA. Ghisellini et al. (2021a) also show that the avoidance of landfilling and the avoided production of primary materials (steel, concrete, gravel, aluminum, other virgin materials) due to the recycling of 1 ton of C&DW have the potential of generating energetic and environmental benefits while reducing the dependence on fossil energy and the contribution to all the considered environmental impact categories (e.g., Global Warming, Ozone formation, Terrestrial Acidification, Land use, etcetera). The potential environmental benefits resulted higher than the environmental impacts of the recycling of C&DW and the highest contribution to the environmentally avoided characterized impacts resulted from steel recycling as the latter avoids the production of primary steel and the associated release of GHG emissions (145.29 kg CO2 equiv./ton of C&DW). Finally, the results by Borghi et al. (2018) evidence that the environmental benefits due to the recycling of the C&DW are higher than the environmental costs, only in a best-case scenario compared to the current scenario of the investigated year 2014. In the best-case scenario, they assumed the recycling of all the C&DW and no landfilling, the use of electricity in the recycling plants, and reduced transport distances. They concluded by providing some suggestions for improving the C&DW management system and its benefits. In fact, they highlighted the need for improving the quality of RA by means of the promotion of selective demolition on-site, with the goal of obtaining purer C&DW materials entering in the recycling plants. As such, the adoption of the concepts of design for reuse/recycling or design for disassembly is considered important in enhancing the circularity rate of a construction product (such as, e.g., buildings), the reuse of C&D products and components in new products or the recycling of C&D materials into recycled aggregates of higher quality (Zhang et al., 2012; Duan et al., 2015; Ghisellini et al., 2018).

The recycling of materials from waste (including C&DW or E-Waste) creates employment benefits (Gálvez-Martos and Istrate, 2020), both in developed [EPA (Environmental Protection Agency), 2020; Ghisellini and Ulgiati, 2020a; Alsheyab, 2022] and developing countries (Asante et al., 2019; Ezeudu et al., 2022). However, C&DW recycling compared to those of WEEE creates employment opportunities at the local level (Hossain et al., 2018; Iodice et al., 2021), while WEEE recycling could be performed very far from the point of collection and generation (Abalansa et al., 2021). Moreover, in the case of WEEE recycling appropriate technologies, infrastructures, and management plans should be adopted as well as rules and regulations be enforced at the political local level to prevent the potential negative impacts on the health of workers (Umair et al., 2015). Vulnerable local groups such as women and, in particular, children involved in e-waste recycling are exposed to very poor working conditions and are often common, e.g., in Pakistan, despite the country having ratified the ILO conventions C182 and C138 (Umair et al., 2015) that promote the abolition of child labor[4]. (McMahon et al., 2021). With recurring droughts as a result of climate change in many African countries, food security is threatened, but when local communities are employed by recycling activities, some income can be earned and used to buy food, thus preventing hunger (Okwu et al., 2022). Adequate technological and financial investments from developed countries, including the sharing of knowledge, should be transferred to developing countries along with the exports of WEEE to promote better recycling operations and favor a more just CE (Abalansa et al., 2021).

3 The average composition in the study area (Province of Torino) by Blengini and Garbarino was: 47.3% mixed C&DW 170,904:28.6%; soil and stones, 170,504:15.7%; bitouminous mixtures, 170,302:15.7%; concrete, bricks, and tiles, 170,107:5.1%; concrete, 170,101:2.3%; other fractions are below 1%. The average composition of C&DW in the Metropolitan City of Naples (Ghisellini et al., 2021a) is the following: Mixed C&DW, 170,904, 47.37%; soil and stones, 170,504, 24.81%; iron and steel, 170,405: 7.03%; bitouminous mixtures, 170,302, 5.25%; concrete, 170,101: 6.69%; dredging spoils, 170,506: 4.5%; track ballast, 170,508: 1.6%; other fractions are below 1%.

4 ILO Conventions on child labor. Available online at: https://www.ilo.org/ipec/facts/ILOconventionsonchildlabour/lang--en/index.htm (accessed July 4, 2022).

TABLE 2 A summary of the main CE principles and related challenges/barriers retrieved from the literature about WEEE and C&DW sectors.

Principles of CE as solutions	Challenges/barriers WEEE	References	Challenges/barriers C&DW	References
Design for disassembly, repair, reuse, recycling, reversable building;	Efficient design for an easy recover of the materials as well as for their safe disposal Strengthen of EU-wide eco-design requirements within the scope of the EU Eco-design Directive 2009/125/EC on circularity Integration of eco-design perceived as costly by designers and producers of EEE	Asante et al., 2019; Rizos and Bryhn, 2022	Promotion of the joint use of digital technologies and environmental sustainability tools such as LCA during the design stage. Promotion of the concept of reversible building in legislation useful to introduce new design and management rules. Obtaining legal authorization for the construction of a reversible building. Disseminating knowledge and provide economic incentives to the adoption of the concept of reversible building as well as create relationships among all the stakeholders (designers, constructors, manufacturers, and demolishers).	Eberhardt et al., 2019; Iodice et al., 2021; Giorgi et al., 2022; Oluleye et al., 2022
Design for durable products	Designing EEE with a longer lifespan (mandatory laws that increase the lifespan as well as their recycling at the end-of-life).	Bressanelli et al., 2020; Abalansa et al., 2021		
Reduction	Increasing annual generation rate; Continuous upgrading of electronic Equipment; Acceleration of the rate of obsolescence driven by e.g., 5G technology, virtual reality. Market competitiveness discourage the adoption of disruptive innovation by producers that are forced to produce EEE with short lifespan at low costs Culture of Consumerism related to WEEE	Abalansa et al., 2021; Pan et al., 2022; Shittu et al., 2021 Rizos and Bryhn, 2022	Improving the importance of reducing the amount of C&DW rather than only recycling in existing regulations.	Ghisellini et al., 2018; Huang et al., 2018

(Continued)

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TABLE 2 (Continued)

Principles of CE as solutions	Challenges/barriers WEEE	References	Challenges/barriers C&DW	References
Repair	Repair cafés are mainly located in urban centers; Negative perception about the reliability of second-hand, repaired and refurbished products. Not uniform perception of functionality of EEE among clients	Ghisellini and Ulgiati, 2020a; Van Langen et al., 2021; Rizos and Bryhn, 2022		
Reuse	Lack of awareness about the benefits of reuse and refurbishment or of the impacts of e-waste	Van Langen et al., 2021; Rizos and Bryhn, 2022	Higher costs of selective demolition compared to conventional demolition, lack of space in urban centers needed for performing selective demolition Low application of reuse in construction due to the lack of certification about the quality, performances and technical characteristics of reused materials. Test procedures to certify a reused product longer and costly than those of new products. Overcome higher costs, performance assessment, and negative end users perception. Reused product perceived as more environmentally friendly but of lower quality.	Da Rocha and Sattler, 2009; Condotta and Zatta, 2021; Cristiano et al., 2021; Iodice et al., 2021; Giorgi et al., 2022
Remanufacturing	It is still immature for WEEE sector both in EU and China Problems in the implementation due to existence of varied series of devices available in the market Negative perception of consumers toward remanufactured WEEE products	Pan et al., 2022 Van Langen et al., 2021; Rizos and Bryhn, 2022		
Recycling	High quality recycling requires investments costs difficult to afford for SMEs Low recycling rates at the global level; Formal recycling systems in developed countries requires high investment costs; Informal recycling is less efficient and embeds risks for workers, society and environment	Abalansa et al., 2021; Rizos and Bryhn, 2022 Pan et al., 2022	Immature local market and low demand for recycled aggregates. Lack of involvement of natural aggregate producers in the recycling of C&DW for the production of recycled aggregates. Low landfilling fees e.g., in Italy to favor the recycling of C&DW.	Sevigné-Itoiz et al., 2014; Cristiano et al., 2021 Cristiano et al., 2021; Giorgi et al., 2022

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Solutions for improving urban mining of C&DW and WEEE management systems

Circular economy principles listed in Table 2 include the adoption of product design (such as design for disassembly, repair, reuse, recycling, reversable buildings, design for product life extension) (Charef et al., 2022), the reduction of the amount of C&DW or WEEE, the repair of products (in particular, for WEEE), reuse of products, materials and components as well as the recycling of materials at the end of their life (Bocken et al., 2016). The adoption of all the CE principles/solutions faces many challenges/barriers as their implementation requires changes in all societal systems (political-legislative, economic, cultural, technical-technological) (Davico, 2004; Fusco-Girard, 2016). The adoption of the solutions depends on different factors and, in particular, from favorable systems conditions such as the presence of policies, the vision of policy makers and their commitment toward the achievement of the CE goals, their capacity of involving and communicating with stakeholders, the role of universities, the involvement of non-profit organizations, collaborations along with the entire production chain and among different sectors and so on (Ellen MacArthur Foundation, 2012; Bosone, 2020; Ghisellini and Ulgiati, 2020b). The principles/solutions in Table 2 have been ordered according to the waste hierarchy (Zhang et al., 2022). The order can also be considered an order that ranks the most promising solutions in terms of their probable realization. The first principles, such as design, reduce, and repair, require changes, in particular, in the cultural mindset and the dissemination of new knowledge. This is the case of design for disassembly both in WEEE and C&DW sectors and design for product life extension whose adoption should be promoted at the political level, also by means of economic incentives (Giorgi et al., 2022). Moreover, a cultural change toward a less consumerist behavior should be done for WEEE as it is a strong barrier to the adoption of the reduction principle (Abalansa et al., 2021). However, policies/regulations in the case of C&DW (e.g., in China) are mainly focused on recycling rather than on the reduction of the amount of C&DW (Ghisellini et al., 2018; Huang et al., 2018), thus creating barriers to much virtuous and less costly solutions (in economic and technical terms) over the waste hierarchy (Zhang et al., 2022).

The other CE principles/solutions, such as reuse, remanufacturing, and recycling, require technological investments rendering much difficult and costly their realization compared to the first set of principles as evidenced by Rizos and Bryhn (2022). The latter authors pointed out the difficulties of SMEs in embarking on a recycling of higher quality for WEEE. In a similar manner, the adoption of best practices, such as selective demolition that would facilitate C&DW reuse, would generate environmental and social benefits but higher costs requiring political tools for supporting such practice (Iodice et al., 2021).

Discussion and conclusions: Moving toward circular and just urban mining

In this brief study, we have shown some data on the trends of the current global consumption and management of natural resources. The data show that their use is still very inefficient, given the high amount of waste generated disposed of in landfills and not recovered as also in the case of C&DW and WEEE. CE proposes to rethink and reverse the pattern of the linear model of consumption of natural resources by means of different solutions for improving production and consumption efficiency and having as central the concept of waste elimination by design, design for disassembly, repair/reuse/recycling/refurbishment (Oluleye et al., 2022). We have underlined that framing the concept of urban mining in the CE practical model is a central message that this study would like to convey as it is relevant for the optimization of the whole urban mining process and prolong the use of virgin materials for achieving more sustainable patterns in their consumption. We have seen by a brief analysis of the metabolism of the Metropolitan city of Lisbon that, in DMC, a relevant share has the consumption of non-metallic minerals, biomass, fossil fuels, and metallic minerals. Stone, cement, and sand are the most significant materials consumed in the nonmetallic minerals category, while iron, steel-alloying metals, and ferrous metals have a share by 80% in total consumed metallic minerals. These materials are stocked temporarily in cities in the form of buildings, infrastructures, durable goods, and so on. The opportunities for their recycling at the end of life (for metals but also for non-metallic materials) are variable, depending, in particular, by their purity. In this view, a key point is the product design for optimizing their recycling potential. In that, the CE model is conceptually focused on product design contrary to the recycling economy model, and this, in turn, provides advantages for optimizing the urban mining as a process within its framework.

We have shown that the recycling of C&DW and WEEE can provide environmental and social benefits, but these processes should be governed to prevent undesirable effects such as in the case of WEEE where, currently, their export for recycling toward developing countries is a matter of high concern, in particular for vulnerable people. Indeed, recycling is only one of the options for strengthening urban mining in the CE framework as other solutions (shown in Section Solutions for improving urban mining of C&DW and WEEE management systems) are available. In this regard, some experiences about cities show how they are catalysts of innovation and extraordinary laboratories for experimenting and testing eco-innovative solutions (Prendeville et al., 2018; Repair, 2018), (Mazzarella and Amenta, 2022), incorporating more circular and socially just urban mining activities (Ghisellini and Ulgiati, 2020a) also useful for improving urban resource management and urban land use (Ulgiati and Zucaro, 2019). Repair cafès and companies specialized in the reuse/remanufacturing of e-waste in big Italian cities (e.g., Turin and Rome) are applying the principles of the CE in a way that is beneficial for the economy, the environment, and people. The repair, reuse, or remanufacturing of an EEE can save up to 80% of the materials needed to produce a new product. Such activities can also be sources of new job opportunities for young people or immigrants (Atlanteeconomiacircolare, electronics 2022)[5].

Good practices beyond recycling can also be found for C&DW across Europe and at the global level (Legambiente, 2016, 2017; Ramakrishna et al., 2021; Oluleye et al., 2022). Several building projects show that, by means of the creation of a synergy between circular design and production, it is possible to design buildings that are easily disassembled at the end of life, and their C&D materials can be reused again for new buildings[6]. Furthermore, it is also possible to construct buildings made of a high share of recovered materials available, e.g., in a short distance of about 15 km from the construction site (Legambiente, 2016, 2017).

Finally, the monitoring and collection of data of urban mining and the CE implementation by means of different tools (including material flow accounting, life cycle assessment, social life cycle assessment) and related indicators are essential in order to improve the traceability of products at the end of their life and evaluate the distribution of the costs, benefits, and opportunities for the society and environment (Graedel, 2019; McLaren et al., 2020; Schroder, 2020; Niskanen et al., 2021). The research project, such as the just transition to circular economy that is funding this research, is the key to creating the needed knowledge base to understand the distribution of the benefits across all the involved stakeholders. Economic activities, due to the presence of externalities, do not always develop in a way that is socially sound, requiring the adoption of policies that correct such market failures and better align CE implementation with the three pillars of sustainable development (Ghisellini et al., 2021b). As just above mentioned, the case of WEEE recycling is exemplary as the European Model of WEEE management is currently mainly driven by the principle of economic efficiency, disregarding those of the environmental and social justice. Another limitation of the model is that it is unable to treat all the WEEE collected in the EU countries, and most of them are exported toward developing countries. In this way, the CE model perpetuates the same logic and values of the linear and recycling economy (Mah, 2021) and does not promote environmental and social innovation and environmental and social justice. We conclude claiming that the opportunities for urban mining in the CE framework are still rather unexplored in terms of resource valorization [agreeing with Zucaro et al. (2022)] and potential social benefits justifying the urgency of improving their awareness in all the stakeholders.

5 See, e.g. Reware: https://economiacircolare.com/atlante/reware/#field-group-tab-2 and Astelav: https://economiacircolare.com/atlante/astelav/#images (accessed April 27, 2022).

6 Circular Pavillion in Amsterdam. Available online at: https://circl.nl/themakingof/en/ (accessed March 27, 2022).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

PG contributed to the conception and design of the study and wrote the first and further revised drafts of the study. All authors contributed to the manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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