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Infrastructure development compromises creation of low-carbon cities

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Abstract. Of the UN SDGs, the role of infrastructure in enabling or compromising the development of future low-carbon settlements falls under the goal #11 "Sustainable cities and communities". However, when it comes to the specific content of the SDG #11, only the sub-goals 11.6 and 11.B-C loosely include these development-phase emissions. If it was shown that infrastructure development compromises creation of low-carbon cities, it would also mean that the SDG #11 might fail to guide the development to sustainable cities and communities. In this study the role of infrastructure and capital development emissions are analyzed from different perspectives by synthesizing the suggested emissions levels from previous studies. Iceland is looked at separately as a case country and the capital Reykjavik as a case city. Previous studies on Iceland are utilized to discuss the infrastructure and capital development related emissions and to compare them to the overall carbon footprints suggested for these locations and their residents. The results suggest that climate-sustainable built environment cannot be built with the currently dominant materials of concrete, steel and asphalt. The issue should quickly receive more attention before we run out of the remaining carbon quota.

1. Introduction

We are on the verge of irreversibly damaging the one globe we live on [1,2]. Halting climate change to a level with adaptable consequences is generally held as the most urgent. However, we are quickly reaching a state when the mitigation pace required for even the 2 degree target is tens of percentages annually [3]. Reaching below zero emissions within a couple decades might also be needed [4]. These estimations are based on the so called carbon budget, i.e. the emissions quota left for likely not exceeding the set warming target, e.g. [5]. According to different estimations, this budget is likely something roughly between 150 gigatons (gt) [6] and 1100 gt [7] for 1.5 degree warming and 1000 gt [8] to 2500 gt for 2 degree warming [7]. The current annual global anthropogenic GHG emissions reach above 40 gt and show no significant slowdown [7].

The built environment is among the key sectors in the fight against warming. It directly or indirectly causes a major share of anthropogenic greenhouse gas (GHG) emissions. Low-carbon energy systems, low-energy buildings, automation and other smart features, infrastructure and support systems for public and active transport modes are considered as key measures for achieving the low-carbon future. While the end result of these actions has been shown to be positive in multiple studies, it is rarely considered that they all need heavy upfront "carbon investments", i.e. high embodied emissions in the development phase. E.g., densifying is among the most common strategies listed when it comes to city-level GHG

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mitigation, aiming at reducing private car use, living space per capita and infrastructure needs per capita. However, even in the case of low-carbon buildings the "carbon payback" time can be decades [9,10]. And no strong evidence exists about the lower infrastructure need. Typically, smaller living spaces mean more service spaces in close proximity; *de facto* a trade-off between possessed living space and utilization of shared spaces to expand the home to [11]. Many support structures, such as underground parking spaces, add much higher emissions in denser settlements compared to simpler structures for the same purpose elsewhere. The ongoing urbanization in all around the globe might mean that the capital stock development becomes the most important emissions sector, exceeding 50% of all GHGs in a certain place [12,13]. Finally, it is common to look at the building and infrastructure related emissions annualized across the long lifecycle of them [10]. This tradition overlooks the essential matter that the early life cycle emissions are the most crucial when the emissions need to be cut extremely rapidly. Overall, the impact and role of the "carbon investment" is weakly understood, whereas it might compromise the whole target of low-carbon cities [14].

Of the UN SDGs, the role of infrastructure in enabling or compromising the development of future low-carbon settlements falls under the goal #11 "Sustainable cities and communities". However, when it comes to the specific content of the SDG #11, only the sub-goals 11.6 and 11.B-C loosely include these development-phase emissions, but only if the one reading the sub-goals decides to pay attention to them. If it was shown that infrastructure development compromises creation of low-carbon cities, it would also mean that the SDG #11 might fail to guide the development to sustainable cities and communities.

In this study the role of infrastructure and capital development emissions are analyzed from different perspectives by synthesizing the suggested emissions levels from previous studies. Iceland is looked at separately as a case country and the capital Reykjavik as a case city. Previous studies on Iceland are utilized to synthesize the infrastructure and capital development related emissions and to compare them to the overall carbon footprints suggested for these locations and their residents. The results suggest that climate-sustainable built environment cannot be built with the currently dominant materials of concrete, steel and asphalt. The issue should quickly receive more attention before we run out of the remaining carbon quota.

2. Built environment development emission estimations in the previous literature

2.1. Built environment development as a component of carbon footprints

Consumption-based carbon footprint literature provides a rarely utilized but a highly useful source for evaluating the importance of the GHGs from built environment development. They, when reporting full footprints, comprise all embodied emissions from the use and development of the built environment, including those from construction of buildings and other infrastructure [Heinonen et al. (forthcoming)]. As they also include the emissions embodied in all the goods and services used or purchased within the selected area, they provide important information about the role of buildings and other infrastructure.

Many of the full carbon footprint studies report capital formation, consisting mostly of buildings and other infrastructure, as the most important source of emissions even on a country-level, e.g. [15,16]. Ivanova et al. [17] report these emissions to cause 24±7% of the full carbon footprint for 43 global countries. Typically, the shares are the highest in developing countries where rapid urbanization is taking place, such as in China. They have been reported high for many developed countries as well, however. Kim [18] reported 37% to come from capital formation of the full carbon footprint in Korea. Wood & Dey [19] found them forming a 20% share and Levitt et al. [20] 23% of the carbon footprint in Australia. Steininger et al. [21] reported an over 10% share for Austria, Ottelin et al. [22] similar share for Finland, and Ferguson et al. [23] 12 and 10% for Canada and USA. Even though the latter shares, those for the highly developed countries, might sound low, they should be taken as extremely high given the high overall carbon footprints in these countries.

When moving to a within-country level, these emissions can potentially exceed 50% of all emissions caused by the operation and development of a region due to construction concentrating in the more urbanized areas. As examples, Mi et al. [12] reported shares of over 60% for capital formation for many rapidly urbanizing Chinese cities, Feng et al. [13] 48 to 60% for Chinese megacities, and Zhang et al. [24] between 40 and 50% for selected Chinese case cities. Chen et al. [25] discuss how economic and population growth driven construction emerged as the dominant emissions sector for all the 10 case cities they studied from Australia and China. The shares reported by Chen et al. [25] varied from 21 to 41% with the higher end found from China.

2.2. Studies focusing on built environment development

A different type of a perspective to the topic of understanding the importance of the development phase (embodied) emissions is provided by case studies of individual structures, but providing an analysis across the life cycle showing the timing of the emissions. In such studies, the "carbon payback" times have in many cases been found long, particularly when compared to the remaining carbon budgets.

Säynäjoki et al. [12] analysed the life cycle emissions of a detached house in Finland, and utilizing a future improvement scenario for the GHG content of energy they reported decades long payback times for the upfront "carbon investment", i.e. the emissions embodied in the pre-use phases. Heinonen et al. [26] utilized the same case study but included the full carbon footprint of an average resident in the region, and still found the embodied emissions of the detached house to dominate the overall cumulative emissions for over 20 years. Several other building LCA studies have also brought up the undermined importance of the pre-use phase, e.g. Blengini and Di Carlo [27] and Stephan et al. [28].

Transport infrastructure systems have been studied with a similar approach and similar conclusions. Chester et al. [29] compared the payback times of transport infrastructure systems with predicted automobile shifts in Los Angeles. They reported the GHG payback to occur during the second decade for a bus rapid transport option, but only during the fourth decade for a light rail option. Chester & Horvath [30] conclude that a high-speed train in California would bring GHG benefits, but only after decades when including the infrastructure development phase emissions, the payback occurring during the fourth decade and sensitivity running from the third until the seventh.

On a city-level, Bergesen et al. [31] created scenarios for the development of 84 cities and estimated the GHGs in the different scenarios, and concluded that only resource-efficient infrastructure development combined with densification and decarbonisation of energy production leads to a decrease in annual emissions by 2050. Kyrö et al. [32] found that higher building energy efficiency is not enough to curb down the city-level cumulative emissions when the construction phase embodied emissions are included in a longitudinal assessment. Chen et al. [33] estimated city-level GHGs for the Chinese cities of Beijing, Shanghai, Tianjin and Chongqing, and show how the infrastructure footprints exceed both the territorial and the consumption-based footprints.

At the broadest level, Müller et al. [14] assessed the GHGs from all global infrastructure development until 2008 and estimated the future contribution with the assumption of the developing countries catching up until 2050. According to them, infrastructure development has already contributed to global warming with 122 Gt CO_2. Further, they estimate 350 Gt CO_2 investment needed in just infrastructure development if developing countries were to catch up, assuming the technologies of their base year 2008. This would mean infrastructure alone consuming the vast majority of the remaining carbon budget for 1.5 degree warming. Consistent with Müller et al. [14], Minx et al. [34] found capital investment, particularly construction, to account for the majority of China's rapidly increased GHG emissions in the early years of the ongoing millennium.

2.3. Summary

While the above reviewed studies do not form a comprehensive overview of studies on the topic, but are rather examples of studies having lifted up somehow the built environment development phase emissions, they still give strong support for the claim of these emissions potentially compromising creation of low-carbon cities. Several studies exist having reported much shorter payback times for building and other infrastructure construction, and naturally the outcome of such an analysis always

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heavily depends on the context and the assessment assumptions. Still, the systematically high estimates given in the carbon footprint literature reviewed in 2.1. and the overall estimation of Müller et al. [14] indicate that concrete, steel and asphalt are questionable materials for development of a climate-sustainable built environment.

3. The Icelandic case study

The Icelandic case study is based on the figures published by Heinonen et al. [35], and on some unpublished data from the same project. The study of Heinonen et al. [35] covered a time-period of 2013-2017, years when Iceland was recovering from the deepest economic recession in any developed country singe the WWII. During the assessment period the emissions embodied in building and other infrastructure construction almost doubled to reach 330,000 tons of CO_2e in 2017. Of the overall load, 70% was caused by building construction, and the remaining 30% other infrastructure. In Iceland this means more than 1.1 tons per capita. Building construction in the capital city Reykjavik was responsible for 100,000 tons, or 30% of the overall load.

At the same time, the capital city Reykjavik is reporting 2.8 tons of CO2e as the per capita carbon footprint [36], excluding the emissions embodied in built environment development. Furthermore, Reykjavik has announced a carbon neutrality target by 2040 [37], but again including only the 2.8 tons per capita reported by the city. To reach the carbon neutrality target, the current, relatively recent, master plan of the city, Reykjavik Municipal Plan 2010-2030 [38] strongly emphasizes densification. While one of the aims is to reduce travel by private cars, deployment of this plan requires heavy construction. The estimate for just residential construction is 50 to 60 thousand square meters on average per year until 2030. In addition, major transport infrastructure development projects are in development to improve the public transport service level in the city. In Reykjavik the dominant construction material is steel reinforced concrete (Portland cement based) and there is no push towards utilization of less GHG intensive materials. Therefore, while the end result, the use phase emissions at some point in the future, might be positive (decreased emissions), the cumulative emissions over time unlikely are lower with all the development. A significant modal shift and decrease in kilometres driven would be needed to turn the result positive when accounting for the emissions embodied in the built environment development. The emissions might still decrease over the period until 2030 due to for example electrification of the vehicle fleet, but this development has little to do with the master plan.

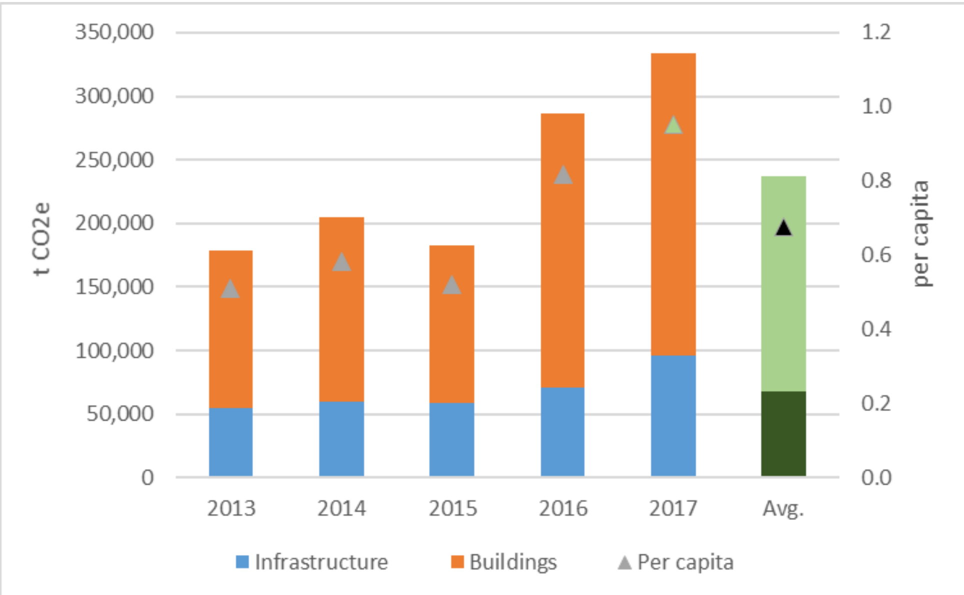

Figure 1. The GHGs from built environment development in Iceland from buildings and infrastructure in 2013-2017 (from Heinonen et al. [35]).

4. Discussion

This paper was set to investigate the claim that infrastructure development might compromise creation of low-carbon cities. Infrastructure is understood broadly to include all built environment development from building construction to other infrastructure systems. The first part included a literature review showing results from studies on different levels from global to site-specific case studies, all showing how the development phase embodied emissions can be highly important, up to the level postponing any gains from the development way beyond the currently set mitigation target years.

The topic is connected to several UN SDGs, but on a broad level particularly to the SDG #11 Sustainable Cities and Communities. However, regardless of the name of the goal #11, it is difficult to see how climate sustainability and environmental sustainability overall would be captured by the goal. Moreover, when looking at the sub-targets, the focus of the goal seems to be strongly on the social component of sustainability, and secondarily on the economic component. Only three sub-targets somehow include the topic of environmental sustainability:

- 11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management
- 11.B By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, …
- 11.C Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials

Of these, the first includes the idea of reducing the adverse per capita environmental impact of cities, but then the focus is turned to air quality, which is largely a human health issue, and to waste, which is important area but still just one and only distantly related to e.g. climate change. 11.B mentions climate change, but without any specific targets in terms of mitigating climate change, halting warming to 1.5 or 2 degrees, or reaching any other targets. Finally, 11.C touches the topic of this paper, but puts the focus on the least developed countries, whereas in this paper it has been shown that alternative, climate friendly, material deployment at a fast pace would be of utmost importance in the developed countries as well. The above cited Müller et al. [14] study also emphasized expanding the scope to other infrastructure systems as well, or development of the less developed countries might lead to utilization of a major part of the remaining carbon budget to reach the 1.5 degree warming target.

To conclude, the UN SDGs do not seem to give much attention to the environmental component of cities and other human settlements, at least from the perspective of global problems like climate change. It is therefore difficult to see that the outcome of reaching for example the targets set for the SDG #11 would lead to a sustainable outcome in global terms.

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