Heinonen, Jukka; Ottelin, Juudit

Carbon Accounting for Regenerative Cities

Published in:
Rethinking Sustainability Towards a Regenerative Economy

DOI:
10.1007/978-3-030-71819-0_6

Published: 01/01/2021

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Heinonen, J., & Ottelin, J. (2021). Carbon Accounting for Regenerative Cities. In *Rethinking Sustainability Towards a Regenerative Economy* (Future City; Vol. 15). https://doi.org/10.1007/978-3-030-71819-0_6

Chapter 6
Carbon Accounting for Regenerative Cities

Jukka Heinonen and Juudit Ottelin

Abstract The carbon budget for limiting global warming to the targeted 1.5 ° is running out. Cities have a central role in climate change mitigation, as the vast majority of all greenhouse gas emissions occur to satisfy the energy and material needs of cities and their residents. However, cities typically only account for their direct local emissions from transportation, industry, and energy production. This may lead to the so-called low-carbon illusion of cities following from producing little and reporting low emissions, while extensively relying on imported material and energy flows. Consumption-based accounting, or carbon footprinting, enables overcoming this problem by assigning the emissions to the end user regardless of the place of production. However, currently the carbon footprinting methods only capture the harm side, and not the potential positive effects, the restorative or regenerative impacts, caused by green infrastructure, reforestation, and carbon capture and storage, for example. These positive impacts are sometimes called "carbon handprint". In this chapter, we create a handprint-extended carbon footprinting method to illustrate how restorative and regenerative impacts can be incorporated consistently in the carbon accounting of cities and carbon footprints of consumers. We also link the discussion on regenerative cities with the remaining carbon budgets.

Keywords City · Carbon budget · Carbon footprint · Carbon handprint · Regenerative · Restorative

J. Heinonen (✉)
Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavik, Iceland
e-mail: heinonen@hi.is

J. Ottelin
Department of Built Environment, Aalto University, Espoo, Finland
e-mail: juudit.ottelin@aalto.fi

M. B. Andreucci et al. (eds.), *Rethinking Sustainability Towards a Regenerative Economy*, Future City 15, https://doi.org/10.1007/978-3-030-71819-0_6

6.1 Introduction

World is continuously becoming more urbanized as population concentrates to growing cities. However, the current type of urbanization, linked to economic growth and increasing consumption, requires a vast amount of natural resources and causes increasing levels of greenhouse gas (GHG) emissions and waste (Rees & Wackernagel, 2008). In order to break this destructive pattern, urbanization needs to be reinvented. Ecologically regenerative urbanization aims to do this by finding new regenerative ways of production, consumption, and urban living (Girardet, 2014). While "regenerative" by definition means going beyond "sustainable", i.e., improving or restoring the state of environment instead of neutral environmental impacts (du Plessis, 2012; Pedersen Zari, 2018; Reed, 2007), it should be realized that, at the global scale, even sustainability is a far target regarding most planetary boundaries (O'Neill, Fanning, Lamb, & Steinberger, 2018). However, local regenerative actions can help to achieve global sustainability.

Reaching regenerative urbanization calls for a systemic approach. Individual solutions cannot be labeled "regenerative" unless their impact is regenerative at the global system level, including life cycle perspective and rebound effects caused by changes in the economic activities, technology, and human behavior. For example, creating and maintaining green infrastructure requires energy and resources, but may also reduce energy and resource consumption of other activities, such as the construction and maintenance of grey infrastructure. At the city level, these environmental spillover effects are most easily captured by using environmentally extended economic input-output (EE IO) models (Ottelin, 2016; Wiedmann, Chen, & Barrett, 2015). In this chapter, we focus on one aspect of regenerative cities: climate change mitigation. We propose a conceptual model for incorporating regenerative actions to the existing comprehensive carbon accounting tools.

Despite the fact that numerous national and international level commitments have been made to address climate change, the global GHG emissions are still rising (aside from times of global recession) (IPCC, 2018). Thus, many cities have recognized their responsibility in taking strong climate action (e.g., C40 CitiesXE "Cities" , 2018; Covenant of Mayors, 2020; ICLEI, 2020). However, the tools that cities have for carbon accounting may limit these actions and sometimes lead to unintended consequences. In particular, cities typically only account for their territorial emissions, meaning the direct local emissions from transportation, industry, and energy production. This may lead to the so-called low-carbon illusion of cities following from producing little and reporting low emissions, but extensively relying on imported material and energy flows (Heinonen & Jóhannesson, 2019). When regenerative actions are added in the equation, cities may even claim to be "carbon neutral" or "carbon negative", but this usually only holds true if the imported emissions are ignored. C40 Cities have made pioneering work by assessing their consumption-based emissions (C40 Cities XE "Cities" , 2018), meaning the life-cycle emissions caused by the consumption of goods and services within a city regardless of the location of production. Consumption-based accounting can be a powerful tool in designing GHG mitigation policies on a city-level, as it accounts for the trans-boundary flows (Ottelin et al., 2019) which tend to become more and more important as the geographic unit of analysis gets smaller (Heinonen et al., 2020). Combined, the two approaches, territorial and consumption-based, give a comprehensive overview of the overall impact of a city (Afionis, Sakai, Scott, Barrett, & Gouldson, 2017). The above-mentioned EE IO models provide these two perspectives simultaneously and coherently.

Consumption-based GHG accounting, also called carbon footprinting, provides unique insights into the climate impacts of global trade. Regardless of where the emissions originate, they are allocated to the final consumer. This accounting approach is becoming increasingly important as the share of global emissions embodied in international trade has increased significantly over the last decades, reaching soon one third of the gross annual emissions (Kanemoto, Moran, Lenzen, & Geschke, 2014; Sato, 2014; Wiedmann & Lenzen, 2018). Moreover, when it comes to cities and their territorial boundaries, the trans-boundary share is significantly higher (Heinonen et al., 2020).

While the inclusion of consumption-based accounting to a city's toolbox indisputably opens up new avenues for GHG mitigation policies, the method also carries along a significant limitation. It inherently only captures the harm side, the gross amounts of emissions caused in the production and delivery chain, and the use phase of a good or a service (see the review of consumption-based carbon footprint literature of Heinonen et al., 2020). Currently, consumption-based carbon footprint models don't take into account the potential improvements in the state of the environment, the restorative or regenerative impacts, and therefore don't incentivize creation of regenerative solutions.

These restorative and regenerative impacts, meaning e.g. increases of carbon sinks and stocks, are sometimes called "carbon handprint" (Grönman et al., 2019; Horváth, 2019). For example, wooden construction, green infrastructure, reforestation, and carbon capture and storage can have positive impacts that are not taken into account by the current consumption-based carbon accounting methods. On the other hand, the negative impacts of land use change are often excluded from the models as well, although not always (Heinonen et al., 2020). It is easy to argue that similarly as in the case of emissions, the positive impacts should also be taken into account either locally (like territorial emissions) or globally by using a life-cycle method (like consumption-based emissions). These can also be combined into a matrix-like city carbon map, as proposed by Wiedmann et al. (2015).

In this chapter, we open the discussion on how to incorporate the regenerative impacts consistently in the consumption-based carbon accounting methods. We create a visualization of such a handprint-extended carbon accounting of cities and consumers. We also link the discussion on regenerative cities with the actual state of annual global GHG emissions and remaining carbon budgets in order to discuss the scale of the needed change.

In the following sections, we first explain the concept of carbon budgets and how it relates to city and consumer carbon footprints, and to the importance of looking at the balance between emissions and stocks and sinks instead of the harm-side only. Next, in Sect. 6.2, we present the various carbon accounting methods for cities, and discuss the current limitations of carbon accounting from the perspective of regenerative actions. In Sect. 6.3, we illustrate how restorative and regenerative impacts, i.e., carbon handprint, could be integrated into the carbon accounting of cities and consumer carbon footprints. In the last section, we provide some final conclusions and policy implications.

6.2 Theoretical Context

6.2.1 The 1.5° Warming Target and Carbon Budgets

Global warming has reached the one-degree milestone (above the pre-industrial level) and is quickly approaching the Paris Agreement's target mitigation level of 1.5 °C (UNFCCC, 2018). Yet the annual anthropogenic GHG emissions are still on an upwards pathway (IPCC, 2018). Reaching the 1.5° halting target, or even staying below two degrees, thus requires massive emission reductions rapidly, or going below zero in the near future (Minx et al., 2017).

Carbon budgets make the reduction requirements tangible, showing how much emissions can still be emitted without exceeding a certain warming target (IPCC, 2018; Le Quéré et al., 2012). The budget estimations are not exact, but subject to uncertainty and vary by source, and also depend on the assumed peak year and zero year (Rogelj et al., 2015). However, they still give a good idea of the magnitude of change required to reach a certain target. IPCC (2018) reports 420 $GtCO_2$ until 2100 as the remaining carbon budget for staying below the 1.5 °C target at 67% confidence level. Budget for 2 °C is estimated at 1170 $GtCO_2$ at the same confidence level. Currently the anthropogenic GHG emissions are around 40–45 $GtCO_2$ per year (Le Quéré et al., 2018; IPCC, 2018). Thus, with annual emissions at this level, the 1.5 °C carbon budget would be used in 10 to 15 years.

The carbon budget only shows the gross allowance over time for meeting a selected warming target. In order to operationalize it for decision making, the budget needs to be divided for countries, cities, companies, individuals, or other meaningful units. One such operationalization is the division of the carbon budget to per capita pathways from the current situation to zero without exceeding the budget (Raupach et al., 2014). The pathways work so that the later the emission reductions begin, the steeper the curve becomes requiring faster and faster reductions (Raupach et al., 2014). According to Raupach et al. (2014)'s work, even reaching the 2° target would already now require annual reductions of 10% until reaching zero around 2080 (Fig. 6.1). Postponing the mitigation for another 5–10 years would lead to a 30% annual reduction requirement and reaching zero already around 2050.

O'Neill et al. (2018) have calculated that the same 2° target would mean global per capita emissions of 1.6 tons annually over the period between 2011 and 2100. The current global average carbon footprint is around 6 tons per capita, and, in the

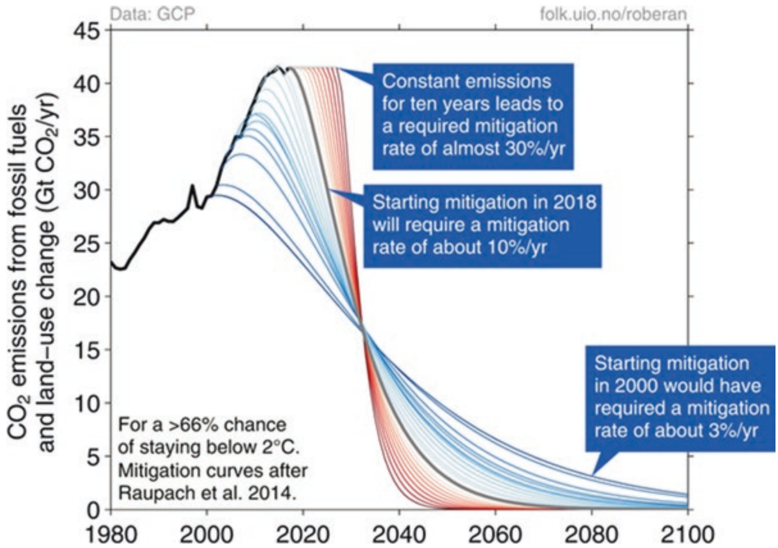

Fig. 6.1 The GHG emissions mitigation curves for 2° warming. (Drawn from Andrew, 2020)

more affluent countries, the current carbon footprints are well above 10 tons per capita on average (Clarke, Heinonen, & Ottelin, 2017; Hertwich & Peters, 2009), and particularly high in affluent cities (Heinonen et al., 2020; Moran et al., 2018). These numbers give benchmarks for mitigation targets and policies at different scales from international bodies to nations, cities, organizations, and even individuals. They also tell how the pace of mitigation in any of the more affluent locations, if considered that all should reach zero at the same time, would need to be tremendous.

6.2.2 Carbon Accounting for Cities

Current climate change mitigation targets and policies, including the Paris Agreement, rely on territorial carbon accounting, which allocates GHG emissions according to the place where the emissions take place. However, many countries, and particularly cities, outsource a large share of the industry, agriculture, and transportation that serves their citizens (Clarke et al., 2017; Heinonen & Jóhannesson, 2019), and even energy production. Thus, alternative system boundaries for carbon accounting of cities have been suggested. For example, community-wide infrastructure carbon footprint includes the life-cycle GHG emissions embodied in the cities' infrastructure (Ramaswami & Chavez, 2013), whereas wide production-based carbon footprints include the direct and life-cycle emissions caused by the industrial production in the area in question (Chen, Long, Chen, Feng, & Hubacek, 2019).

Consumption-based carbon footprints, as an opposite to territorial, assign the emissions to those causing them by their consumption of resources, energy, goods, and services, regardless of the geographic location of the emissions (Baynes & Wiedmann, 2012). They cover the emissions through the whole production and delivery chain to the final consumer, including trans-boundary flows. Thus, consumption-based carbon footprints are compatible with life cycle thinking. According to Wiedmann (2016, p. 163), consumption-based carbon footprints include the "impacts of local production minus impacts embodied in exports plus impacts embodied in imports". Heinonen (2012) describes that the method assigns "to a consumer the GHG emissions caused by his/her consumption regardless of the geographic location of the occurrence of the emissions".

Consumption-based carbon footprints are therefore demand-focused assessments. Typically, they are based on EE IO models, although a few alternative attempts have been presented (Heinonen et al., 2020). Following from the dominance of input-output basis, the footprints are also usually presented and explained in terms of national accounts for areal demand, in which the areal demand consists of private consumption, governmental consumption, capital formation, and non-profit institutions (Fig. 6.2). Since the residents of an area can consume within

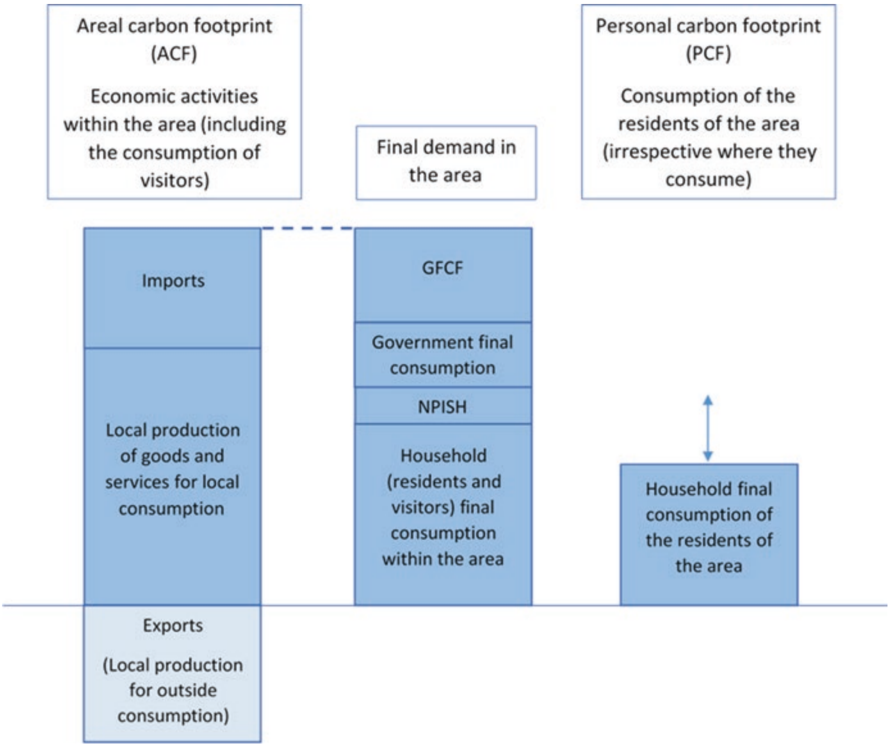

Fig. 6.2 The composition of the two main types of consumption-based carbon footprints (ACF and PCF). (Drawn from Heinonen et al., 2020). *GFCF* gross-fixed capital formation, *NPISH* non-profit organizations serving households

it, or outside, and visitors can purchase goods and services as well, the private consumption component can be different from the consumption of the residents. Figure 6.2, drawn from Heinonen et al., 2020, shows schematically the different definitions of consumption-based carbon footprints given above, and their relation to the gross final demand of an area.

Due to the extensive outsourcing in developed countries and in wealthy cities, consumption-based emissions are typically much higher than territorial emissions, since their consumption relies on imports from other regions. In other words, the imports component in Fig. 6.2 is much larger than the exports component, often even larger than the local production for local consumption-component (Heinonen et al., 2020). Similarly, in growing cities, the GHG emissions embodied in buildings and infrastructure play a major role.

Unfortunately, the usability of consumption-based carbon footprints as policy tools has remained limited, mainly because of methodological issues and perhaps also because of political will (Afionis et al., 2017; Ottelin, Ala-Mantila, et al., 2019). While territorial emissions are rather straightforward to report and examine, the other accounting methods with broader system boundaries require somewhat different know-how. Nonetheless, some cities around the world, for example C40 Cities, have made efforts to include the consumption-based carbon footprints in policy-making (C40 Cities XE "Cities" , 2018). Yet, the efforts to connect the footprints to the remaining carbon budgets are still rare. It should be noted that the total global territorial and consumption-based emissions are equal. The two approaches simply allocate the same global emissions differently to nations, cities, companies, and individuals. Consequently, the same carbon budget limits both.

6.2.3 Regenerative Impacts in Carbon Accounting

Regenerative actions are in general actions that improve or restore the state of the environment. Circularity of resources and energy has been highlighted as an important part of regenerative urbanization (Girardet, 2014) and buildings (Gou & Xie, 2017). Circular economy aims at slowing, narrowing, and closing material and energy loops, which lead to a more regenerative economy with lower environmental impacts (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). However, the strict definition of regeneration states that it goes beyond reducing environmental impacts to actually restore or improve the state of the environment (Pedersen Zari, 2018; Reed, 2007). In the case of climate change, this means that emissions are not only reduced, but carbon is absorbed from the atmosphere, leading to so-called "negative emissions".

Currently, there is a significant weakness in the otherwise comprehensive consumption-based carbon accounting of cities: it focuses only on the harm-side. Any positive actions leading to carbon negative impacts are not taken into account as is evident also from the definitions of carbon footprints given above. On a city-level, this may have harmful consequences. Sink and storage creation is not incentivized, and where these are anyway created, the carbon footprint comparisons show false outcomes. Though some steps have been taken to include the land-use and land-use change (LULUCF) sector in the underlying databases (e.g., Eora, https://worldmrio.com/), a broader discussion and conceptualization on negative emissions is missing from the literature of spatial carbon footprints (Heinonen et al., 2020).

Solutions to create negative emissions are generally called negative emission technologies (NETs), although many of the solutions are more natural than technological. NETs include for example afforestation and reforestation, bioenergy with carbon capture and sequestration, biochar (e.g., in agriculture and green infrastructure), enhanced weathering (spreading of minerals that naturally absorb carbon), and direct air capture of CO_2 (Minx, Lamb, Callaghan, Bornmann, & Fuss, 2017). Since NETs have been suggested as an important component in the pathway to 1.5 or 2.0° targets (Minx et al., 2018), it is becoming essential to develop carbon accounting methods that can cover these. For example, looking at Fig. 6.1, it becomes obvious that the mitigation curves quickly become steep beyond reach if radical reductions don't start taking place very soon. NETs will then become the hope that remains, allowing for going beyond zero later, and restoring the earth system to a lower level of warming, for example to 1.5° (IPCC, 2018). It should be also noted that the existing annual carbon uptake by mainly forests and oceans is already taken into account in the IPCC's carbon budgets, and thus the NETs have to come on the top of these to have a real impact.

While negative emissions have not yet been incorporated into EE IO models, many other aspects of regenerative cities are captured by them. For example, the environmental impacts of increased recycling rates, up-cycling, and *servitization* (shifting from consumption of products to consumption of services) can be studied with the current models (Aguilar-Hernandez, Sigüenza-Sanchez, Donati, Rodrigues, & Tukker, 2018; Greenford, Crownshaw, Lesk, Stadler, & Matthews, 2020). However, it should be more clearly defined when these activities actually are regenerative instead of just reducing the emissions, wastes, and virgin material consumption. In this chapter, we use the term "carbon handprint" to denote the negative emissions. Any reductions of carbon footprint are captured by the existing carbon footprint models and should not be included in the handprint, in order to avoid double counting.

6.3 Proposed Model

6.3.1 Incorporating Regenerative Impacts into the Carbon Accounting of Cities

The regenerative impacts of cities could be integrated into the current carbon accounting methods by assessing carbon handprint, meaning negative emissions, alongside carbon footprint and territorial emissions, as illustrated in Fig. 6.3. The figure is applied from the concept of city carbon map introduced by Wiedmann et al. (2015).

The columns in the figure stand for the place of consumption and the rows the place of production. Thus, the emissions are classified as follows:

- E1 = Global life cycle emissions caused by products produced and consumed in the city
- E3 = Global life cycle emissions caused by products produced outside but consumed in the city (imported emissions)
- E1d = Local direct emissions (from the burning of fossil fuels and industrial processes) caused by products produced and consumed in the city
- E2d = Local direct emissions caused by the products produced in the city but consumed outside the city (exported emissions).

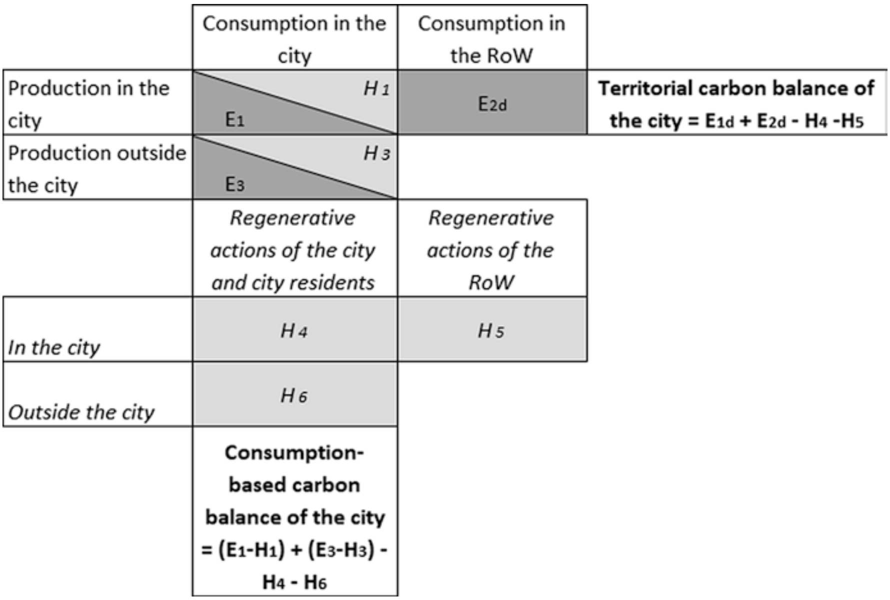

Fig. 6.3 City carbon balance. (Applied from Wiedmann et al., 2015, "City carbon map"). *E* emissions, *H* restorative impacts (handprint), *d* direct emissions, *RoW* Rest of the World

Following the same logic, we have added the negative emissions (handprints) to the model as follows:

- H1 = Global life cycle handprint of products produced and consumed in the city
- H3 = Global life cycle handprint of products produced outside but consumed in the city
- H4 = Local handprint of the city and city residents in the city
- H5 = Local handprint of other actors in the city
- H6 = Global handprint of the city and city residents outside the city (e.g., via carbon offsets).

The consumption-based column (E1, E3, H1, H3, H4, H5) represents life cycle perspective and focuses on the city residents and the city as a public actor, whereas the territorial perspective includes only the direct emissions originating from local production (E1d, E2d) and direct negative emissions created within the city borders (H4, H5). In practice, the life-cycle regenerative impacts of the production chains (H1 and H3) might be impossible to take into account, unless they are integrated into the global input-output models used for consumption-based accounting, or accounted for case-by-case following the production and delivery chains of, e.g., major industrial producers. However, adding the local restorative actions (H4 and H5) to the accounting is fully possible without any sophisticated tools. In addition, carbon offsetting, meaning that cities, companies, or consumers pay for offsetting their emissions and the money is used for, e.g., reforestation or emission reductions elsewhere, can be included relatively easily. However, there are several risks related to this. First, emission reductions of global industries are already covered by the footprint models, thus leading to a double counting problem. Second, in the case of afforestation and reforestation, it is difficult to ensure that the impact is real and permanent, meaning that the forest is not destroyed later, or the cuttings just shift from one area to another. Thus, in the future, it would be important to develop the global input-output models to cover the overall positive and negative changes in carbon balance due to land-use change.

Following this presentation (Fig. 6.3), there are actually some emissions and negative emissions included in both accounting methods: direct emissions produced and consumed inside the city (E1d) and handprint created by the city and city residents within the city borders (H5). However, if the whole map is used for the assessment, double counting is avoided. If just one of the two approaches is chosen, territorial or consumption-based, one should be careful not to mix territorial emissions and global handprint, or consumption-based carbon footprint and local handprint by outside actors, because this leads to an ambiguous interpretation of the carbon balance. This mistake is often made when cities or companies declare to be “carbon neutral”: only direct local emissions are included, but international compensation mechanisms are used.

In any case, the introduction of these regenerative and restorative components opens new policy options and encourages cities to work towards sink and storage creation, instead of just searching for ways to reduce the harm-side. Next, we

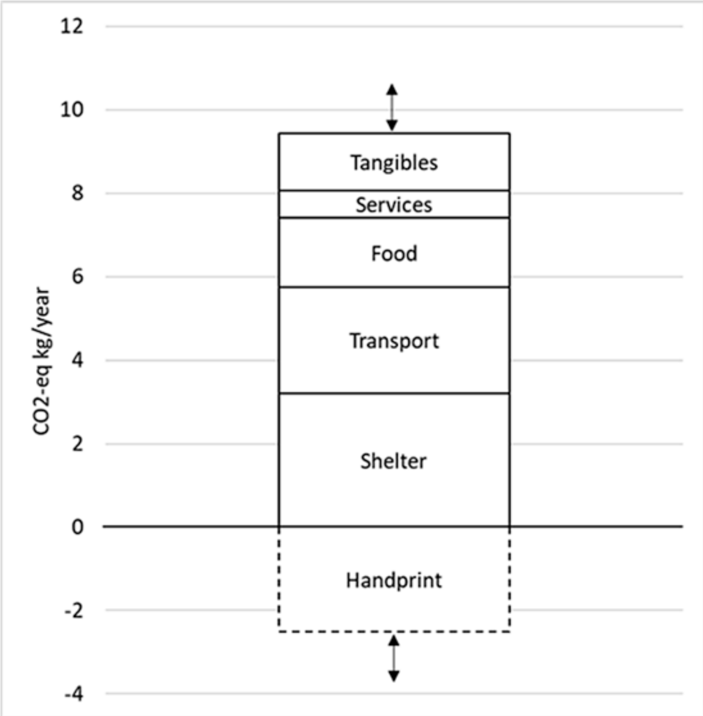

Fig. 6.4 Consumer carbon balance. The figure is illustrative: the sizes of footprints, handprints, and their components, vary in reality. The footprint components can also be categorized differently, but the division of overall household consumption into Tangibles, Services, Food, Transport, and Shelter is common

demonstrate how the handprint component could be integrated into the carbon footprints of individual consumers, or groups of consumers, such as city residents.

6.3.2 Consumer Carbon Footprint and Handprint

The consumer carbon footprint is dominated by emissions related to housing, transport, and food (Fig. 6.4, see also, e.g., Ottelin, Heinonen, Nässén, & Junnila, 2019). The carbon footprints include the life-cycle emissions caused by purchasing of goods and services, but also the direct emissions caused by the burning of fossil fuels in everyday activities, such as driving and heating (Heinonen et al., 2020). The regenerative actions of consumers, i.e., carbon handprint, can be added to the carbon footprint assessments as illustrated in Fig. 6.4. These actions could include, for example, products storing more carbon than caused by their manufacture, sustainable gardening and forestry, purchasing of carbon offsets, and wooden construction materials.

It should be noted the annual carbon footprint and handprint, presented in Fig. 6.4, cumulate into the emissions in the atmosphere and carbon stocks, respectively. Carbon stocks can be destroyed as well (e.g., by burning wooden products at the end of their life cycle), which releases the embodied emissions back into the atmosphere. Thus, the carbon handprint in one year can transform into carbon footprint some year in the future. Similarly, sometimes burning of wood and biofuels are considered causing zero emissions in carbon footprint models (Heinonen & Junnila, 2014). However, if the carbon handprint of using renewable biofuels is separately taken into account, these emissions should be added to the carbon footprint in order to avoid double counting of the negative emissions.

6.4 Discussion and Conclusions

The aim of this chapter was to open the discussion on adding regenerative impacts to the consumption-based carbon accounting of cities and consumers, and to illustrate how this can be done coherently and consistently. In other words, we brought together two research fields: regenerative urbanization and consumption-based carbon accounting.

Previous literature has highlighted that the environmental impacts of cities go far beyond the territorial environmental impacts taking place within the city borders. Consumption-based accounting reveals the life cycle environmental impacts of the final consumption of cities and city residents, including the trans-boundary flows. However, the existing consumption-based carbon footprint literature has largely ignored the regenerative impacts that nations, cities, and individuals may have (see the review by Heinonen et al., 2020). Sink capacity creation, natural carbon storages, and even more high-tech end NETs could already be in an important role in the quest for low-impact living, and even more so in the future along with the development of these technologies. Thus, it is essential to incorporate these aspects to the accounting methods as well.

Similarly, as emissions, regenerative impacts can also be assessed either locally (territorial accounting) or globally by using a life-cycle method (consumption-based accounting). The most comprehensive picture is achieved by examining both of these at the same time, as shown by Wiedmann et al. (2015) regarding emissions, and as presented in this chapter with the handprint addition. However, if just one of these two approaches is chosen, one should not mix territorial emissions and global handprint, or consumption-based carbon footprint and local handprint by outside actors, since this leads to a false picture on the carbon balance of a city. In fact, instead of seeking “carbon neutrality” by choosing convenient system boundaries that allow for such balance, it would, in many cases, be more beneficial if cities would take responsibility for their consumption-based emissions and aim to reduce them. Regenerative actions may help to achieve carbon neutrality, but looking from the consumption-based perspective, the cities and consumers of the developed world are very far from having a zero carbon balance.

In the context of climate change, we defined regenerative impacts here as "negative emissions", meaning that GHG emissions are not only reduced but carbon is absorbed from the atmosphere. This is a more stringent definition than some previously presented. For example, increased circularity of resources and energy has been described as regenerative by previous literature, but, from the perspective of climate change, it only reduces emissions instead of absorbing them. These sorts of impacts are already covered by the current "harm-side" accounting methods. In general, regenerative impacts should be more clearly defined. Some solutions may be regenerative in one environmental impact category, but harmful in another. Broad life cycle methods, including several environmental impact categories, have been created specifically to address these types of dilemmas and should be applied to assess the overall environmental impacts of potentially regenerative solutions.

To conclude, regenerative impacts should be incorporated into city carbon accounts to incentivize and support the creation and use of regenerative solutions. However, this should be done consistently and, at the same time, cities should take responsibility for the imported emissions that serve the consumption of the city and city residents. Otherwise, cities may create a "low-carbon" or even "carbon neutral" illusion that does not tell the whole truth of their climate impacts. Although thinking through the positive side is important, it should be grounded on the real planetary limits and, in the case of climate change, the remaining carbon budgets.

References

Afionis, S., Sakai, M., Scott, K., Barrett, J., & Gouldson, A. (2017). Consumption-based carbon accounting: Does it have a future? *Wiley Interdisciplinary Reviews: Climate Change, 8*(1), e438.

Aguilar-Hernandez, G., Sigüenza-Sanchez, C., Donati, F., Rodrigues, J., & Tukker, A. (2018). Assessing circularity interventions: A review of EEIOA-based studies. *Journal of Economic Structures, 7*(1), 14.

Andrew, R. (2020). *It's getting harder and harder to limit ourselves to 2°C*. http://folk.uio.no/roberan/t/global_mitigation_curves.shtml. Accessed 6 Feb 2020.

Baynes, T., & Wiedmann, T. (2012). General approaches for assessing urban environmental sustainability. *Current Opinion in Environmental Sustainability, 4*, 1–7.

C40 Cities. (2018). *Consumption-based GHG emissions of C40 cities*. https://www.c40.org/. Accessed 3 Feb 2020.

C40 Cities. (2020). *C40 cities*. https://www.c40.org/. Accessed 3 Feb 2020.

Chen, S., Long, H., Chen, B., Feng, K., & Hubacek, K. (2019). Urban carbon footprints across scale: Important considerations for choosing system boundaries. *Applied Energy, 259*, 114201.

Clarke, J., Heinonen, J., & Ottelin, J. (2017). Emissions in a decarbonised economy? Global lessons from a carbon footprint analysis of Iceland. *Journal of Cleaner Production, 166*, 1175–1186.

Covenant of Mayors. (2020). *Covenant of Mayors for climate and energy*. Available at: https://www.covenantofmayors.eu/en/. Accessed 3 Feb 2020.

Du Plessis, C. (2012). Towards a regenerative paradigm for the built environment. *Building Research & Information, 40*(1), 7–22.

Geissdoerfer, M., Savaget, P., Bocken, N., & Hultink, E. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production, 143*, 757–768.

Girardet, H. (2014). *Creating regenerative cities*. London: Routledge.

Gou, Z., & Xie, X. (2017). Evolving green building: triple bottom line or regenerative design? *Journal of Cleaner Production, 153*, 600–607.

Greenford, D., Crownshaw, T., Lesk, C., Stadler, K., & Matthews, D. (2020). Shifting economic activity to services has limited potential to reduce global environmental impacts due to the household consumption of labour. *Environmental Research Letters, 15*(6), 064019.

Grönman, K., Pajula, T., Sillman, J., Leino, M., Vatanen, S., Kasurinen, H., et al. (2019). Carbon handprint – An approach to assess the positive climate impacts of products demonstrated via renewable diesel case. *Journal of Cleaner Production, 206*, 1059–1072.

Heinonen, J. (2012). *The Impacts of Urban Structure and the Related Consumption Patterns on the Carbon Emissions of an Average Consumer, Aalto University publication series*. DOCTORAL DISSERTATIONS 25/2012, Espoo, Finland.

Heinonen, J., & Junnila, S. (2014). Residential energy consumption patterns and the overall housing energy requirements of urban and rural households in Finland. *Energy and Buildings 76*, 295–303.

Heinonen, J., & Jóhannesson, S. E. (2019). More consumption, less production: The low-carbon illusion of cities. In J. L. Boucher & J. Heinonen (Eds.), *Sustainable consumption, promise or myth? Case studies from the field* (pp. 9–27). Newcastle upon Tyne, UK: Cambridge Scholars Publishing.

Heinonen, J., Ottelin, J., Ala-Mantila, S., Wiedmann, T., Clarke, J., & Junnila, S. (2020). Spatial consumption-based carbon footprint assessments – A review of recent developments in the field. *Journal of Cleaner Production, 256*, 120335.

Hertwich, E., & Peters, G. (2009). Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science and Technology, 43*(16), 6414–6420.

Horváth, M. (2019). *Net positivity perspective of renewable fuel production impacts on climate and resource consumption – A case study*. Master's thesis. Helsinki, Finland: Aalto University.

ICLEI. (2020). *Local governments for sustainability*. https://www.iclei.org/. Accessed 3 Feb 2020.

IPCC. (2018). *Global warming of 1.5°C An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (32 p). In V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.). Geneva, Switzerland: World Meteorological Organization.

Kanemoto, K., Moran, D. D., Lenzen, M., & Geschke, A. (2014). International trade undermines national emission reduction targets: New evidence from air pollution. *Global Environmental Change, 24*, 52–59.

Le Quéré, C., Andres, R., Boden, T., Conway, T., Houghton, R., House, J., et al. (2012). The global carbon budget 1959–2011. *Earth System Science Data Discussions, 5*(5), 1107–1157.

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., et al. (2018). Global carbon budget 2018. *Earth Systems Science Data, 10*, 2141–2194.

Minx, J., Lamb, W., Callaghan, M., Bornmann, L., & Fuss, S. (2017). Fast growing research on negative emissions. *Environmental Research Letters, 12*(3), 035007.

Minx, J., Lamb, W., Callaghan, M., Fuss, S., Hilaire, J., Creutzig, F., et al. (2018). Negative emissions – Part 1: Research landscape and synthesis. *Environmental Research Letters, 13*, 063001.

Moran, D., Kanemoto, K., Jiborn, M., Wood, R., Többen, J., & Seto, K. (2018). Carbon footprints of 13 000 cities. *Environmental Research Letters, 13*(6), 064041.

O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability, 1*(1), 88–95.

Ottelin, J. (2016). *Rebound effects projected onto carbon footprints-implications for climate change mitigation in the built environment*. Doctoral thesis, Helsinki, Finland: Aalto University.

Ottelin, J., Ala-Mantila, S., Heinonen, J., Wiedmann, T., Clarke, J., & Junnila, S. (2019). What can we learn from consumption-based carbon footprints at different spatial scales? Review of policy implications. *Environmental Research Letters, 14*(9), 093001.

Ottelin, J., Heinonen, J., Nässén, J., & Junnila, S. (2019). Household carbon footprint patterns by the degree of urbanisation in Europe. *Environmental Research Letters, 14*(11), 114016.

Pedersen Zari, M. (2018). *Regenerative urban design and ecosystem biomimicry*. London: Routledge.

Ramaswami, A., & Chavez, A. (2013). What metrics best reflect the energy and carbon intensity of cities? Insights from theory and modeling of 20 US cities. *Environmental Research Letters, 8*, 035011.

Raupach, M. R., Davis, S. J., Peters, G., Andrew, R., Canadell, J., Ciais, P., et al. (2014). Sharing a quota on cumulative carbon emissions. *Nature Climate Change, 4*, 873.

Reed, B. (2007). Shifting from 'sustainability' to regeneration. *Building Research & Information, 35*(6), 674–680.

Rees, W., & Wackernagel, M. (2008). Urban ecological footprints: Why cities cannot be sustainable – And why they are a key to sustainability. In J. M. Marzluff et al. (Eds.), *Urban ecology*. Boston: Springer.

Rogelj, J., Schaeffer, M., Meinshausen, M., Knutti, R., Alcamo, J., Riahi, K., et al. (2015). Zero emission targets as long-term global goals for climate protection. *Environmental Research Letters, 10*(10), 105007.

Sato, M. (2014). Emissions embodied in trade: A survey of the empirical literature. *Journal of Economic Surveys, 28*(5), 831–861.

UNFCCC. (2018). *The Paris agreement*. https://unfccc.int/process/the-paris-agreement/the-paris-agreement. Accessed 10 Apr 2020.

Wiedmann, T. (2016). Impacts embodied in global trade flows. In R. Clift & A. Druckman (Eds.), *Taking stock of industrial ecology* (pp. 159–180). Cham, Switzerland: Springer.

Wiedmann, T., Chen, G., & Barrett, J. (2015). The concept of city carbon maps: A case study of Melbourne, Australia. *Journal of Industrial Ecology, 20*(4), 676–691.

Wiedmann, T., & Lenzen, M. (2018). Environmental and social footprints of international trade. *Nature Geoscience, 11*, 314–321.