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Critical Review

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Taking stock of built environment stock studies: Progress and prospects

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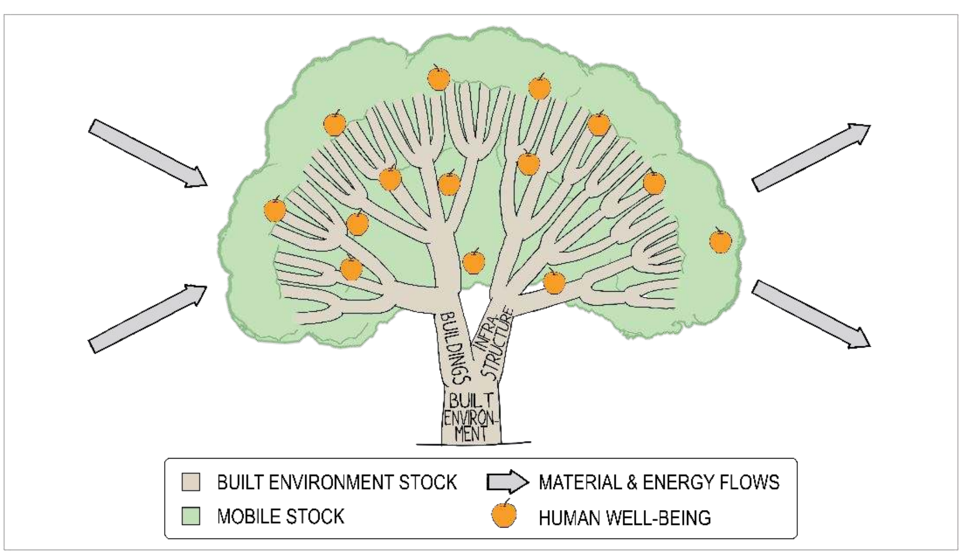

Abstract

Built environment stocks (buildings and infrastructures) play multiple roles in our socio-economic metabolism: they serve as the backbone of modern societies and human well-being, drive the material cycles throughout the economy, entail temporal and spatial lock-ins on energy use and emissions, and represent an extensive reservoir of secondary materials. This review aims at providing a comprehensive and critical review of the state of the art, progress, and prospects of built environment stocks research which has boomed in the past decades. We include 249 publications published from 1985 to 2018, conducted a bibliometric analysis, and assessed the studies by key characteristics including typology of stocks (status of stock and end-use category), type of measurement (object and unit), spatial boundary and level of resolution, and temporal scope. We also highlighted the strengths and weaknesses of different estimation approaches. A comparability analysis of existing studies shows a clearly higher level of stocks per capita and per area in developed countries and cities, confirming the role of urbanization and industrialization in built environment stock growth. However, more spatially refined case studies (e.g., on developing cities and non-residential buildings) and standardization and improvement of methodology (e.g., with geographic information system and architectural knowledge) and data (e.g., on material intensity and lifetime) would be urgently needed to reveal more robust conclusions on the patterns, drivers, and implications of built environment stocks. Such advanced knowledge on built environment stocks could foster societal and policy agendas such as urban sustainability, circular economy, climate change, and United Nations 2030 Sustainable Development Goals.

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1. Introduction

Society relies on the use of resources to fuel the multitude of socio-economic activities satisfying human needs and well-being such as food, shelter, transportation, and communication. But today, as the biophysical boundaries of our planet are increasingly transgressed,[1,2] the environmental impacts from primary resource production (e.g., energy use and greenhouse gas emissions) and waste disposal have become burdensome.[3,4] Materials accumulated in the anthroposphere in the form of buildings, infrastructure, and consumer goods, however, constitute an extensive reservoir of secondary raw materials as urban mines that should not be overlooked:[5] more than half of all resources extracted globally are used to expand and maintain anthropogenic material stocks and these stocks have increased 23-fold in the past century.[6] Considering further urbanization and industrialization worldwide and the yet limited contribution of resource use reductions, re-use, and recycling in alleviating pressures on the environment,[7,8] substantial further growth of in-use stocks and consequent resource use and environmental pressures are to be expected.[9]

Already in 1941, Ostrolensk realized that “junked buildings, machinery, and automobiles” would, in the near future, become an important source of raw materials.[10] Two decades later, Jane Jacobs regarded cities as “mines of the future”[11] and argued that “the largest, most prosperous cities will be the richest, the most easily worked, and the most inexhaustible mines.”[12] But until the early 2000’s, socio-economic metabolism research mostly focused on characterizing annual flows while the size and dynamics of anthropogenic stocks remained the least understood parts of material cycles.[13,14]

The recent decade have witnessed a fast-growing interest in the characterization of the patterns and impacts of anthropogenic stocks, due largely to efforts of the industrial ecology and especially material flow analysis (MFA) community. These studies cover a large variety of scopes, analyze numerous aspects of stocks, and are conducted for very different purposes. For example, a number of studies estimated the quantity and composition of materials accumulated in different reservoirs in different parts of the world in order to identify potentials of secondary resources recovery.[5,15–21] Economic considerations on such recovery potentials have also been a focus.[22,23] The temporal dynamics of stock development have been analyzed[24–28] to explore their historical patterns and socio-economic drivers.[29] The interaction between stocks and flows has been investigated in order to better understand the influence (including possible lock-in effect[30]) of stocks on material and energy demand[1,29,31–34] and on emissions.[35–38] Life cycle assessment has been combined to material stock characterization to assess the embodied energy[39] and end-of-life scenarios[40] of buildings and infrastructure stocks. The role of anthropogenic stocks in human development, measured either by specific socio-economic indicators (such as population and GDP)[41] or composite indicators (such as Human Development Indicators[36]) have also been explored.

As anthropogenic stock research expands, gaps in knowledge, methodology, and data are also becoming clear. To our knowledge, three relevant reviews in the past have identified gaps and progresses of anthropogenic stock studies: in 2008, Gerst and Graedel[14] synthesized the status and implications of 54 studies on in-use stocks of metals; in 2014, Müller[42] reviewed the methodologies applied in 60 dynamic MFAs assessing past, present, and future stocks and flows of metals; in 2016, Augiseau[43] reviewed 31 publications published between 1998 and 2015 focusing specifically on non-metallic construction minerals. These reviews identified several patterns and gaps in anthropogenic stock research, which we will build on in this review and elaborate further below.

- First, previous empirical studies have limited coverage geographically (e.g., few studies for less-developed countries[14,43]), material wise (e.g., lack of studies on some metals used in large quantities such as zinc[14]), and end-use category wise (e.g., infrastructure stocks are less studied[43]).
- Second, most existing studies focus on the quantification of anthropogenic stocks itself, but its socioeconomic drivers (e.g., urban form), impacts (e.g., lock-in effects), and potentials to inform relevant resource and environmental policy remain largely untapped yet.[43,42] This is especially due to lack of more spatially explicit results which could provide in-depth understanding for local decision makers.[14]
- Third, methodologies in existing studies vary based on data availability[42,43] and aim of study, but they are often not consistent, making comparison and synthesis difficult, and uncertainty analysis and full sensitivity analysis are often lacking as well.[14,42]

However, these three reviews have a strong focus either on metals[14,42] and non-metallic construction materials[43] or dynamic modelling approach.[42] Considering the booming research on anthropogenic stock studies in the past decade and their varying scopes, purposes, and approaches, the aim of this review is to provide an updated and comprehensive compilation of built environment stock studies. It widens the scope to include all available literature, to our knowledge, on parts or totality of the built environment stock, static or dynamic, from global to neighborhood level, and quantifying one or several materials in terms of weight, dimensions, or number of items. This body of literature consists of 249 publications in English, German, French, Chinese, and Japanese, including grey literature such as reports from different organizations (More information on the literature collection can be found in the Supporting Information.) The earliest retrieved case-study dates back to 1985,[44] and the cut-off date of literature search is 31 March 2018.

We provide an overview of the state of the art, progress, and prospects of built environment stocks research through the analysis of bibliometrics (section 2), scope (section 3), estimation approaches (section 4), and purposes (section 5) of all these studies published between 1985 and March 2018. We have also included a comparability analysis of existing studies on construction material stocks at the urban and national level (section 6), inferred the possible contributions of built environment stocks results to informing a sustainable socio-metabolic transition and made recommendations for future research (section 7).

2. Definition and bibliometric analysis of built environment stock studies

2.1 Defining built environment stocks

The anthropogenic material stocks consist of materials and products staying in the anthroposphere over a certain period of time (usually more than one year in MFA). We categorized them into mobile stock (e.g., consumer durables, machinery, and electronic equipment) and non-mobile stock (buildings and infrastructure).[45] More precisely, the latter includes man-made buildings (residential and non-residential) and infrastructure such as transportation infrastructure (road and rail network) and technical infrastructure (e.g., for energy supply, telecommunication, water distribution and waste collection networks) and is often called "built environment stocks"[45] (which is used consistently hereafter).

Figure 1a visualizes the anthropogenic stock in a "tree" structure: the different end-use categories of the built environment stocks are represented in the form of branches upon which the mobile stocks, represented by leaves, can be found. Human activities (e.g. to nourish, clean, transport, communicate, reside, and work[46]) and well-being, represented here as fruits, are structured in and supported by these

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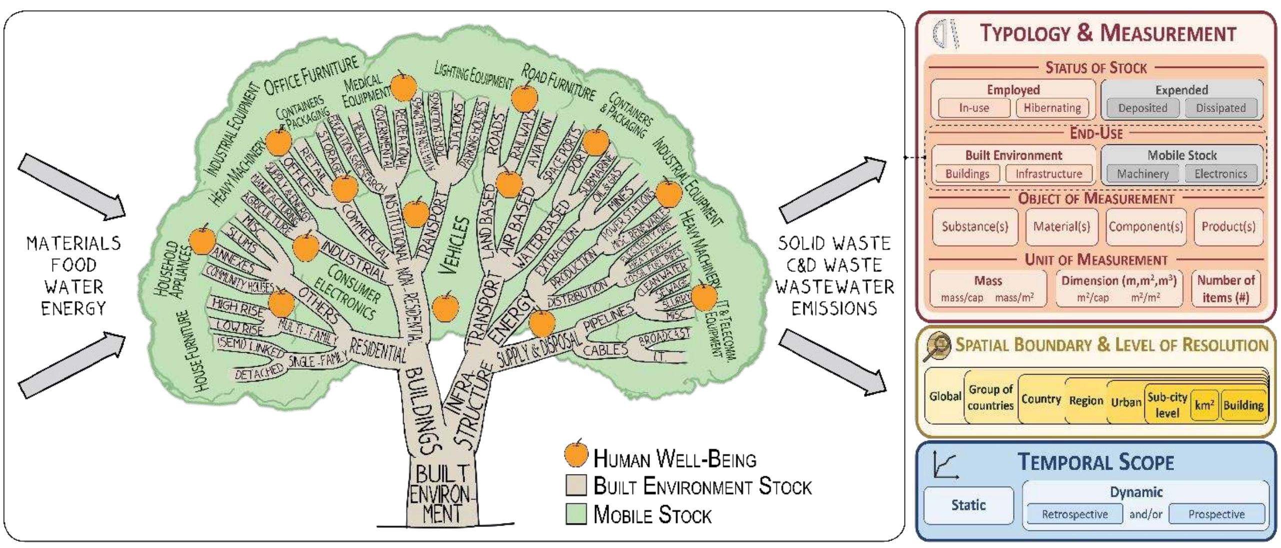
anthropogenic stocks. They are also sustained through continual inputs of materials, food, energy, and water and generate outputs of wastewater, construction and demolition waste, solid waste, and emissions.

The present review specifically covers the built environment stock and thus excludes studies focusing solely on mobile stocks. However, studies analyzing the aggregated anthropogenic stock, and thus including both mobile and built environment stocks, are within the scope. An example of such study is the quantification of copper stocks in Cape-Town,[47] which includes copper in buildings and infrastructures, but also in electrical and electronic products.



(a) (b)

Figure 1 (a) Anthropogenic stocks as a tree. Branches represent the built environment stock end-use categories, and foliage represents the mobile stock categories. Information on the number of publications relative to each end-use can be found in SI. (b) The different dimensions of the scope of study in any stock analysis. The categories in grey are not considered in the present review.

2.2 Bibliometric analysis

The studied body of literature is composed of 249 studies, of which 178 are peer-reviewed journal articles. The remaining studies include conference proceedings (14), theses (13), and reports from different organizations (44) such as research project reports, white papers, and public or governmental reports. The number of studies has been increasing over the last two decades (Figure 2a), reflecting a growing interest in the understanding of built environment stocks. More than half of the peer-reviewed journal articles were published in four journals (Resources, Conservation and Recycling, Journal of

Industrial Ecology, Building Research & Information, and Environmental Science & Technology) (Figure 2a).

Additionally, an evaluative bibliometric analysis was conducted on peer-reviewed journal articles published in English. The two most prolific authors in the field, Daniel B. Müller and Hiroki Tanikawa (Figure 2b), are also at the center of two clusters of built environment stock researchers (Figure 2c) based in Europe (mainly Norway, Denmark, Netherlands, Austria, and Germany) and East Asia (mainly Japan and China). In Europe, Müller's dynamic MFA model for quantifying future material stocks[29] has been further developed and used by his colleagues in a number of studies, mostly at a national level. In Japan, Tanikawa developed a methodology integrating Geographical Information System (GIS) into bottom-up studies[48] for quantifying and locating construction material stocks over time (4d-GIS) at an urban and national level, which has since been widely used in case studies elsewhere.

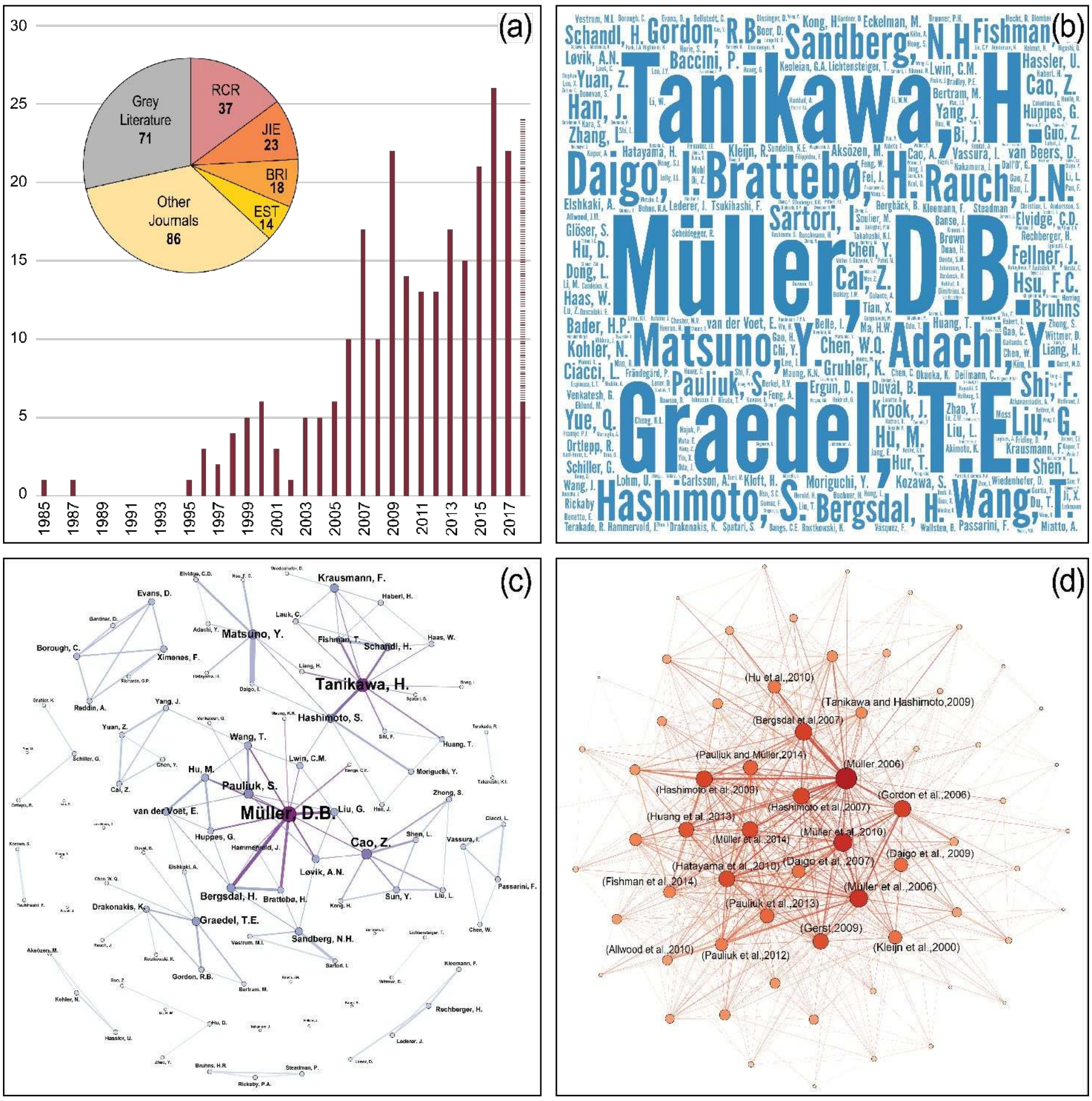


Figure 2. Bibliometrics over the body of built environment stocks literature (Figure (a) includes all 249 publications, and Figures (b)-(d) include peer-reviewed journal articles in English only). (a) Number of publications per year and number of articles published in different peer-reviewed journals or grey literature. Note that the year 2018 only includes publications up to March 2018, and a factor 4 was applied to approximate a result over the whole year. Abbreviations – RCR: Resource, Conservation & Recycling; JIE: Journal of Industrial Ecology; BRI: Building Research & Information; EST: Environmental Science & Technology; (b) Tag cloud of the journal article authors, with the size of names proportional to number of journal articles that author published (both first author and contributing author roles are counted; see details in Table S2 in Supporting Information); (c) Network of co-authorship; and (d) Co-citation network of key literature on built environment stocks. The top twenty cited articles can be found in Supporting Information.

3. Characteristics of built environment stock studies

The scope of a stock study is defined through three dimensions (Figure 1b), namely "typology and measurement", "spatial boundary and level of resolution", and "temporal scope". Figure 3 shows the results of the scope analysis for the reviewed body of literature.

3.1 Typology and measurement

The typology and measurement dimension can be categorized into "status of stock", "end-use category", "object of measurement", and "unit of measurement".

3.1.1 Status of stock

The status of stock, derived from Kapur and Graedel's work, includes employed stock (extracted from nature for human use, not yet discarded) and expended stock (discarded after use or dissipated).[49] The present review focuses on employed stock, composed of "in-use stock" (being used by humans, e.g., vehicles on the road) and "hibernating stock" (not actively used anymore but not yet discarded, e.g., obsolete underground water pipes).[49] The majority of studies include in-use stock, except a few studies focusing solely on hibernating stock.[18,50] However, inconsistencies in typology of stocks in the body of literature hinder a deeper analysis of the status of stocks under investigation. An example of such definition mismatch is the one on dissipated stock. While Kapur and Graedel[49] define it as the amount of resources that went back to nature and is impossible to recover, Tanikawa and Hashimoto[48] exemplify it as material stocked underground and remaining there after the above structure was removed, thus equivalent to Kapur and Graedel's "hibernating stock" definition. Kapur and Graedel's[49] in-use stock is coined as "social stock" by Yue et al.[51] Daigo et al[52] name the combination of obsolete stock and in-use stock "overall stock", while Kapur and Graedel coin it "employed stock". Krook et al[53] classify metal stocks into "active" (including in-use stocks) and "inactive" (subdivided into "controlled", thus including hibernating stocks, and "uncontrolled"). In general, it seems that in-use stock studies often include hibernating stocks as part of the in-use stocks, unless stated specifically.

3.1.2 End-use

The end-use category refers to different functional uses of buildings (e.g., residential, office, and commercial) and infrastructure (e.g., roads, power plant, and pipes). A detailed categorization of end-use categories was developed (Figure 1a) to consistently classify each case study and allow for identification of patterns in the body of literature. (See Figure S1 in Supporting Information for detailed frequency count on end-use in the body of literature).

Almost half of the studies (48%) consider the totality of the anthropogenic stock, which can be explained by the large amount of studies quantifying the amount of a specific material (often a metal) stocked in the anthroposphere, through a top-down approach that uses statistical data for material consumption in major product categories and their lifetime (see details in section 4). Of the remaining studies, about half look at the building stock while only a few focus on infrastructures, reflecting a higher interest in buildings which may cause an oversight of the importance of infrastructures in stock dynamics.

One striking feature is that definitions of different end-use categories vary a lot. For example, a residential building stock may be referred to as a domestic building,[54] or dwelling stock.[55] Non-residential buildings can be studied as an end-use of its own,[3] or can be defined as "non-domestic building" by opposition to domestic buildings.[54] Some studies refer to commercial buildings[56] or industrial buildings,[47] and some also refer to non-residential buildings as part of the overall dwelling stock.[47] Classifying building uses is a complicated task, and many countries have their own classification. Such inconsistencies in definitions hinder comparisons between studies, thus making it difficult to identify patterns in a transparent way.

3.1.3 Object of measurement

The object of measurement includes substance (e.g., copper[18]), material (e.g., cement[57]), component (e.g., window frame[58]), product (e.g., floor[59]), or the entire building. It should be noted that in cases measuring stocks in dimensions or number of units, such as a study of the number of buildings in a city's building stock, the object of measurement (building) is the same as the end-use category.

Almost half of the literature on stocks focuses on one or several metals. A large share focuses on several construction materials, including metals and bulk construction materials. The list of construction materials under consideration is different for each study, making results difficult to compare. The most studied materials are steel, copper, timber, concrete, and aluminum (Figure 3b).

The rest of the studies measure stock in terms of number of items or dimensions and typically do not focus on any specific material.

3.1.4 Unit of measurement.

A stock can be quantified through different units: number of items (e.g., number of buildings[60]); dimensional units such as the total length of pipe in a city[61] (m), the floor area of a residential building stock[59] (m^2), or the total volume of material (e.g., m^3 of clay in single detached housing stocks[21]); or weight of material (e.g., tons of steel[52]). The stock results are also sometimes displayed through indicators measured as stock values relative to land area (e.g., mass of material per square meters) or population (e.g., mass per capita and floor area per capita) for comparability.

Most studies (88%) characterize stocks in mass-related units (Figure 3a), including indicators derived from absolute results (e.g., mass/capita or mass/sq.km) which allow for comparison of stocks in different places or times. As specified earlier, a small share of the literature quantifies stocks in terms of physical dimensions such as volume[16,21,62] or floor area of building stocks,[32,59,63] or length of roads,[64] while the remaining studies accounts for the number of specific items (e.g., buildings[25,65–67] or windows[58]).

3.2 Spatial boundary and level of resolution

Stock studies are conducted at different geographical scales, ranging from neighborhood, urban, regional, national, multinational (several countries) to global scale. While some studies quantify the total stock within the given geographical boundary, others include a higher spatial resolution (e.g., a global stock study could have resolution for each nation and an urban stock study could have data per square kilometers).

The spatial boundaries over the body of literature span from global (17) to building-level (3), while the spatial resolution varies from virtually no resolution[68–71] to spatially very refined results.[72]

- A few studies at the global scale have results refined to the level of groups of countries[6] or to national levels.[27,69]
- 55% of the studies were conducted on a national level (Figure 3d). Each country in the world has been studied at least once, as part of an effort to characterize the stock of a single material

such as aluminum[27] or steel[73] of all world's countries. China and Japan were studied the most, with respectively 43 and 29 studies related to (parts of) their built environment stock (Figure 3e). Most studies at the national level resulted in stock characterization at the nation level. A handful are however refined to a regional level[74–79] or further.

- Seventeen articles report results for stocks on regional levels (part of a country). It is worth noting that due to differences in country size, a regional study in a country can be geographically wider than a national study for another country.
- On an urban scale, 86 cities were studied in 58 publications. For example, studies for the city of Beijing in China calculated the amount of construction material stocked in its entire built environment stock,[80] residential building system,[81] and road system,[82] and the amount of concrete stocked in its residential buildings.[83] Vienna is another city that has been studied from different angles: construction material stocked in its buildings over time[84] and in its subway network[85], and the total amount of copper[86] and lead[87] stock in the city. One single study estimated the material stocked in infrastructure in 40 US cities based on road scaling patterns and distance from the city center[64], explaining the numerous urban studies "dotted" in the U.S. on the map. Studies at the urban level can be refined to a neighborhood,[47,87,88] hectare[40] or up to square meters resolution.[64,89,90] In other cases, results are presented at the study object level. This is the case for studies on transportation networks, where the geographical resolution is visualized through maps depicting the location of the network under study, e.g., different subway lines[85] or different road types over a city.[82]
- Four articles also report stock results at a neighborhood scale, i.e., the PolyVinyl Cholride stock in buildings in an Amsterdam neighborhood,[91] the dynamics of the material stock of buildings, roadways, and railways in Salford Quays in Manchester, UK and Wakayama City Center in Japan.[48]

3.2 Temporal scope

41% of the reviewed studies characterize stocks in a static way, giving a snapshot of the state of the stock at a specific year. The rest of studies are dynamic, as they consider the evolution of stock over time. Studies focusing on the historical dynamics of stock are "retrospective", while studies analyzing future development of stock are "prospective". The temporal scope of dynamic studies varies greatly, from a few years to over a century (Figure 3c). Studies taking into account long historical periods[48,73,92–95] are good basis for analyzing dynamics of stocks over time and providing insights into the non-linear waste and recycling potentials due to stock dynamics. By coupling changes in stock to events such as natural disasters[96,97] or wars,[25,93] links to broader socio-economic issues can be made.

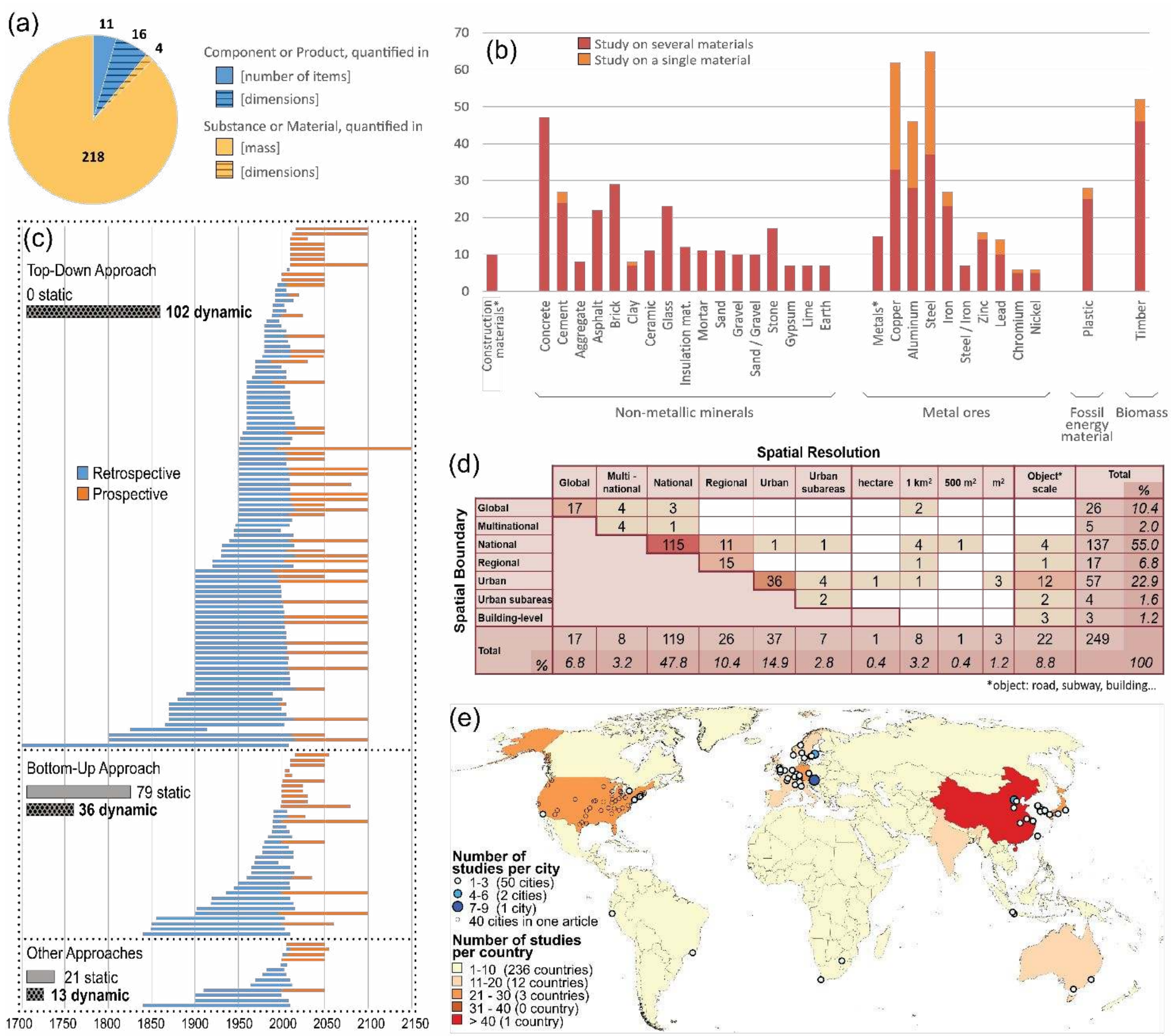


Figure 3 Scope of the built environment stocks literature. (a) Object and unit of measurement over the body of literature. (b) Main materials studied over the body of literature. *A number of studies present results aggregated in material groups such as "construction materials" or "metals". (c) Time scopes of studies categorized by methodologies (top-down, bottom-up and other approaches are defined and discussed in details in section 4). The blue-orange bar charts depict the time scales of retrospective and/or prospective dynamic studies. Note that two publications include two case studies at once, resulting in a total of 251 case-studies over 249 publications. (d) Spatial boundary and spatial resolution of studies. Almost half of the case studies were performed at the national scale, with no further spatial differentiation. "Object-scale" refers to studies spatially refined to the levels of e.g.,

buildings, or entire subway network. (e) Geographical distribution of case studies on the national and urban levels.

4. Overview, development, and critical discussion of the different estimation approaches

The body of literature was screened in terms of estimating approaches which are generally categorized into top-down approach, bottom-up approach, and their combination and extension.[14,42,72,73,98] Figure 3c shows that the numbers of studies using the top-down approach (102) and the bottom-up approach (115) were almost equal. A few other methods were also used in the literature, especially a remote sensing based approach (10) and hybrid approaches (7) that use bottom-up results to calibrate top-down models. These different estimating methods each have strengths and weaknesses, and should be chosen in accordance with the purpose of the study and data availability.

4.1 Top-down approach

The top-down approach builds on the mass-balance principle that the change in stock is the result of the difference between inflows and outflows of a material over time, usually over a year.[42] Over the body of literature, the term "top-down" is used inconsistently, leading authors to sometimes name their methodology in a more descriptive manner (e.g. residence time model[99] or population balance model[52]). In top-down studies, historical development of employed stocks (retrospective study) is thus actually calculated through a flow-driven approach.[100] Data on inflows of material are usually available (e.g., from statistical agencies, industry associations, non-governmental organizations, and scientific literature) over long period of time. But outflow data are much more difficult to track, and are thus often calculated through estimated lifetime of product and infrastructure.

The approach is particularly efficient in achieving an overview of the stock dynamics over long periods of time (Figure 3c). For example, based on a top-down approach, per capita in-use iron stocks in a few industrialized countries are found to saturate since the 1970s,[101] and a few advanced economies (e.g., Japan, Italy, Germany) show trends of steady speed or deceleration in their material stock accumulation.[24] However, globally and for major world-regions, no saturation of total in-use material stocks can be found.[6]

These identified historical patterns of built environment stocks in industrialized countries may be used as a benchmark for future development pathways (e.g., potential saturation levels of stocks) of developing countries. Such an approach to use identified stock patterns as driver for simulating future material cycles and demand, introduced by Müller in 2006[29] in a study of the Dutch dwelling stock from 1900 to 2100, has been further used and developed in many other studies over the past years.[45,59,63,83,96,102] The underlying logic of this method is that in-use stocks reflect directly the service levels (e.g., m^2 of shelter and ton- or person-km of mobility), behave more robustly than flows in the long term as they are not affected by short-term oscillations in consumption,[74] and set boundary conditions for raw material demand and potentials for recycling at the end-of-life of products and infrastructure.[96]

However, since historical shipment or apparent consumption data are mainly available on the global and national levels and for broad categories only through industry statistics, the spatial resolution of top-down studies rarely surpasses the national level and they usually do not have a resolution on the individual product or infrastructure level (aggregated product categories instead). This hinders a detailed understanding of the location and quality of anthropogenic stocks. In addition, average lifetime is a key parameter for modeling stock accumulation in the top-down approach (lifetime distribution functions almost does not affect the stock modeling, but is a key factor in accurately projecting future flows of demolition waste),[103] but there are very few empirical data and thus huge uncertainty on lifetime (particularly difficult to assume a reasonable average lifetime for product categories that include many heterogeneous products[104]). For example**,** Huang et al estimated the Chinese building stock through a top-down approach as 84 tons/cap in 2010.[105] A bottom-up approach of only the residential buildings in China yielded a result four times inferior (24 tons/cap) for 2008.[75] Although the bottom-up study investigated a smaller part of the built environment than the top-down study, this difference in results is still noteworthy and might also be explained by methodological differences. For example, lifetime of buildings is a critical factor of top-down estimations that is very poorly understood in China.[106]

4.2 Bottom-up approach

The bottom-up approach (also called coefficient based approach[5]) quantifies the amount of stock "piece by piece", by counting all items containing a specific material and multiplying the number of each specific product by its material intensity. Bottom-up approach for stock estimation is therefore highly data and labor intensive.

Because they are directly derived from information on stock inventory, results of bottom-up studies are usually deemed to be more accurate than those obtained through a top-down approach. Moreover, the bottom-up approach is advantageous in regards to spatial and content differentiation of results. Bottom-up studies thus contribute to an improved comprehension of the physical arrangement of the system[107] and provide a detailed understanding of the composition of the stock,[72] especially for studies focusing on a defined areas.[107]

However, because of the large amount of data required to conduct such study, the scope of bottom-up studies is often narrowed down to a smaller geographical scale (national level or below), specific year (snapshots),[28] specific materials, and usually to those types of stocks, where such information is actually available (which partially explains why so many studies on residential buildings exist). Indeed, if the bottom-up approach is applied to a wide scope, limitations and uncertainties arise concerning data for inventories of products, material applications, and material intensity data.[107] In order to overcome these limitations (on material intensity and stock inventory), researchers have identified a few complementing ways.

- **The use of building archetypes.** The use of "building archetype" consists of classifying the building stock according to types (or building use), cohorts (or age of construction), and/or the combination of the two into theoretical buildings called "archetypes".[108] By weighting each archetype by the number of buildings fitting the archetype description, the heterogeneous data sets of building stocks are homogenized, thus facilitating analysis.[109] Though the approach has primarily been used for modelling energy performance of building stocks,[110–113] building archetypes have also been used for material stock studies, by applying an average material intensity coefficient to each archetype stock. For example, Ortlepp used building archetypes on a national scale in Germany, by homogenizing the heterogeneous stock that are non-residential buildings.[114] Ergun used the approach on the urban scale and inventoried the amount of clay bricked stocked in Toronto's single detached house to examine the availability of the material for urban mining purposes.[21] In the Netherlands, researchers developed building stock models by linking building archetypes with cadastral information, for the purpose of city planning and the circular transition.[115–122] It is worthy to note that, the archetype approach unavoidably generates uncertainties at different levels.[123] For example, Ortlepp et al raised the representativeness issue of building materials content data based on sample buildings (due to lack of official statistics). By comparing a simplified archetype classification (based only on building type) to a building-age concept (archetypes based on both building type and age cohort), they also found that an increased level of differentiation could better model reality, allow for more precise estimation of uncertainties, and increase the range of applicability of results, but meanwhile raise the data collection challenge and level of uncertainty.

- **Integrating Geographical Information System (GIS) tools and data in bottom-up studies.** GIS, as a tool for handling, processing and analyzing large amount of geospatial data, allows for higher spatial resolution and improved understanding of the physical system and composition of built environment stock. In order to conduct a GIS-based bottom-up analysis, two crucial types of data are required.[124] First, spatial data that contains information on the geo-localization of buildings and infrastructures, as well as attributes such as type of buildings and infrastructure or year of construction. Second, material stock intensity data that informs on the material composition of buildings and infrastructures and that, ideally, should be specific to each and every building and infrastructure. But as of today, most GIS databases do not include such "bill of material" information, and studies rely on average material intensity coefficients derived from building archetypes. Still, the few existing GIS-based bottom-up studies have proved to yield more detailed results than other methodologies. Tanikawa, a pioneer in the integration of GIS in bottom-up studies, analyzed the Japanese built environment stock through a GIS-based bottom-up study[48] that resulted in an estimation of 170 tons/cap in 2010. In contrast, top-down studies of Japan resulted in higher estimations ranging from 236 tons/cap of construction minerals in 2000[125] to 310 tons/cap of construction materials in 2005.[28] On an urban level, Beijing's 2013 road stock was studied in a bottom-up fashion in two different studies. While the study without use of GIS yielded c.a. 1 ton/cap of construction material,[80] the GIS-based study yielded results 7-fold higher.[82] Although the difference can be partly explained by the inclusion of e.g., ancillary facilities (20% of the results), such difference reflect also the usefulness of GIS for a detailed assessment of built environment stocks.
- **Refining archetypes with GIS data.** The use of average material intensity for building archetypes also generates uncertainties as they fail to capture detailed information on the geometry and

construction assemblies of each building. For example, Stephan et al estimates a possible error of 20% in calculating the amount of material stocked in outer walls, depending on the geometry of the buildings.[39] Since this uncertainty was calculated based on outer wall geometry only, the potential variation in material stocks of the whole buildings, neighborhoods, or cities could be even higher. To address such geometrical issues, the authors drew on GIS data of Melbourne's buildings footprints. They studied the city's building stock through a disaggregated approach integrating building geometry and architectural knowledge of experts in order to derive bill of material and assemblies quantities for each building. Developing systematic reporting of bill of materials for each building within a country would be commendable in order to facilitate detailed studies of built environment material stock composition. Some on-going initiatives include for example "Building Passports" or "Materials Passports" tools and database (sets of data describing defined characteristics of materials in products that give them value for recovery and reuse), e.g., in the EU project "Buildings As Material Banks"[126] and Dutch Madaster platform.

- **Integrating the time dimension in bottom-up studies.** The majority of bottom-up studies in the literature have been conducted in a static manner. Thirty-five studies, though, yielded dynamic results in an effort to depict and analyze the changes of stock over time. Dynamic bottom-up studies are in fact dense series of static results. Increments vary from one[72,80] to ten years[88] in the literature. For example, in 2009, Meinel et al studied the spatial and temporal development of building stock of a German city over 20 years.[90] Topographic map data and information on the buildings physical structures were added into a GIS model, which showed the changes of material stock over time in the city.[90] The same year, Tanikawa and Hashimoto[48] studied the development of material stock in two urban neighborhood, one in Japan and one in the UK. They developed a 4d-GIS framework in which the time dimension is integrated into the GIS tool to geo-reference the changes in material stock distribution over time, which has since been used for a few other studies (e.g., Ezhou city in China from 1970 to 2013[127] or the whole Japan at a spatial resolution of 1 sq.km over 65 years[72]). Integrating the time dimension to GIS studies allows to answer both questions of "when" and "where" did material accumulate, which enables a spatial-temporal analysis of patterns and impacts of stock accumulation regarding, for example, the role of urban forms in urban stock accumulation and urban mining potentials.[48]

4.3 Remote sensing

The use of remote sensing technologies has been on the rise in the recent years in material stock research, inspired by the findings that the radiance of nighttime lights (NTL) correlate well with human activity and socioeconomic parameters[128–130] such as population, energy consumption, gross domestic product (GDP), and CO_2 emissions.[130,131] Rauch[132] used the linear relationship between GDP and a handful of available stock data to estimate the global in-use stock of four metals (Al, Cu, Fe, and Zn) in 2000 and produced a 1km-by-1km resolution map. Takahashi et al.[133,134] confirmed the feasibility of this approach by studying the relationship between NTL and in-use copper stock (the correlation originated from the copper in electric wiring), and concluded that the "NTL/in-use stock method" yields more accurate results than "GDP/in-use stock method". Additionally, studies showed that building steel stock is highly correlated to urban NTL, while infrastructure steel stock is correlated to total NTL,[79] and that certain types of NTL images have greater modeling capability than others for in-use steel stock studies.[135]

This method is beneficial as NTL images are readily available for the entire world, over many years, and countries lacking statistical data can still be analyzed in a relatively low cost, high spatial resolution (generally 1 km [79,132,134] and up to 500m[135]), and highly efficient manner.[135] Therefore, the results can be used to identify stock-intensive areas that would deserve further refined study. However, these generated data at a high-resolution level should be interpreted with care due to inherent limitation of this method, such the full nighttime light saturation effect[132] and scale effect. Furthermore, these results do not robustly describe the physical system (e.g., no information for underground built environment stocks), nor the material composition, age and quality of the stocks studied. They generally present static results only as well because the NTL imagery are literally picture of light-emitting structures at one point in time (Similarly to bottom-up studies, the time dimension can be introduced through the compilation of results over a series of years[134]).

4.4 Other approaches

Chen and Graedel[104] classified stock estimation approaches using product level data over long time spans as four quadrants: flow-based vs stock-based and using physical data vs. using monetary data. They found the use of monetary data (both flow-based and stock-based approaches), coupled to "material content per monetary unit" coefficients, could allow the physical quantification of related in-

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use stocks. Such monetary data have the advantage of becoming increasingly available in the form of annual investment flows and Input-Output (I/O) tables, particularly in the US and Japan, over long timespans. They successfully apply the methodologies to the case of aluminum use in automobiles in the US. Although not specifically applied to built environment stocks, the "Flow-Based using Monetary Data" method is deemed usable for calculating in-use stock of materials that have detailed I/O tables in relevant sectors. In the US for example, aluminum, copper, iron, and plastics have products or products groups in the sectors of building and structures and transportation facilities.

Bottom-up and top-down approaches have been used complementarily in order to reduce uncertainties by using elements from a methodology to support the other approach in cases where data are lacking.[98] Schiller et al increased the robustness of their conclusions by quantifying the uncertainty in their study of Germany's anthropogenic stock and by contrasting complete but less detailed top-down results with incomplete but partially more robust bottom-up results.[5] In very few studies, bottom-up results were integrated in top-down studies as a mean of calibrating the model.[136–138]

Tanikawa[72] and Fishman[139] argued that such calibrated top-down studies could in turn be used to calibrate remote sensing approaches, and could also help develop more accurate scenarios based on an improved understanding of the relation between material stock and socio-economic indicators. In conclusion, the different approaches to characterize material stocks are thus not self-excluding, and comparing and hybridizing approaches would be a fruitful way to increase robustness of results[72] and overcome limitations inherent to each approach.

5. Purposes and implications of studies

In addition to theoretical and methodological development mentioned above, existing built environment stock studies often go beyond and aim to inform relevant stakeholders in their waste management, urban mining, spatial planning, circular economy, and resource efficiency strategies.

Retrospective dynamic studies are useful to identify trends and patterns (e.g., potential levels of saturation[101]) as well as potential drivers such as economical growth[33,140,141] or population growth[142] in historical stock development. The age distribution of stocks and connected operational energy use and future waste flows can also be investigated, as well as potentials for recycling[143–146] (extent to which recycling has occurred[68,93,147,148] or material turnorver[92]). Such information can assist authorities and governmental decision-makers, and ultimately different industry stakeholders, in developing appropriate life cycle management measures.[57]

In prospective dynamic studies, scenarios are developed to forecast the evolution of stocks and related flows under different conditions. Drivers identified in retrospective studies can be used to develop these scenarios and model possible future developments of material cycles, such as their demand,[27,29,69,105,125,149,150] production and consumption,[151,152] waste generation,[29,105,153] availability as secondary resources,[16,99,153] associated energy use[27,151] and CO2 emissions.[27,35,105,151,154] Developing scenario also allows to study the impact of introducing policies and strategies such as material efficiency,[155] energy reduction,[32,108] technological substitution,[156] prolonging lifetime of buildings and infrastructures,[157] or improving material recovery rate.[20] Scenario development can also be used to assess what strategies are needed and what are their contributions to reach a specific target, e.g., a global saturation of per capita stocks,[69] developing countries reaching infrastructure levels of industrial countries,[35] emission cuts,[37] and addressing housing deficiency in developing countries.[66]

Stock studies are also conducted to characterize stocks in a high level of detail to gain knowledge on material quantity in different products or end-uses (mostly at the urban or regional scale), which yield results valuable to different stakeholders. For example, potentials for city-level material reuse and recycling[19,21,158] can assist decision makers for sustainable planning, while new or improved knowledge on recycling, mining and mineral processing sectors[159] can assist waste management companies in targeting relevant waste categories for recycling.[160]

A number of case studies include additionally the spatial distribution of different material stocks across a city or a region to identify urban mining opportunities[5,39,161] such as materials stocked in hibernating infrastructure stocks.[18] Spatial information is also used for assisting development of location-specific strategies for the reduction of environmental impacts of buildings and settlements.[162] Construction and demolition waste management[15,40,163] can be planned in more details by assessing the technology required to recover future available secondary material or product,[159] as well as planning of transportation routes and location of facilities for storage of recovered secondary resources.

However, developing recycling and urban mining strategies requires additional information on technical and socioeconomic drivers and constraints, but such feasibility analysis is still largely missing. Worth noting is the work of Van Beers et al which analyzed copper and zinc recycling potential in Australia and developed a priority assessment matrix to evaluate all copper and zinc's end-of-life flows from in-use stock according to quantity, material properties, and location (most economical in the dense urban centers).[164] Krook and colleagues analyzed the economic conditions to mine copper from hibernating power cables in Swedish cities,[23,165] and concluded that, unless infrastructure managers integrate the resource recovery process into their system upgrades project, the extraction of copper does not make economic sense.

6. Drivers and comparability of built environment stock results

We have collected empirical results of all studies whose scope focus on the weight of the totality of construction materials, in one or several parts of the built environment stock, at the national or urban scales, to allow for comparability or consistency check on a per-capita and per-km^2 level. At the urban scale, 22 publications satisfied such scope, covering 26 cities or urban areas; at the national scale, 19 countries are covered over 18 publications. Figure 4 visualizes the results on per capita and per km^2 levels. Although the heterogeneity of the scopes of the studies (different spatial scale, end-use, type of stock, materials, years, and methodologies) hinder accurate comparison, a number of key conclusions can be drawn.

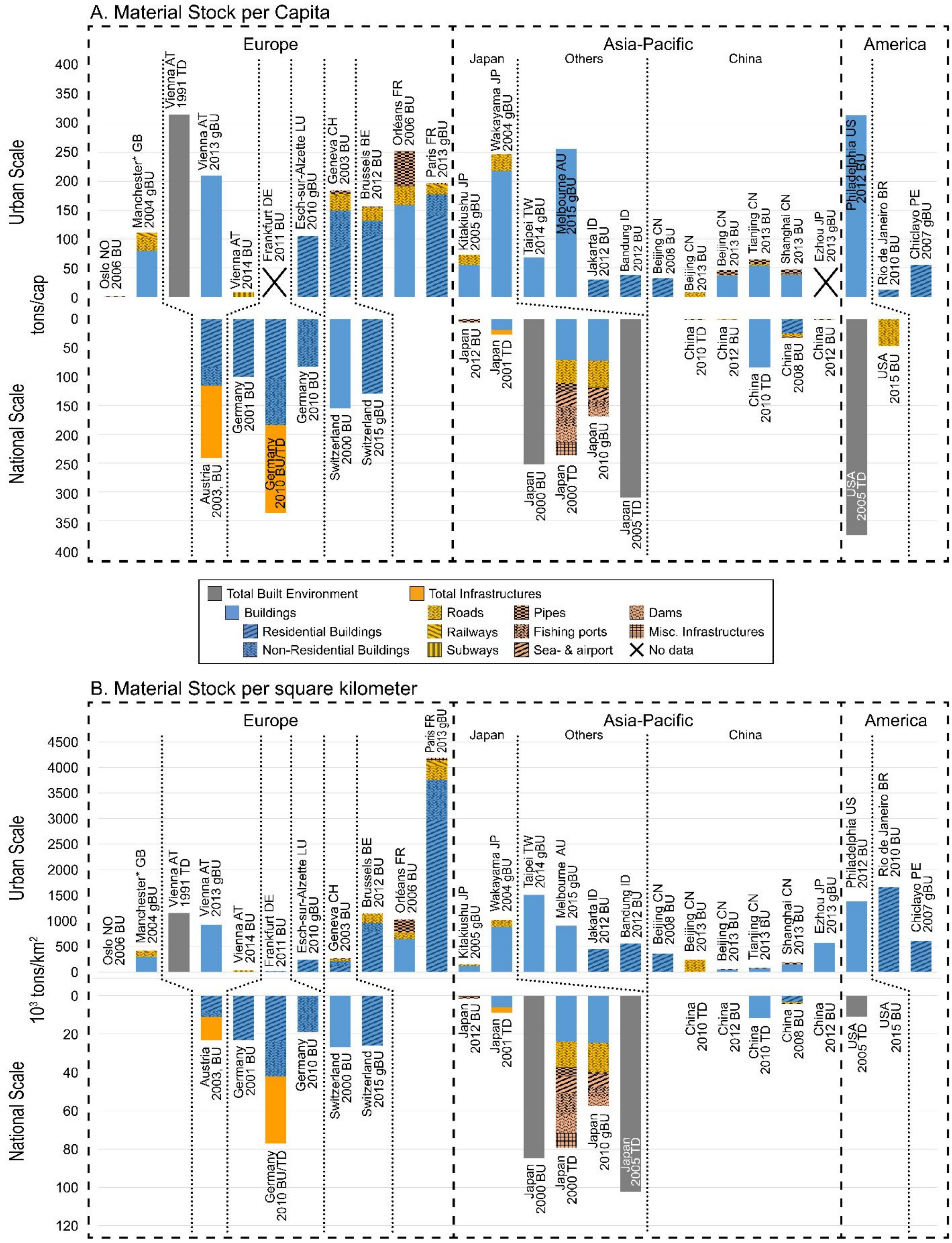

Figure 4. Results of studies quantifying construction material stocks in terms of mass at the urban and national scales. (a) Material Stock per capita (t/cap). (b) Material Stock per km^2 (kt/km^2). Note the scale difference between urban and national results. Abbreviations of estimation approaches – BU: Bottom-Up, gBU: GIS-based Bottom-Up, TD: Top-Down; Abbreviations of countries – AT: Austria, AU: Australia, BE: Belgium, BR: Brazil, CH: Switzerland, CN: China, DE: Germany, FR: France, GB: United-Kingdom, ID: Indonesia, JP: Japan, LU: Luxembourg, NO: Norway, PE: Peru, TW: Taiwan, US: USA. *2.6 km^2 in Philadelphia (University City); 11 km^2 in Manchester (Salford); 8 km^2 in

Wakayama (City Center). Urban studies: Oslo (NO)[166], Salford Quays Manchester (GB)[48], Vienna (AT)[84,85,167], Frankfurt (DE)[3], Esch-sur-Alzette (LU)[40], Geneva (CH)[168], Bruxelles (BE)[169], Orléans (FR)[170], Paris (FR)[171], Kitakyushu (JP)[172], Wakayama (JP)[48], Taipei City (TW)[17], Melbourne (AU)[39], Jakarta (ID)[173], Bandung (ID)[173], Beijing (CN)[80–82], Tianjing (CN)[80], Shanghai (CN)[80], Ezhou City (CN)[127], Philadelphia (US)[174], Rio de Janeiro (BR)[163], and Chiclayo (PE)[15]. National studies: Austria[175], Germany[5,77,114], Switzerland[162,176], Japan[28,72,78,94,125,153], China[75,105,177–179], and USA[28,142].

Urban areas accumulate the largest share of anthropogenic stock. Indeed, as center of population, production and consumption, they are characterized by a higher density of buildings and infrastructures than their hinterlands. While national built material stock accounts range from about 20 (Austria) to 100+ (Japan) kt/km^2, urban accounts rise to about 1000-1200 kt/km^2 in Vienna (Austria) and about 1000 kt/km^2 in Wakayama City (Japan). The smallest area studied in the literature, 2.6 km^2 of Philadelphia, US, accounts for about 1400 kt/km^2 of construction material stock, against 10 kt/km^2 for the US national average. Studies focusing on urban areas are thus very appropriate to better characterize and understand materials stocks, be it for urban mining purposes or overall understanding of stock dynamics and drivers.

Per capita levels of developed countries are overall higher than developing countries, both at a national and urban level. Overall construction material stocks in Chinese and Indonesian cities, as of 2012-2013, are less than 50 t/cap in residential or total building stocks while European cities levels are up to 4 times higher, with Vienna amounting to about 200-300 t/cap. Material stocks in Wakayama (Japan) and Melbourne's (Australia) reach about the same level as Vienna's, indicating a potential common pattern in mature cities. The differences between developing cities and mature cities could empirically be explained by differences in socio-economic development. Fishman et al showed that material stock accumulation in Japan prefectures was linked to driving factors such as economic and population growth, as well as population density.[41] In countries like Japan, high levels of material stocks in the built environment are also explained by the demanding infrastructure and building codes necessary to prevent damages from earthquake and typhoons.[48] But it is presently challenging to analyze in details the reasons and drivers of such differences due to different focus of each study. More empirical studies on other typical cities across the world would thus be profitable to obtain better understanding of their drivers and implications.

Non-residential buildings account for an important share of the building stocks. Bottom-up studies quantified their share from about a quarter[175] to almost half [5,114] of the total building stock. Still, non-residential buildings are less studied than residential buildings because their diversified functions and components lead to a lack of data thus hindering their analysis.[114] But such buildings are believed to contain a high share of valuable secondary resources such as metals[3] due to these very characteristics. Moreover, a share of non-residential buildings (e.g., commercial or industrial buildings) is dependent on the dynamics of the economy, and as such their in-use time may be shorter than that of residential buildings.[3,180] Non-residential building are thus a valuable part of the stock that ought to be investigated more in the future.

Urban form, which reflects the physical layouts, structures, and patterns of a city, is also an important driver behind the varying urban material stock levels. As cities are complex networks of interconnected subsystems,[181] characteristics of one subsystem are tied to the other subsystems. For example, the level of infrastructure stock is intrinsically correlated to the density of buildings.[171,182] In densely built areas, the size of infrastructure stocks is about one-sixth of the total built environment stock, while this number rises up to two-fifth in low building density area.[182] Augiseau calculated the share of infrastructure stock in Paris and its suburbs, and found that infrastructures account for 10% of the total built environment material stock of the city, while it increases to 18% in the inner suburbs and 40% in the outer suburbs, both typically less dense than the capital.[171] Another important aspect of urban fabrics is the vertical distribution of built environment stocks. Tanikawa calculated that in Wakayama city center (Japan), material stocked underground in for example building foundations and sewer network amounted for almost half of the total construction materials in 2004.[48]

7. Prospects and recommendations

Built environment stocks play multiple critical roles in our socio-economic metabolism and a better understanding of built environment stocks can assist in addressing many of our societal and policy agendas such as urban sustainability, circular economy, climate change, and United Nations 2030 Sustainable Development Goals (e.g., SDG 11 “Sustainable Cities and Communities” and SDG 9 “Industry, Innovation and Infrastructures”). Based on the present review, we summarize below the main roles of built environment stocks and infer their possible contributions to informing a sustainable socio-metabolic transition.

- First, built environment stocks represent an extensive reservoir of secondary raw materials,[1,5–7,183] therefore a deepened knowledge of the amount, quality, location, and time availability of these material stocks can support urban mining, smart demolition, and waste management strategies for a variety of stakeholders (e.g., waste and recycling companies, architects, developers, and planners. This would lead to a decrease in the final amount of waste disposed, thus fostering circular economy and limiting the excess production of building material and lack of waste disposal capacity.[127]
- Second, stock dynamics drive the material cycles and provide boundary conditions for related energy use and environmental impacts throughout the life cycle. The build-up, maintenance, and end-of-life management of built environment stocks lead to indirect energy use and emissions from their pre- and post-use phases (e.g., production and recycling of concrete).[36] The size, quality, and composition of stocks strongly influence the amount of direct energy used and greenhouse gases emitted for their operation to support human needs and activities (e.g., heating of a poorly insulated house).[1,5,13,28,184] A sustainable socio-metabolic transition and understanding of future resource, energy, and emission pathways would require improved knowledge on the drivers (e.g., population size, levels of affluence, technological change, institutions, policies), patterns (e.g., speed of accumulation and potential saturation levels), and intra-linkages (e.g., systemic relationships between different built environment end-uses) and interlinkages (e.g., relationships between material stock density and energy use and emissions) of built environment stocks.[185,186]
- Third, the built environment stocks entailed temporal and spatial lock-in effects are important for decision-making for the long term and at the urban scales. Stocks stay in use from years to over a century, potentially causing technological lock-ins and hindering a switch to more material- and energy-efficient systems. Decisions related to maintenance and development of built environment stocks are thus to be carefully considered before being implemented. Buildings and road infrastructure are also closely linked, and accessibility to services and commuting distances affect residents' preferred transportation mode[1] and thus influence transport-related environmental impacts. Understanding the interactions at stake between different types of built environment stocks would provide valuable information for urban planners and decision makers for building more energy-, resource- and cost-efficient cities.[36]

- Last but not least, built environment stocks provide essential services on which societies rely to satisfy primary needs (e.g., shelter, mobility, energy production and transmission, and water distribution) and improve social and economic conditions (e.g., communication networks, waste collection, and facilities for education, work, healthcare, or entertainment).[1,6,36,41,185] Therefore stock levels could indicate levels of human development. The historical patterns (e.g., potential levels of saturation[101]) of built environment stocks in industrialized countries/cities could also help benchmark future development of developing countries/cities. Such a stock perspective of human well-being measurement has raised similar discussion in economics, where flow-based indicators such as GDP have been criticized as they do not keep tracks of the assets actually producing the GDP, such as infrastructures and natural and human capital.[187,188]

Although attention to the importance of built environment stocks can be dated back to several decades ago, the booming of empirical case studies on stocks started only after the 2000s. We summarize below the main gaps and barriers in the development of built environment stock research, and put forward recommendations to address them.

- Most studies were conducted on the country level, and only a few have a high spatial resolution (often via an integration of GIS tool and bottom-up data) and a dynamic perspective. In order to draw more robust conclusions on the patterns, drivers, and implications of built environment stocks, more spatially refined case studies especially focusing on less studied geographical regions (e.g., developing countries and cities) and stock categories (e.g., non-residential buildings and infrastructure) are urgently needed. Meanwhile, consistent terminology, standardized methodology, and larger-scale meta-analysis of existing data (e.g., based on a framework such as Figure 1 we developed) would increase the comparability of results and facilitate identification of patterns and drivers.
- Data quality and unavailability are identified as a major barrier for the expansion of built environment stock studies, especially concerning the lack of information on buildings and infrastructure lifetime and material intensity (when less representative and accurate averages were often used). Material intensity databases[189–191] and studies of transferability of data between cities or countries,[192] which allows for the analysis of regions where data are incomplete or missing, are still sparse and should be investigated more. To this end, collaborating with key data providers (e.g., municipalities, utility companies, demolition companies, and building contractors and

developers), harnessing new types of data (e.g., increasing amount of big data in social media and transportation), and nurturing interdisciplinary collaboration have been proven fruitful. For example, architects and civil engineers could contribute with knowledge on more accurate material intensity; GIS and remote sensing related tools and data in the fields of geography and urban planning would allow for a more spatially refined understanding of built environment stocks; the building energy use[193] and efficiency[56] modelling could help retrieve useful spatial and temporal data and understand the roles and drivers of built environment stocks.

- The role of built environment stocks in economic, social, and environmental development is less understood and thus often overlooked in governmental and industry policy arena. How such generated knowledge on stocks is useful for decision-making should be demonstrated via more dialogue among stakeholders in the future. For example, on an urban scale, the mapping and understanding of the dynamics of built environment stocks could provide an urban sustainability indicator (e.g., the weight of cities) from an important yet often overlooked stock perspective and help city councils in urban planning,[48] construction and demolition waste management, decarbonization, and dematerialization policy setting. Construction and waste management companies would benefit from detailed information on building stocks in implementing circular economy thinking within their activities, by reusing or recycling materials and products from their renovation and demolition activities. But if urban mining actions are to take place to recover stocked material, better understanding of the amount and location of materials (e.g., via GIS tools and architectural knowledge) and the technical feasibility and socioeconomic viability[194] (e.g., coupled with Life Cycle Assessment, Cost Benefit Analysis, and other decision supporting tools) are yet to be analysed.[18]

In 1966, Kenneth E. Boulding wrote in his seminal essay "The Economics of the Coming Spaceship Earth" that, as the earth has no unlimited reservoir of anything, "what we are primarily concerned with is stock maintenance, and any technological change which results in the maintenance of a given total stock with a lessened throughput (that is, less production and consumption) is clearly a gain".[195] Over five decades later, the statement holds even more true in an increasingly resource and environment constrained world. Based on the significance and gaps of stock research we identified in this review, we call for more studies and attention on built environment stocks, and particularly highlight the urgency and necessity for research towards standardized terminology and methodology to facilitate consolidation of existing results and further larger-scale analysis, development of more spatially refined case studies and material intensity databases, collaboration with key data providers and other academic fields such as architectural engineering and geography, understanding of socioeconomic drivers, and dialogue with stakeholders and decision-makers for harnessing knowledge on built environment stocks in addressing societal sustainability challenges.

Associated content

* Supporting Information

S1: Materials and Methods, Complementary analysis of the body of literature, Reference list of the body of literature. S2: Body of literature database (results of systematic screening of publications) The Supporting Information is available free of charge on the ACS Publications website at DOI: XXX

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Notes

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