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RESEARCH AND ANALYSIS

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Extending urban stocks and flows analysis to urban greenhouse gas emission accounting

A case of Odense, Denmark

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Abstract

Cities generate greenhouse gas (GHG) emissions both in the construction phase of their built environment stocks and durable goods and in their operation phase with energy and material flows. Existing urban GHG accounting methods, however, focus largely on emissions related to energy and material flows and have rarely considered the role of urban stocks. In this article, we have extended urban stocks and flows analysis to urban GHG accounting, using bottom-up and high-resolution urban stocks and flows information for a case of Odense, Denmark. We introduced a complementary indicator of carbon replacement value (CRV) to account for emissions embodied in the urban stocks and determined the CRV of Odense as 10.7 megatons of CO_2 equivalent (or 53 metric tons per capita) in 2017, equivalent to 13 years of Odense's operational emissions. The comparison between CRV and operational emissions across urban activities facilitates a better understanding of the carbon profile of the city and opportunities for decarbonization. Such urban metabolic based GHG accounting and inclusion of stocks can help to estimate the amount of GHG emissions to be expected from the further urbanization in developing countries as their urban stocks continue to increase and inform their potentials for leapfrogging in emission reduction.

KEYWORDS
carbon emissions, carbon replacement value, Odense, stocks and flows, urban carbon accounting, urban metabolism

1 | INTRODUCTION

Urban areas cover about 2–3% of the terrestrial surface (Grimm et al., 2008) and host 55% of the world's population, a share predicted to rise to 60% by 2030 (United Nations, 2018b). As a result, the production and supply of energy, materials, goods, and services necessary to sustain the well-being of urban residents have major environmental impacts: UN Habitat estimated that cities are responsible for almost 80% of the global energy consumption and 60% of global greenhouse gas emissions (GHG) (United Nations, 2018a).

Despite such an undebatable role of urban socioeconomic activities and metabolic patterns in global GHG emissions, accounting for city-level GHG emissions has proved challenging (G. Chen et al., 2019). For example, while emissions related to energy, materials, and goods both produced and consumed within a city's spatial boundary are logically imputable to the city itself, the allocation of emissions associated with transboundary flows (e.g., import for use in the city, export for consumption elsewhere, and cross-boundary transportation) requires careful considerations

(Chavez & Ramaswami, 2011, 2013). Meanwhile, because urbanization reflects a heterogeneous process of accumulating materials in products, buildings, and infrastructure for human needs (Liu et al., 2019), accounting for such spatiotemporal differences for cities at different levels of development is also very challenging.

In the past years, several urban carbon accounting methodologies have been developed, each reflecting different perspectives of urban socioeconomic activities.

- Territorial emissions (TE) accounting (Cai et al., 2019; Dodman, 2009; Hoornweg et al., 2011), also called pure-geographic production-based emissions, account for emissions taking place solely inside the city spatial boundaries. This is similar to the production-based emission inventory developed for GHG accounting at the national scale, which does not take into account emissions embodied in goods and services imported in a country. TE accounting includes emissions from fossil fuel combustion for in-boundary transportation and from industrial processes within the city (including energy production and emissions from waste).
- The community-wide infrastructure footprint (Hillman & Ramaswami, 2010; Kennedy et al., 2009, 2010; Qi et al., 2018; Ramaswami et al., 2008) aims at unveiling the impact of infrastructures on GHG emissions. In addition to TE, it accounts for emissions embodied in the supply chains of infrastructure-related imports (e.g., energy supply, water and wastewater, construction material, or transportation fuels).
- The consumption-based footprint (Feng et al., 2014; Larsen & Hertwich, 2009; Lin et al., 2015; Mi et al., 2016; Ramaswami et al., 2011) focuses on the impact of urban consumption on climate change. It thus takes into account the part of TE associated with the production of goods and services directly consumed within the city, as well as emissions embodied in all imports (both infrastructure-related and non-infrastructure-related goods and services). TE associated with exports is excluded as they do not reflect consumption taking place within the city boundary.
- The production-based footprint (S. Chen et al., 2018, 2019; Lin et al., 2015) focuses on emissions from all production activities linked to the city. It includes emissions embodied in both imports and exports as well as territorial emissions, but excludes direct emissions from households and governments as those are not production-related.

Those approaches have different advantages and disadvantages as a result of varying scopes and purposes. They have been compared in several studies (Chavez & Ramaswami, 2013; Hu et al., 2016; Lombardi et al., 2017) and results showed that urban GHG accounts can greatly differ depending on the approaches deployed. Chavez and Ramaswami (2011) highlighted that a sole metric such as GHG/capita might not be sufficient to characterize and inform the low-carbon city transition, and a combination of different approaches and key variables might be needed instead.

In line with the above-mentioned accounting methods, a number of standards have been developed by intergovernmental bodies to help cities and municipalities benchmark and monitor their progress towards climate change mitigation (ICLEI, 2009; IPCC, 2006; UNEP et al., 2010; WBCSD & WRI, 2001). For example, in 2014, the World Resources Institute, C40 Cities, and Local Governments for Sustainability, and Climate Leadership Group (2014) released their "Global Protocol for Community-Scale Greenhouse Gas Emission Inventories" (GPC) with the aim of harmonizing GHG accounting to allow for consistent calculations across cities. The GPC is a sector-based accounting that encompasses emissions (direct and embodied) from both consumption and production activities of a city. Emissions are categorized into six sectors: stationary energy (e.g., electricity or heat production), transportation, waste (solid waste and wastewater), industrial processes and product use, agriculture, forestry, and other land use, and, although not mandatory, "any other emission occurring outside the geographic boundary as a result of city activities".

These types of sectoral emissions are often accountable across three scopes that depend on the geographical location of the physical emission. Scope 1 is defined in the same way as TE: it encompasses all emissions taking place within the city boundaries. Scope 2 emissions are those related to the production of grid-supplied energy (electricity, heat, steam and cooling) used in the city, regardless of the location of the power station. Scope 3 includes all emissions that occur outside of the city boundaries, as a reason of activities taking place in the city. Those include, for example, embodied emissions from goods and services imported in the city for consumption, or produced in the city and exported. Kennedy and colleagues categorized Scope 3 emissions into single process emissions (Scope 3_{SP}; e.g., emissions from combustion of aviation and marine fuels) and product-chain emissions (Scope 3_{PC}; e.g., embodied emissions in food and materials consumed in cities) (Kennedy et al., 2010).

Cities generate GHG emissions both in their construction phase ("embodied emissions" for the construction of building and infrastructure stocks and production of durable goods) and in their operation phase ("operational emissions" due to, e.g., transportation and residential energy use). Existing GHG accounting methods, however, focus largely on emissions related to energy and material flows and have rarely considered the role of urban stocks. These stocks are critical to urban sociometabolic patterns and GHG emissions for several reasons. First, their type, quantity, and quality decide the material and energy flows necessary to provide services in the use phase (Baynes & Müller, 2016; Pauliuk & Müller, 2014). Second, they are made of past material inflows that accumulated within the city over years or decades and, as such, embed energy and emission flows from their production processes (Mao et al., 2020). Third, urban stocks indicate the potential of circular economy initiatives in reducing flow-related emissions by reuse/recycling of material already manufactured and recoverable from stocks when they become available at end of life (Lanau & Liu, 2020).

An indicator entitled carbon replacement value (CRV) has been proposed to account for the amount of GHG emissions required to build a specific stock from scratch using currently available technologies (Müller et al., 2013). In other words, CRV does not reflect the amount of GHG emissions historically embodied in a specific stock, but rather the levels of GHG emissions that would be emitted from building such stock today. We argue that

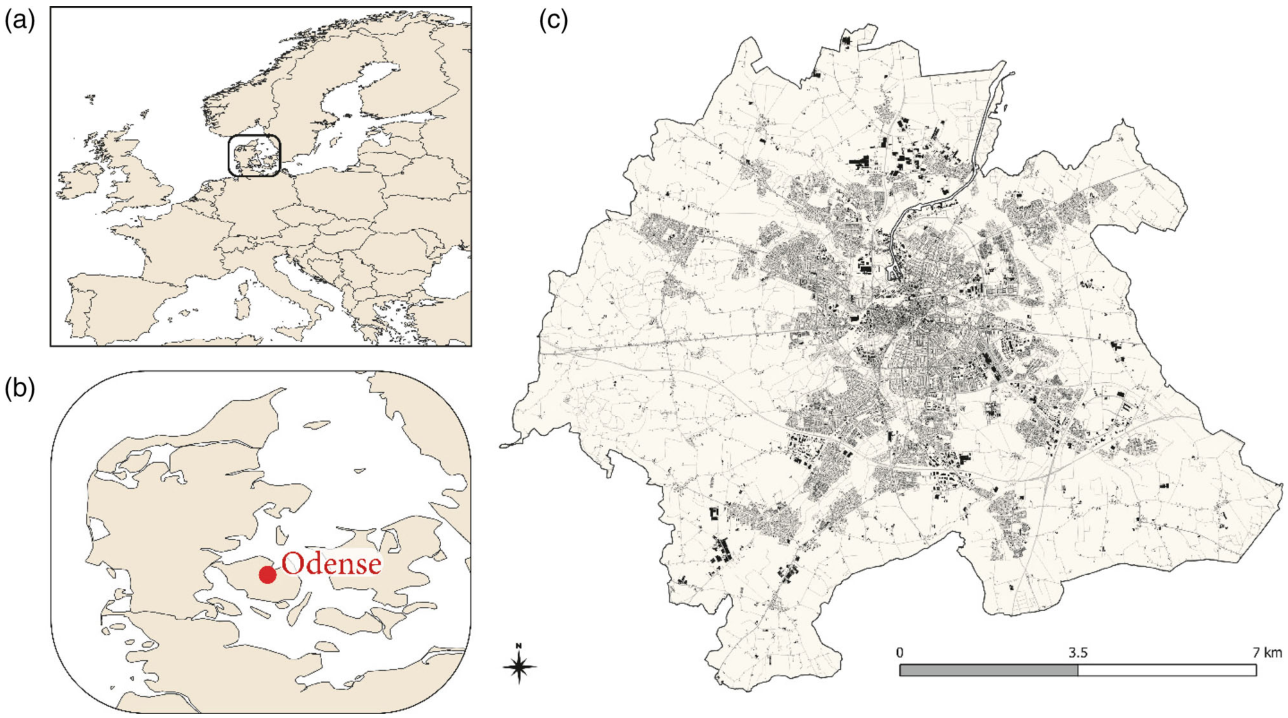


FIGURE 1 Location of (a) Denmark in Europe; (b) Odense in Denmark; and (c) a map of the municipality of Odense

such CRV accounting can be used at the city level as well and brings added values to urban decarbonization discussion. For example, CRV values can be compared to flow-based GHG emissions to gain a full understanding of urban emission patterns across cities, among urban (economic) activities (e.g., building and transportation), and between embodied emissions and operational emissions. And more importantly, calculating the CRVs of mature cities could facilitate the understanding of GHG emissions to be expected from the further development of cities in developing countries as their urban stocks continue to increase, which could help inform their leapfrogging potentials in GHG emissions reduction. (Müller et al., 2013)

Such urban GHG emission accounting based on both urban stocks and flows has not yet been performed, to our knowledge, in particular at a refined level for different urban (economic) activities. As high-resolution mapping of urban stocks and flows has boomed in the past years (C. Chen et al., 2016; Mesta et al., 2018; Miatto et al., 2019; Schandl et al., 2020; Symmes et al., 2019; Tanikawa et al., 2015; Tanikawa & Hashimoto, 2009), this task becomes increasingly possible. In this study, we aim to test how to extend such detailed urban stocks and flows analysis to urban GHG emission accounting by supplementing flow-based accounting with CRV of stocks, and to discuss their implications for urban decarbonization strategies. The case city is Odense (Figure 1), the third largest city of Denmark hosting 202,250 inhabitants over an area of 304 km^2. Odense is selected due to availability of data on both its material stock (Lanau & Liu, 2020) and GHG emission accounts (Danish Energy Agency, 2019), but we believe such an approach can be used for any other cities as well.

2 | METHODS AND DATA

2.1 | Urban sociometabolic system and scope of urban GHG emissions accounting

Figure 2 defines the sociometabolic system for Odense municipality, including all main processes, material and energy flows, and GHG emissions related to urban socioeconomic activities. Key characteristics and justifications of the system definition are detailed below.

1. Processes are placed in-, out-, or across the municipality boundary, according to their geographical location. For example, water extraction takes place entirely within the city boundaries, contrarily to, for example, mining (material extraction) that is conducted outside the city boundary. Processes that take place both in- and outside the city are placed across the city boundary. This is the case of land use, as Odense municipality includes agricultural and forest areas in the outskirts. Still, imported food and timber were produced through land use processes that took place outside the boundary.
2. Material flows include, but not differentiated between, all tangible materials and goods that are key for urban socioeconomic activities, such as construction materials, food, consumer goods, fuels, water, as well as downstream outflows (e.g., solid waste and wastewater). Note that the

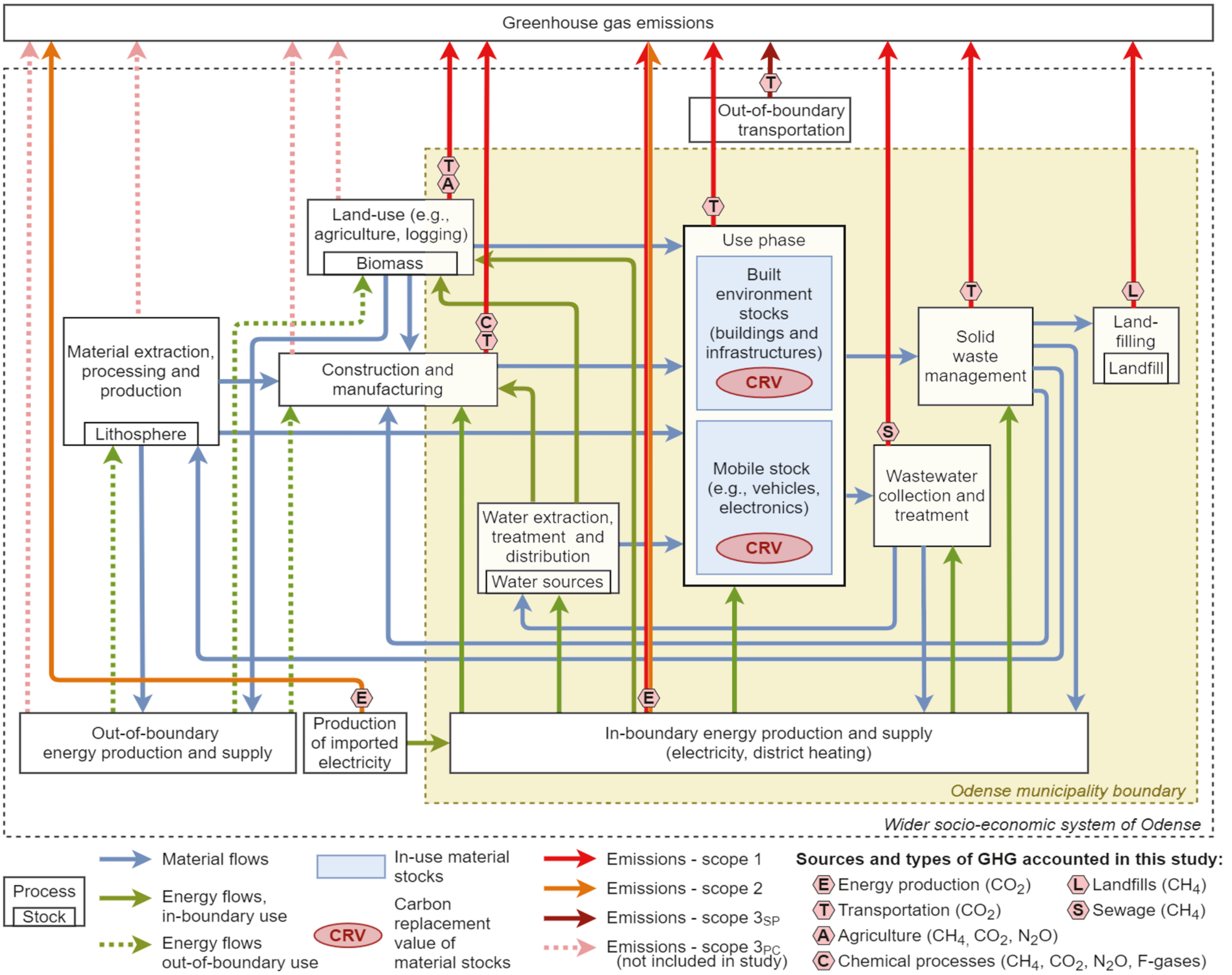


FIGURE 2 The sociometabolic system of Odense and scope of GHG emissions accounting, based on (Müller et al., 2013). Note that exports of materials (and goods) are not depicted. F-gases include hydrofluorocarbons and perfluorocarbons

complexity of water flows was simplified to not overburden the system visualization; in reality, all processes (especially land use) have an inflow of clean water and outflow of wastewater.

3. Stocks of materials relevant to each process are specified, with a focus on material stocks in the use phase. The use phase is understood as the process during which urban residents make use of the city by accessing its goods and services made available via both built environment and mobile stocks and consequent operational material and energy flows. This includes, for example, transportation through the use of vehicles and infrastructures, communication through the use of electronics, residence, work through the use of buildings and appliances, and cleaning through the use of water and wastewater pipe networks. Note that physical buildings and power stations in which processes take place are considered part of the building stock.
4. Energy flows are depicted as outflows from energy production fed to all processes across the system. Note that the process of energy production is divided into three categories, depending on the locations of production and consumption. This consideration is important for the allocation of greenhouse gas emissions, which we discuss in detail below.

The scope of GHG emission accounting in the present study includes GPC scopes 1, 2, and 3_{SP}. Scope 3_{PC} emissions (dashed arrows) are out of scope due to lack of data, but it is worth noting that the inclusion of scope 3 emissions can significantly raise the total carbon accounts of a city (by 45% on average in the study of eight US cities (Hillman & Ramaswami, 2010)). Emissions from energy (electricity, heating, and cooling) produced and consumed within the boundary (Scope 1) are accounted for, as well as emissions from imported electricity production (Scope 2). Emissions from in-boundary land-use include emissions from machinery and off-road transportation (denoted by ‘T’ on Figure 2) and from agricultural processes (A). Regarding construction and manufacturing processes, emissions sources include machinery and off-road transportation (T), and chemical processes (C) taking place within the municipality. Wastewater collection and treatment take place entirely within the city boundaries, and sludge (S) is a source of methane emissions from anaerobic digestion. Regarding solid waste management, Odense is characterized by a large amount of waste being sent to incineration for energy recovery. This process takes place within the city boundary, but it should be noted that emissions from waste incineration are allocated to the energy production process (E). A share of solid waste is recycled, and a small share of waste is sent to an in-boundary landfill that emits methane emissions (L). Emissions from transportation of waste (T) within the city boundary also occur.

The use phase of the municipality is characterized by emissions from passenger transportation. Scope 1 emissions include transportation by on-road vehicles, trains and ferries taking place within the municipality boundary. Scope 3_{SP} emissions include transportation by air as those take place outside of the city boundary, and combustion of marine fuels from the fishing industry (land use). Note that Figure 2 allocates all stationary energy-related emissions to the energy production process. This allocation might differ depending on the GHG accounting methods under use: a consumption-based accounting would allocate energy-related emissions to the energy consumer (e.g., households), while a production-based accounting allocates them to the energy production process. In the present system, the latter option was chosen for clarity of depiction, but results of energy-related emissions are disaggregated into three consumer sectors: private (including both industrial and commercial sectors), public, and households.

We calculated the CRV of both built environment stocks and mobile stocks located within Odense municipality. Built environment stocks include residential buildings, nonresidential buildings (further subdivided across sectors, see 2.3.1), roads, and pipe networks for water, wastewater and natural gas. Mobile stocks include eight types of vehicles (both on-road and off-road transportation), 18 types of electronics, and five types of household appliances. A detailed list of these mobile stocks can be found in Table 2.

2.2 | Methods and data for GHG emission accounts of Odense

The Danish Energy Agency (DEA) maintains the energy and CO_2 accounts of all Danish municipalities from 2010 to 2017 (Danish Energy Agency, 2019). Methodological details reveal that these accounts were conducted following the GPC guidelines (Viegand maagøe, 2016b), although results are not strictly presented across GPC scopes 1–3. GHG emissions were calculated for five sectors: energy production, transportation, chemical processes, agriculture, landfills, and sewage. By combining the understanding of Odense's sociometabolic system (Figure 2) and methodological details supplied by the DEA (Viegand maagøe, 2016a), we were able to allocate all emissions to their relevant scopes (1, 2, and 3_{SP}) and aggregate them into four main urban sectors (private, public, transportation, and households).

2.2.1 | Stationary Energy

GHG emissions from stationary energy production are available at a disaggregated level, which include emissions from electricity and heating consumption in households (E_{HH}), the public sector (E_{PUB}), and the private sector (E_{PRIV}). Using the detailed building end-use classification of the Danish building registry, the DEA attributed each building's energy consumption to its relevant sector (see the Supporting Information for sectoral classification of buildings uses). Additionally, emissions from the small share of electricity imported into the municipality were specified. The sum of those emissions (across sectors plus imported) form the total Scope 2 emissions of Odense municipality. Emissions from individual heating systems running on renewable energies (e.g., firewood, solar heating) are not included.

2.2.2 | Transportation

Data on CO_2 emissions from transportation (T) are categorized into on-road traffic, non-road traffic, train travels, air travels, and ferries and fisheries. On-road traffic is further divided between emissions from personal cars, bus, and other road traffic (including but not differentiating between vans, trucks, motorcycles, and mopeds). Note that traffic from foreign road users is not included. Non-road traffic emissions (i.e., emission from machinery and non-road vehicles) are disaggregated across the different types of industrial or commercial processes taking place within the municipality boundary: agriculture, logging and forestry, parks management, construction, and other industrial or commercial processes. Note that the first three sectors were aggregated into the "land use" sector.

Data on emissions from railway passenger transportation were calculated by the DEA to reflect the amount of emissions taking place within the city boundary (scope 1). Emissions from freight transport and local trains are not included. Emissions from air transportation and from ferries and fisheries do not take place within the city boundary (scope 3_{SP}), and were derived from national accounts using a scaling factor of population. In the case of ferries and fisheries, emissions were weighted according to the share of Danish fisheries and ports located on Odense coasts.

2.2.3 | Chemical processes, land use, sewage, and landfills

Emissions from chemical processes (C) originate from industrial processes and organic solvents, and we allocated them to the "construction and manufacturing" process. Emissions from the agricultural sector (A) account for digestive process of livestock, livestock manure in barns, cultivation and fertilization of agricultural land, and cultivation of organic soil. We allocated those to the "land use" process. Note that carbon sequestration in the soil is not included.

Emissions from sewage (S) account for methane emissions. Regarding landfills, the DEA calculated their emissions (L) based on scaling down national values of quantity of methane emitted by all landfills by a population ratio. While this result might not perfectly fit the actual emissions taking place within Odense, they are deemed acceptable given the low quantities of landfilled waste in Denmark. Indeed, since the so-called landfill tax from 1987 and landfill ban from 1997, landfilling rates have remained stable in the last decades in Denmark, with only 4% of all solid waste sent to landfills (Dansk Affaldsforening et al., 2016).

2.3 | Carbon replacement value of Odense's material stocks

2.3.1 | CRVs of built environment stocks

Equation (1) shows the calculation of CRV of built environment stocks (CRV_{BE}). To calculate the CRV of a built environment stock s ($CRV_{BE,s}$), two types of data are required: the quantity of material m stocked in stock s ($MS_{m,s}$ in kilograms), and the embodied carbon emission factor of material m (CF_m), in kilograms of CO_2eq per kilogram of material m.

$$CRV_{BE} = \sum_{s} CRV_{BE,s} \quad = \sum_{s}\sum_{m} \left(MS_{m,s} \cdot CF_m\right) \tag{1}$$

Quantities of built environment material stocks were calculated in previous work (Lanau & Liu, 2020) and include quantities of 46 construction materials across residential buildings, nonresidential buildings, roads, supply water pipe, wastewater pipes, and natural gas pipes. Infrastructure stocks are easily attributable to their corresponding process (e.g., water supply pipes for water supply and natural gas pipes for energy supply). In the case of buildings, the detailed end-use classification of the Danish building registry was used to recalculate building material stocks according to the DEA classification for calculation of energy consumption across sectors. Buildings were thus categorized into buildings for public sector (e.g., buildings for education and research, hospitals, libraries), households, and private sector (e.g., industrial and commercial buildings). The latter was subdivided so as to fit as many industrial processes as possible, that is, buildings for land-use, construction and manufacturing, energy supply, and other private buildings. Finally, a new category was created to reflect the amount of buildings used in the transportation sector (see detailed classification in the Supporting Information).

Carbon emission factors of construction materials were retrieved from multiple sources, in the following descending order of preference: Danish environmental product declarations (EPDs), Nordic countries EPDs (Norway, Sweden, Finland), European EPDs, and dataset from the German Thinkstep database for Life Cycle Assessment (Thinkstep, 2019). Emissions are accounted for the raw material supply, transport, and manufacturing processes only (cradle-to-gate); transportation of the manufactured product to the construction site is excluded. Table 1 presents the CRV factors used in our analysis, as well as data sources, production site, and location of the company's headquarters (in the case of EPDs).

2.3.2 | CRVs of mobile stocks

Equation (2) shows the calculation of CRV of mobile stock (CRV_{mob}). To calculate the CRV of a mobile stock s ($CRV_{mob,s}$), two types of data are required: the number of items i in stock s ($N_{i,s}$)„ and the embodied carbon emission factor of item i (CF_i), in kilograms of CO_2eq per item i.

$$CRV_{mob} = \sum_{s} CRV_{mob,s} \quad = \sum_{s}\sum_{i} \left(N_{i,s} \cdot CF_i\right) \tag{2}$$

Stocks of vehicles are available in the Danish statistics for the year 2017, in number of items and at the municipality level (Statistics Denmark, 2019a). Stocks of home electronics and appliances were available as a percentage of households owning each item under consideration (Statistics Denmark, 2019b), and the municipality number of households was used to estimate the actual number of items. Note that, in the case of small personal electronics such as smartphones, an underestimation might occur as there most probably are more than one person per household owning such artefact.

TABLE 1 Embodied carbon emissions factors (CF) of construction materials, used to calculate the carbon replacement values (CRVs) of Odense's built environment stocks

Material [location of production/headquarters]	CF (kg.CO_2eq/kg.material)	Data source
Materials used in buildings		
Aerated concrete [DE/DE]	0.381	Xella Baustoffe Gmbh, 2017
Aluminum [EU/EU]	10.64	Thinkstep, 2017a
Carpet [EU/NL]	4.031	Forbo Flooring Systems, 2019
Cement roof tiles [DK/DK]	0.25	Designit, 2014
Ceramic tiles [DE/DE]	0.694	IBU - Institut Bauen und Umwelt e.V., 2016
Clay [DK/DK]	0.314	Same as clay brick
Clay brick [DK/DK]	0.314	Randers Tegl A/S, 2018
Clay brick roof tiles [DK/DK]	0.45	Designit, 2014
Clay pebbles [DK/DK]	0.496	Saint-Gobain Danmark A/S, 2015
Concrete [DK/DK] (28% cement, 72% aggregate)	0.232	Aalborg Portland A/S, 2017; Thinkstep, 2017a
Concrete brick [DK/DK]	0.232	Same as concrete
Concrete screeds [FI/FI]	0.345	Saint-Gobain Finland Oy, 2019
Copper [EU/EU]	0.981	Ruuska, 2013
Expanded polystyrene [DK/DK]	2.789	Plastindustrien, 2017
Fiber cement [HU/DK]	0.654	Cembrit Holding A/S, 2018
Fiber cement roof plates [CZ/DK]	0.819	Cembrit Holding A/S, 2016
Glass [EU/n.a.]	1.23	Carrillo Usbeck, Pflieger, and Sun, 2011
Gypsum [NL/DK]	0.264	Siniat B.V., 2016
Lightweight concrete [DK/DK]	0.281	RC Beton A/S, 2015
Lime mortar [DK/DK]	0.144	Same as limestone cement mortar
Limestone cement mortar [DK/DK]	0.144	Saint-Gobain Denmark A/S -Weber, 2019
Linoleum [EU/NL]	4.171	Forbo Flooring Systems, 2018
Mineral wool [DK/DK]	1.33	Saint-Gobain Denmark A/S ISOVER, 2018
Polyethylene (damp insulation) [NO/NO]	2.259	Tommen Gram Folie AS, 2015
Polyvinyl chloride [NO/NO]	2.341	Protan AS, 2019
Sand and gravel [DE/n.a]	0.033	Thinkstep, 2017b
Slag [DE/n.a]	0	Thinkstep, 2016a
Steel (reinforcement) [DK/DK]	0.447	Celsa Steel Service A/S, 2015
Stones [DE/n.a.]	0.192	Thinkstep, n.d.
Straw [DK/DK]	−1.1	Carlo F. Christensen A/S, 2017
Tared paper [DK/DK]	3.564	Designit, 2014
Timber [NO/NO]	−1.340	Sørlaminering AS, 2014
Wood wool cement [DK/DK]	0.208	Troldtekt A/S, 2015
Zinc (roofs) [DK/DK]	3.662	Designit, 2014
Materials used in roads		
Asphalt concrete [DE/n.a]	0.077	Thinkstep, 2016b
Granit [TH/n.a.]	0.003	Kittipongvises, Chavalparit, and Sutthirat, 2016
Sand and gravel [EU/n.a]	0.003	White et al., 2010
Materials used in pipes		
Acrylonitrile butadiene styrene (sewer pipe) [DE/n.a]	4.440	Thinkstep, 2017b
Clay brick [DK/DK]	0.314	Randers Tegl A/S, 2018
Concrete pipe [DK/DK]	0.145	IBF A/S, 2018

(Continues)

TABLE 1 (Continued)

Material [location of production/headquarters]	CF ($kg.CO_2eq/kg.material$)	Data source
Ductile iron [EU/n.a.]	1.615	Spirinckx, Boonen, and Peeters, 2012
Glass Fiber Reinforced Plastic [DE/n.a.]	3.910	Thinkstep, 2017c
High density polyethylene (sewer pipe) [DE/n.a]	5.5	Thinkstep, 2017d
Polypropylene (sewer pipe) [DE/n.a]	2.620	Thinkstep, 2017e
Polyvinyl chloride (sewer pipe) [DE/n.a]	9.720	Thinkstep, 2017f
Steel pipe [SE/n.a.]	1.438	Lewis and Lewis, 2016

Abbreviations: CZ, Czech Republic; DE, Germany; DK, Denmark; EU, European Union; FI, Finland; HU, Hungary; NL, Netherlands; NO, Norway; SE, Sweden; TH, Thailand; n.a., not applicable.

CFs of mobile stocks, as detailed in Table 2, were retrieved from life cycle assessment studies. For all factors, emissions are accounted for the production phase of the item (cradle-to-gate). In the case of electronics, the environmental declarations of products from major electronic brands were also consulted.

2.4 | Uncertainty analysis

The DEA addresses uncertainties in their GHG accounts qualitatively. We summarize the main sources of uncertainties in section 4.1. We focus our uncertainty analysis of CRV results on the building stock, which showed to make for the grand majority of the city's total CRV. Uncertainties in CRV results originate from two sources: the stock inventory data and carbon factors. The uncertainties in material stock inventory are addressed qualitatively, while uncertainties in carbon factors are investigated quantitatively. Indeed, most of our carbon factor dataset is made of values retrieved from EPDs that are often developed by companies as a tool for communication of their environmental work. It is thus credible to assume that these certified products are top of the market – environmentally speaking – thus suggesting a potential underestimation of our carbon factors.

We retrieved five alternative carbon factor datasets that are not specific to Denmark. (1) The Inventory and Carbon and Energy (ICE) v3.0 (Jones & Hammong, 2019), whose primary intent is to be used in the United Kingdom, although a number of factors are global averages. (2) The Carbon footprint for building products ECO2 database (Ruuska, 2013), containing both country-level data from Europe and average European-level data. (3) The embodied CO_2 emissions module for AccuRate (D. Chen et al., 2010, in Schandl et al., 2020), in which Australian data was used whenever possible. Finally, carbon factors were retrieved from the works of (4) Müller et al. (2013), who used various industry and life cycle assessment databases and (5) Mao et al. (2020) who retrieved factors from Ecoinvent and eBalance databases. Note that the number of alternative carbon factors for each material differs as not all datasets include carbon factors for each and every construction material used in this study. In the rare cases where no alternative carbon factor could be found (e.g., bituminous felt and straw), an uncertainty of 20% was assumed. For all other materials, the uncertainty of their carbon factor is set as the standard deviation of the collection of carbon factors, assuming a normal distribution (See the Supporting Information). The uncertainty in building stock's CRV due to carbon factors was then calculated using a Monte Carlo simulation (5,000 simulations). Additionally, carbon uptake from timber and straw are included in this study, but we investigated the extent to which results are affected by the exclusion of carbon uptake.

3 | RESULTS

3.1 | Total emissions and CRVs

Figure 3 depicts results for Odense's GHG emission accounts, at a disaggregated level to the highest possible extent, based on an urban sociometabolic system with stocks and flows. In 2017, Odense's Scope 1–3sp emissions (hereafter referred to as total GHG emissions) amounted to 844 $kt.CO_2eq/year$ (Figure 4a), or 4.17 $t.CO_2eq/(year.cap)$. Territorial emissions (Scope 1) account for 95% of the total emissions with 798 $kt.CO_2eq/year$, or 3.95 $t.CO_2eq/(year.cap)$. Emissions from energy production consumed in Odense (Scope 2) amount to 52% of the city's emissions (442 $kt.CO_2eq/year$ or 2.18 $t.CO_2eq/(year.cap)$). As Scope 2 includes all emissions from energy production consumed in the city regardless of the location of the power station, it includes those that take place within Odense spatial boundaries (thus explaining the overlap between scope 1 and 2 emissions in Figure 4a). Almost all of Scope 2 emissions (97%) take place within the city boundary. Only two emissions belong to Scope 3sp (combustion of marine and aviation fuels totaling to 32 $kt.CO_2eq/year$); those are placed at the top of the chart on Figure 3, vertically aligned with

TABLE 2 Embodied carbon emissions factors (CF) of mobile stock items used to calculate the carbon replacement values (CRVs) of Odense's mobile stocks (vehicles, electronics, and household appliances)

Item	CF (kg.CO_2eq/item)	Data source
Vehicles		
45-Mopeds	545	Cox and Mutel, 2018
Agricultural tractors	16,674	Zimmermann, 2019
Buses	197,286	Cooney, Hawkins, and Marriott, 2013; McCreadie, 2016
Lorries	15,000	Volvo Trucks, 2020
Motorcycles	3,858	Cox and Mutel, 2018
Passenger cars	5,600	Patterson and Johnson, 2018
Road tractors	16,674	Same as agricultural tractors
Vans	8,000	Patterson and Johnson, 2018
Electronics		
BluRay-player	15	Same as CD-player
CD-player	15	Ashby, 2012
Digital camera	24	ADEME et al., 2018
Digital video camera	28	ADEME et al., 2018
DVD-player without hard disk	15	Same as CD-player
E-book reader	26	ADEME et al., 2018; Teehan and Kandlikar, 2013
Game console	69	ADEME et al., 2018
GPS navigation	26	Same as E-book reader
GPS-watch	29	Apple, 2020
Hard disk-recorder	12	Ashby, 2012
Mobile phone	11	Singhal, 2005
Monitors	299	Dell, 2020; Teehan and Kandlikar, 2013; ADEME et al., 2018
MP3 Player	18	ADEME et al., 2018; Teehan and Kandlikar, 2013; Apple, 2020
Portable computer	256	ADEME et al., 2018; Dell, 2020; Teehan and Kandlikar, 2013; Apple, 2020; Ashby, 2012
Smartphone	49	Huawei, 2020; Apple, 2020; ADEME et al., 2018; Singhal, 2005; Andrae and Vaija, 2014
Stationary computer	204	ADEME et al., 2018; Dell, 2020; Teehan and Kandlikar, 2013
Tablet PC, mini-computers	101	ADEME et al., 2018; Teehan and Kandlikar, 2013; Apple, 2020
TV	487	Huulgaard, Dalgaard, and Merciai, 2013; ADEME et al., 2018
Household appliances		
Dishwasher	212	ADEME et al., 2018; Faberi et al., 2007; Ardente and Talens Peiró, 2015
Dryer	264	Boyano et al., 2017; ADEME et al., 2018
Microwave oven	108	Gallego-Schmid, Mendoza, and Azapagic, 2018; ADEME et al., 2018
Vacuum cleaner	36	ADEME et al., 2018; Bobba, Ardente, and Mathieux, 2015
Washing machine	262	ADEME et al., 2018; Boyano et al., 2017; Faberi et al., 2007

CD, compact disc; GPS, global positioning system; MP3, MPEG (moving picture experts group audio) layer-3; PC, personal computer.

the activity they belong to, as they take place outside of the municipality boundary. As depicted in Figure 3, combustion of marine fuels is allocated to emissions from machinery and off-road transport (M/T) from the land-use process, while combustion from aviation (T_{air}) is allocated to emissions from the transportation sector. Both are located outside the city boundaries.

The total CRV of built environment and mobile stocks in Odense amounts to 10,665 kt.CO_2eq, or 52.73 t.CO_2eq/cap. This amounts to more than 13 years of the city's annual Scope 1 emissions. Note that scope 1 is chosen as a basis for comparison as CRV was calculated for stocks located within the city boundaries. Of this total CRV, built environment CRV dominates the results (Figure 4b) with a CRV of 9,884 kt.CO_2eq. Buildings make up for 93% of this built environment CRV, while roads and pipe network make up for 5% and 2%, respectively. It should be noted that the CRV of pipe networks for energy distribution only includes natural gas pipes. District heating pipes, that constitute the major part of the municipality's heating system, are not included in this study due to lack of data. The actual contribution of pipes to the city's CRV is thus believed to be higher than

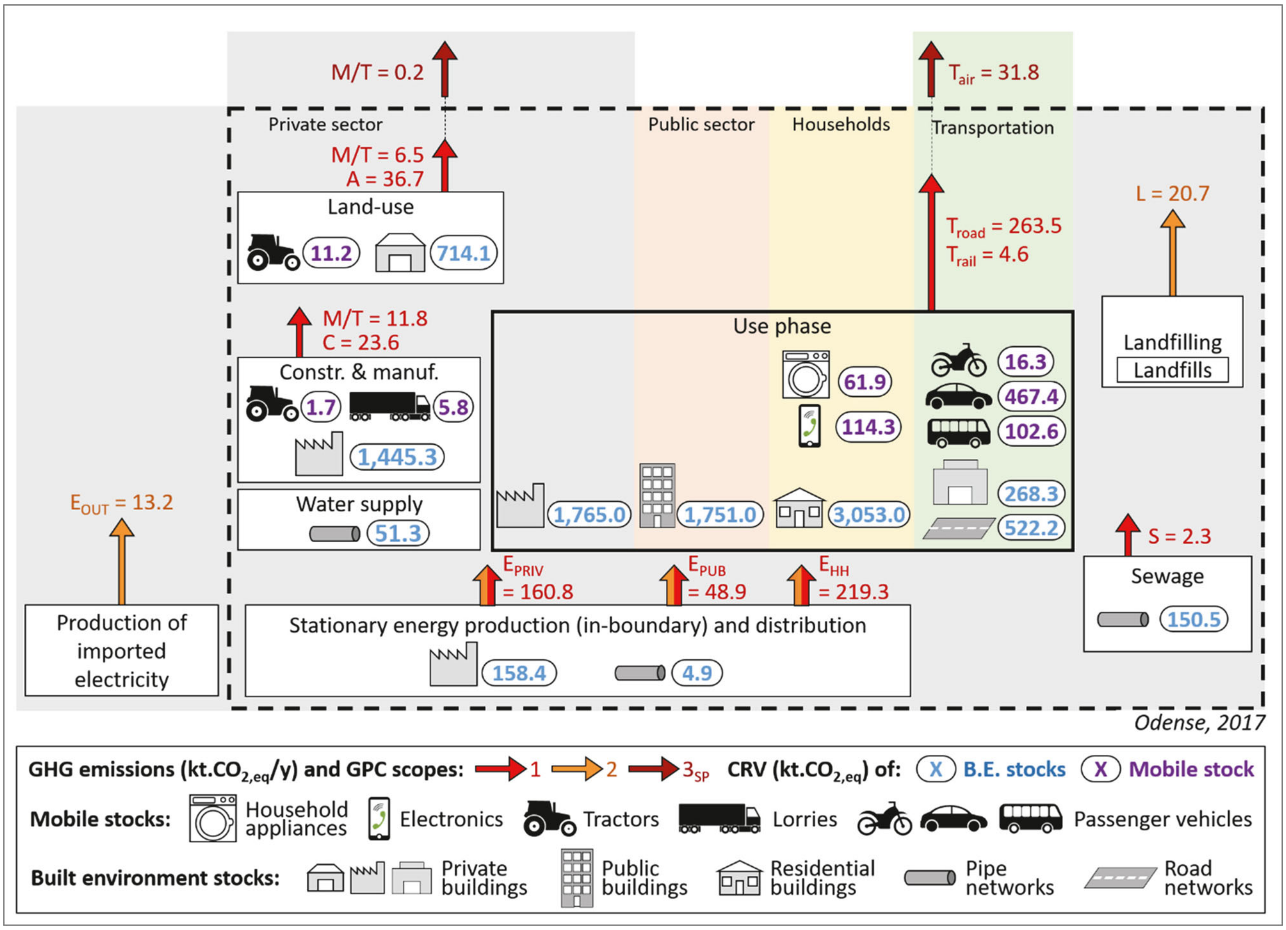


FIGURE 3 Odense's GHG emission accounting based on urban sociometabolic system with stocks and flows. The accounting includes the carbon replacement value (CRV, in kilotons of CO_2eq) of built environment and mobile stocks, as well as GHG emissions (in kilotons of CO_2eq per year) from urban activities according to their GPC scopes: machinery and off-road transportation (M/T), agricultural processes (A), sewage (S), landfills (L), chemical processes (C), passenger transport on road (T_{road}) and by train (T_{rail}), emissions from production of imported electricity (E_{OUT}), and emissions from electricity produced within the municipality boundary and distributed to households (E_{HH}), the public sector (E_{PUB}) and the private sector (E_{PRIV})

calculated here. Mobile stock CRV (731 kt.CO_2eq) is 13 times lower than that of built environment stocks, and is dominated by vehicles CRV that accounts for three quarters of the mobile stock CRV. Electronics and household appliances amount to 16% and 8% of mobile stock CRV, respectively.

3.2 | Sectoral contributions to total emissions and CRVs

Figure 4 presents results at different levels of aggregation, including absolute values of emissions and CRVs, and a comparative chart of the relative importance of those two indicators across the four main sectors under study (private, public, and transportation sectors, and households). This comparative chart was developed to bypass issues of temporal differences that arise when comparing Scope 1 emissions (expressed on a yearly basis) and CRV of stocks (linked to stocks that developed over many years). We also express CRV in terms of number of years of Scope 1 emissions to reflect the scale of CRV results. It should be noted that this ratio on its own does not indicate any sustainability level.

The relative contribution to CRV and Scope 1 emissions differ significantly across sectors (Figure 4c). Passenger transportation is the only sector with a share of Scope 1 emissions (34%) higher than its share of CRV (13%). This sector also has the highest sectoral emissions, and lowest sectoral CRV. Emissions are mostly due to the combustion of fuel for on-road transportation (264 kt.CO_2eq/year against approximately 5kt.CO_2eq/year for rail transportation; Figure 3). The CRV of the transportation sector is dominated by passenger vehicle stocks (43% of transportation CRV; Figure 4c), in which passenger cars contributed the most (467 kt.CO_2eq), followed by buses (102 kt.CO_2eq) and two-wheeled vehicles (16 kt.CO_2eq), respectively (Figure 3). The second largest contributor to the transportation sector CRV is roads (38%), while transportation-related buildings (e.g., stations, garages, and carports) account for the rest. The CRV of the transportation sector is worth 5 years of its annual operational emissions.

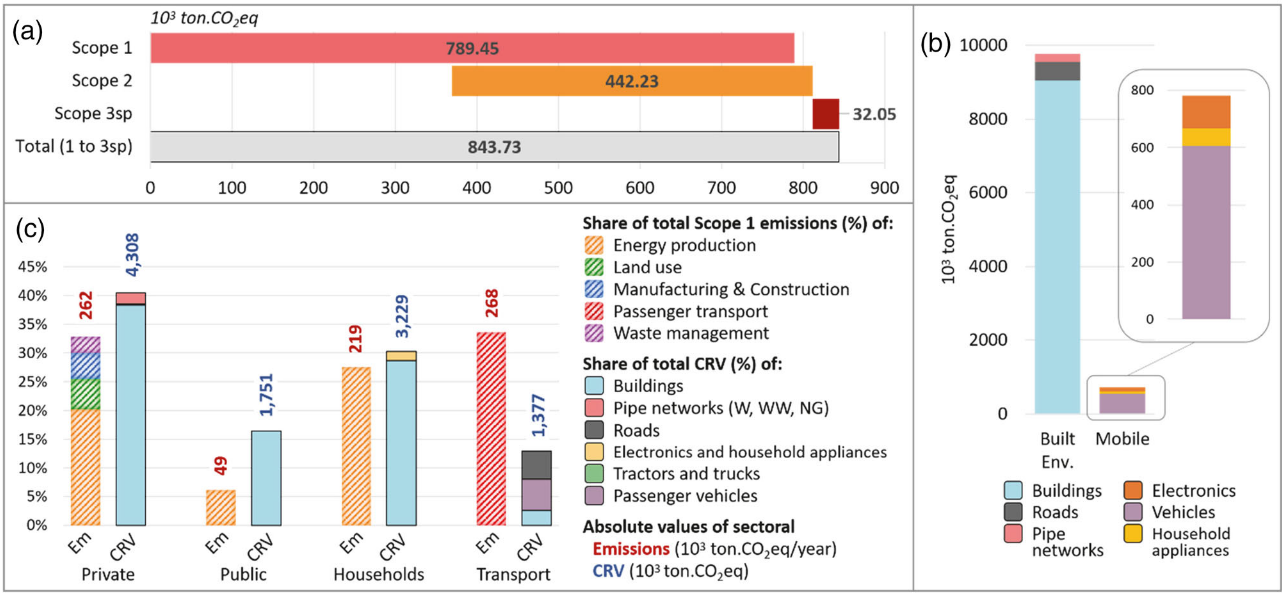


FIGURE 4 GHG accounting of Odense in 2017: (a) GHG emissions in 2017, total and by Scopes 1, 2, and 3sp, in kilotons of CO_2eq; (b) carbon replacement value (CRV) of built environment and mobile stocks, in kilotons of CO_2eq; and (c) contribution (in percentage) of each sector (private, public, household, and transport) to total Scope 1 emissions (left bars) and total CRVs (right bars), disaggregated into sources of emission and stock type relevant to each sector (W, water supply; WW, wastewater; NG, natural gas). Underlying data used to create this figure can be found in the Supporting Information

Note that the CRVs of trains and railways are not accounted in this study, but are not believed to dramatically change our results on the transportation sector. For example, a study of the environmental impacts of railways in Sweden showed that the construction of railways' foundations and tracks amounts to 1.26 kt.CO_2eq/km.railway (Stripple & Uppenberg, 2010), thus making the CRV of Odense railways (circa 60 km) amount to 75.6 kt.CO_2eq, that is, 5.5% of our calculated CRV of the transportation sector.

For all other sectors, sectoral emissions are lower than sectoral CRV. The public sector has the lowest share of sectoral emissions (6%), all originating from the production of energy consumed in public buildings. The CRV of public buildings accounts for 17% of Odense's CRV, and amounts to 36 years of its operational emissions. Households' emissions, originating entirely from the production of energy used in residential buildings, amount to 27% of Odense's Scope 1 emissions, a percentage comparable to the CRV of household-related stocks (27% of total CRV) that is greatly dominated by residential building stocks (CRV of 3,053 kt.CO_2eq against 114 kt.CO_2eq for electronics and 62 kt.CO_2eq for household appliances; Figure 3). The CRV of households in total amounts to 15 years of their operational emissions.

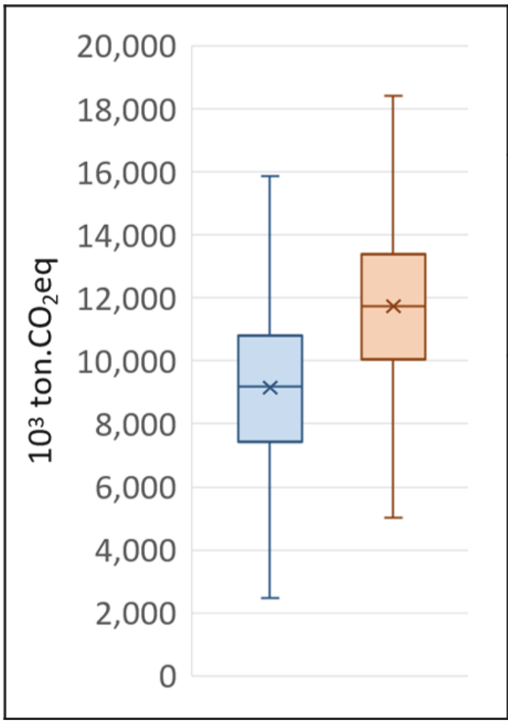
The private sector accounts for the highest share of sectoral CRV (40%), and the second highest share of Scope 1 emissions (33%). Emissions are dominated by the production of energy used in this sector (61% of private emissions), while the rest of emissions originate from subsector-specific emissions. For example, land-use specific emissions arise mainly from agricultural processes (Figure 3), which are six times higher than those from fuel combustion in machinery and off-road transportation. In construction and manufacturing, emissions from chemical processes are twice higher than those from machinery and off-road transportation. In waste management, emissions from landfill surpass those from sewage by a factor nine (20.7 versus 2.3 kt.CO_2eq/year). CRV of private buildings accounts for 38% of Odense's CRV, and 95% of private CRV. Pipe networks account for 5% of private CRV, while the CRV of tractors and trucks is negligible. CRV of buildings for construction and manufacturing sector is notably high, with 1,445 kt.CO_2eq, while CRV of land-use buildings accounts for 714 kt.CO_2eq. Other private buildings amount to a CRV of 1,765 kt.CO_2eq (Figure 3). Overall, the CRV of industry-related stocks amounts to 16 years of the sector's operational emissions.

4 | DISCUSSION

4.1 | Uncertainty analysis

4.1.1 Uncertainties of GHG accounts

The DEA considers results on emissions from energy production to be "relatively accurate", with most uncertainties originating from the data quality of the Danish building registry used to calculate emissions from energy production for households, and from possible double accounting of emissions



Statistical measure	CRV_B incl. carbon uptake	CRV_B excl. carbon uptake
Mean	9,155	11,741
Standard deviation	2,510	2,492
Relative standard deviation	27.4%	21.2 %
Minimum	2,482	5,004
Q1	7,437	10,032
Median	9,176	11,747
Q3	10,819	13,390
Inter Quartile Range	3,382	3,358
Maximum	15,864	18,426

FIGURE 5 Results of Monte Carlo simulation (5,000 simulations). Input variables: carbon factors; output variable: CRV of buildings (CRV_B). See details in the Supporting Information

from district heating systems. Results on emissions from on-road transportation are assessed to be "relatively accurate". For off-road transportation, whose contribution to total emissions is minor, calculations used consistent data but "distribution keys" might be inaccurate. For landfill emissions, the biggest uncertainty comes from scaling down of national data according to population ratios. For sewage emissions, uncertainties might arise from the use of an average Danish technological choice to calculate emissions from wastewater treatment plants. Uncertainties of emissions from land use mostly come from the large uncertainty (up to 300%) on emission factors for nitrous oxides. Finally, uncertainties in emission results from chemical processes might be due to the incompleteness of data, as the DEA states their data account for almost 90% of Danish industrial chemical emissions.

4.1.2 Uncertainties of CRV of buildings

The uncertainty analysis of the CRV of Odense's building stock was performed using five alternative datasets of carbon factors. Results show a standard deviation of 27%, that is, 9,155 ± 2,508 kt.CO_2eq (Figure 5). The use of alternative carbon factors would thus produce results within the same order of magnitude as our results. Additionally, the uncertainty analysis was conducted for the case where carbon uptake (from timber and straw) is excluded. While the relevance of including or not carbon uptake in embodied carbon is out of the scope of this study, it is still interesting to understand to which scale results are affected. Results show that, by excluding carbon uptake, the CRV of Odense would increase by 28%, reaching 11,741 ± 2,492 kt.CO_2eq. It should be noted that the present uncertainty analysis focuses only on uncertainties brought by carbon factors. Even though uncertainties from stock inventory are not investigated quantitatively, it is worth mentioning that results of material stock quantification with a bottom-up approach include non-negligible (Lanau et al., 2019)—but often unquantified—uncertainties that would increase the uncertainties of CRV results.

4.2 | Odense's GHG emissions and CRVs in a global context

The Scope 1 emissions of Odense were of 4.17 t.CO_2eq/(year.cap) in 2017. These results are along the lines of Scope 1 emissions previously calculated for other European cities such as Berlin, Oslo, Copenhagen, London, and Stockholm which range between approximately 2.5 t.CO_2eq/(year.cap) and 7 t.CO_2eq/(year.cap) (Broekhoff et al., 2019). Odense's Scope 1 emissions are lower than those of US cities such as Iowa city, Fort Collins, Portland and San Francisco that are estimated to range from 7.5 t.CO_2eq/(year.cap) to 14 t.CO_2eq/(year.cap) (Broekhoff et al., 2019), while Denver's was estimated to be 18.9 t.CO_2eq/(year.cap) by Ramaswami et al. (2008). For Chinese cities, Dhakal (2009) calculated territorial emissions from Beijing, Shanghai, and Chongqing to be between 11.9 t.CO_2eq/(year.cap) and 16.7 t.CO_2eq/(year.cap) in 2004, while Tianjin's amounted to 3.3 t.CO_2eq/(year.cap) only. S. Chen et al. (2019) calculated those four cities' territorial emissions to range between 5 and 9.5 metric t.CO_2eq/(year.cap) in 2012. Such reduction, though partly attributable to differences in data and methodology, was likely driven by a decrease in emission intensity as was the case for Beijing (S. Chen & Chen, 2017). Additionally, the inclusion of Odense's Scope 2 emissions only adds 0.07 t.CO_2eq/(year.cap) to the Scopes 1+2 total, raising it to 4.24 t.CO_2eq/(year.cap). This is still lower than the average of Scope 1+2 emissions of the eight US cities calculated by Hillman and Ramaswami (2010) to be 14.9 t.CO_2eq/(year.cap). While these results depend on the scope of accounted emissions as well as data quality, it seems that urban GHG emission levels greatly vary across regions, regardless of levels of development. Therefore, more in-depth analysis and consistent accounting of urban GHG emissions are urgently needed to draw more robust conclusions on urban emission patterns.

The development of Odense's stocks took place decades ago and are thus not reflected in the city's annual emissions. We here introduced the CRV values of stocks to add a stock-related carbon indicator to urban GHG accounting. The CRV of Odense was calculated to be 52.73 t.CO_2eq/cap in 2017, of which 93% originate from the CRV of the city's built environment. It is difficult to place these results within the context of similar research as no other urban CRV studies have yet been performed, to our knowledge. At the national level, Müller et al (2013) calculated that the average CRV of infrastructures in industrialized countries was of 51 t.CO_2eq/cap, a value surprisingly close to ours (in particular considering we have included 49 construction materials while Müller et al used steel, aluminum, and concrete as a proxy). Due to the characteristic of urban areas, we would expect to see higher per capita built environment stocks (and thus CRV as well) in cities than the national averages (Lanau et al., 2019). We speculate several factors might explain this surprising similarity. Firstly, methodological approaches used to estimate material stocks differ: Müller et al used a top-down approach that usually results in higher stock estimations than the bottom-up approach used in our study. Secondly, a number of metal-intensive infrastructures accounted by Müller et al were not included in our study due to data gaps, such as telecommunication networks, machinery, and electricity grid. Accounting for those stocks will increase the CRVs of Odense stocks. Thirdly, the carbon factors used to calculate our built environment CRV can be seen as calculated under the most environmentally friendly scenario (see 2.1).

The replication of the present study across more cities—in particular the calculation of CRV of stocks—would allow to investigate patterns and drivers of emissions embedded in urban stock development. Interesting areas of future research could include, for example, the analysis of CRV in relation to urban forms, geography, typical construction techniques, as well as societal and economic levels of development.

4.3 | The significance of stocks and complementary role of CRV indicator for urban GHG accounts and decarbonization strategies

GHG accounts, although widely recognized as key indicators to track cities progress (or lack thereof) toward climate change mitigation (Duren & Miller, 2012) and to identify key opportunities for climate change mitigation (Dhakal, 2010; Duren & Miller, 2012; Kennedy et al., 2010), are calculated based on material and energy flow information and often do not account for nor reflect the level and quality of services available within a city. Because many key urban flows are intrinsically linked to the type and quality of urban stocks available in a city, it is the combination of the two that allows to physically deliver a range of different services to citizens. For example, transportation requires energy as well as vehicles and road infrastructures. In the case of Odense, the city-wide presence of bike lanes has allowed citizens to safely use bikes for short commutes, thus decreasing the consumption of fuel for personal cars. Energy production and supply is another service that relies heavily on well-developed infrastructures. For example, the district heating system of Odense supplies 97% of the city's heating demand. Because the transmission system can be connected to all forms of heat production (Danish District Heating Association, 2019), the system can easily be adjusted upstream to greener heat production processes with no modification to the rest of the underground pipe network system. Stocks are thus important parts of our socio-economic metabolism whose levels of development ought to be reflected in urban GHG accounts. The inclusion of CRV indicator in urban GHG accounts could provide a complementary, yet critical and not fully accounted, perspective on trade-offs and synergies between urban embodied emissions and operational emissions in urban low-carbon transition (World Green Building Council, 2019).

The CRV indicator, for example calculated for Odense here as 13 years of its operational emissions, shines a clearer light on the potential amount of GHG emissions that can be avoided through the reuse and recycling of the existing urban stocks and thus integrates climate change mitigation and circular economy for urban sustainability. But as the entire stock will not become available at once, a clear understanding of areas of opportunities is necessary in order to develop relevant and efficient strategies for urban mining. In addition to secondary resource cadasters (Kleemann et al., 2016; Lanau & Liu, 2020; Oezdemir et al., 2017; Schandl et al., 2020; Schebek et al., 2017) that inform on the location, type, and quantity of material stocks across a city, the sectoral CRV indicators can be used to spot decarbonization opportunities across sectors. For example, it has been suggested that the amount of materials available in nonresidential buildings is of particular interest for circular economy strategies, as they tend to have a shorter lifetime and contains a higher amount of carbon-intensive materials than residential buildings (Lanau et al., 2019; Schebek et al., 2017). Our study confirms such claim in the case of Odense where buildings for construction, manufacturing and land use amount to almost a quarter of Odense's buildings CRV, and buildings for other industrial and commercial uses contribute to an additional 20%.

CRV accounting is also valuable to benchmark the amount of emissions that would be needed for developing cities to reach the same level of services as industrialized cities. Using Odense's CRV, as 0.97 billion more people are expected to move into urban areas by 2030 (United Nations, 2019), the building of new urban stocks would amount to 49.11 Gt.CO_2eq. This equals to 12% of the remaining carbon budget for a 66% probability of limiting warming to 1.5 degrees Celsius (420 Gt.CO_2eq), a target encouraged by the IPCC (as opposed to 2.0 degrees Celsius of the Paris' agreement) (Allen et al., 2018). While a result of 12% might suggest that managing emissions from stock development is not as important as other sectors' contribution to climate change abatement, it is of outmost importance to note that we believe this result to be an underestimation. In addition to possible underestimation of our CRV results (see previous section), our analysis does not include future emissions from the construction of rural stocks nor from the maintenance of existing stocks. For comparison, Müller et al calculated that emissions embedded in future stocks could amount to 35–60% of the remaining carbon budget. At any rate, such amount of emissions is not to be neglected and calls for an increased focus on sustainable strategies in stock maintenance and development.

Future GHG emissions from stocks were calculated on a number of premises that reflect relevant areas of focus for urban decarbonization. The first premise is the assumption that the future stock will be developed using the same construction and manufacturing techniques and materials used for stock building of industrialized cities. This highlights the need to explore if and how much we can switch to less carbon intensive materials and production processes. The second premise is that all countries should reach the same levels of services as industrialized countries and that these levels of services can only be reached through the duplication of urban sociometabolic patterns in industrialized countries (third premise). While basic human needs (e.g., access to food, clean water, security, healthcare, and education) need to be met globally, the over-materialistic aspects of industrialized countries and "western consumerism" have rightfully been at the center of sustainability discussion (Allwood et al., 2013; Urry, 2013). Concepts such as material service economy and sharing economy are key to dematerialization of society, and those ought to be investigated further so future stocks are not developed and organized in a way that results in technological (Grübler, 2003) and societal lock-ins (e.g., lifestyle habits (Barnes, Gartland, & Stack, 2004)) at play in industrialized cities.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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