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Greenhouse gas emissions from built environment development in Iceland

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Abstract. Without rapid and radical greenhouse gas (GHG) mitigation, irreversible damage threatening life on the globe might occur already during the next decades. One of the key sectors in finding solutions to climate change is the built environment, which currently directly or indirectly causes the majority of anthropogenic GHG emissions. The transition towards more sustainable settlements requires massive use of materials and energy, but it is not well known at all how much GHG emissions are "invested" into the development of the future low-carbon built environment. In this study we use input-output analysis to calculate an estimate of the GHGs embodied in the built environment development in Iceland. The input data consists of annual economic turnover data of different construction sectors for the years 2013-2017. The GHG estimates are derived using the EIO-LCA input-output model. We find that the built environment development emissions of Iceland are significant even though the actual emissions largely take place outside the country, being thus outsourced emissions. Surprisingly the development of the capital region did not stand out as the engine of these emissions, but the spread appeared to be relatively equal between the capital region and the rest of the country.

1. Introduction

We are facing an ever-growing need to rapidly reduce the environmental pressure we are currently causing [1]. Whereas several other important environmental problems exist and new are already in the horizon, climate change mitigation is among the most urgent. Without rapid and radical mitigation, irreversible damage threatening life on the globe might occur already during the next decades [2].

One of the key sectors in finding solutions to climate change is the built environment, which currently directly or indirectly causes the majority of anthropogenic greenhouse gas (GHG) emissions leading to climate change. However, the transition towards more sustainable settlements requires massive use of materials and energy, be it new energy efficient buildings or supporting infrastructures. Several studies have found built environment development, buildings and infrastructure, the most important source of GHG emissions in rapidly urbanizing regions (e.g. [3-6]). However, these are broad scale studies which include also other capital investments than construction and offer little details about the distribution of these emissions.

In bottom-up studies of the built environment structures, buildings have received the most interest. However, the focus has been on the use phase emissions and traditionally the emissions embodied in construction materials have not been considered of high importance [7], but they are actually becoming the key issue due to the rapidness of the need to cut the emissions and to their increasing relative importance along with improving building energy efficiency [8-12]. Furthermore, few embodied building GHG studies have included even the building specific infrastructures, such as parking lots and pedestrian pathways. It is also typical to divide the emissions equally over the life cycle of the assessment object, be it a building, street, bridge or other structure, for annual loads. This omits the important issue that the early life cycle emissions are the most crucial. Thus it is not well known at all how much GHG emissions are "invested" into the development of the built environment if looking at the bottom-up perspective.

Estimating the environmental loads embodied in construction materials has also appeared challenging [13] and despite the significant research on the environmental impacts of construction materials around the world, the reliability of the published impact estimates is still highly questionable [7,14]. Overall we don't have good understanding about the embodied impacts caused by the development of the built environment, while at the same time these impacts can hinder us from achieving the set mitigation targets [8] or postpone the GHG gains far into the future [15]. Thus, more reliable information from the construction sector is needed for advised decision-making.

In this study we use input-output analysis to calculate an estimate of the greenhouse gas (GHG) emissions embodied in the built environment development in Iceland. The input data includes annual development costs and comes from Statistics Iceland. We use annual economic turnover data of different construction sectors for the years 2013-2017 from Statistics Iceland to estimate the GHG loads caused by the built environment development in Iceland. The GHG estimates are derived using the EIO-LCA input-output model, which offers the highest resolution construction data of the available IO models, and, as inherent for the IO method, allows tracing of the full life cycle emissions through the full production and supply chains [16]. What is shown is that the built environment development emissions of Iceland are significant even though the actual emissions largely take place outside the country, being thus outsourced emissions. Surprisingly the development of the capital region did not stand out as the engine of these emissions, but the spread appeared to be relatively equal between the capital region and the rest of the country.

2. Materials and methods

2.1. Study materials

Two datasets were utilized to estimate emissions from built environment development in Iceland, one for transport related infrastructure and another for buildings. Data for total annual expenditure from transport infrastructure was collected from annual reports published by The Icelandic Road and Coastal Administration (Vegagerðin). The reports included expenditure data from several different categories, although the total expenditure was reported for the country as a whole and data from the Capital Region was not available separately. Table 1 shows a summary of annual expenditure (in m.kr, nominal) from the main categories reported for roads, bridges and tunnels for 2013-2017.

Table 1. Expenditure (in m.kr, nominal) by category and year.

Main category	Sub-categ.	2013	2014	2015	2016	2017
Operation & management		676	750	709	715	727
Service		4,500	4,417	4,607	5,677	4,440
Maintenance	Roads	3,900	3,890	4,550	4,600	6,500
	Bridges	355	400	500	450	600

	Tunnels	140	130	130	130	140
Initial costs	Roads	5,636	4,666	5,344	6,099	6,589
	Bridges	283	38	140	140	250
	Tunnels	1,410	3,390	3,010	3,180	3,810
Sea related infrastructure		153	356	106	1002	3029

Data for buildings was provided by Registers Iceland (Þjóðskrá). The dataset contained both annual data on area (m^2) of housing built and total expenditure (in million kr., nominal). Buildings in the Reykjavík Capital Region were reported separately from the rest of the country and the dataset included three categories with several sub categories. Residential buildings we split into detached houses, semi-detached houses and apartment buildings. Commercial housing was split into industrial housing, specialized, shops and offices and warehousing. The “Other” category included the subcategories garages and sheds, summer houses and outbuildings. Table 2 presents the annual expenditure (in million kr.) by main category and year built, Reykjavík Capital Region is separated from the rest of the country. Table 3 shows reported building infrastructure area (m^2) by main category, year built and location.

Table 2. Total expenditure (in m.kr., nominal) of new buildings by location, type and year built.

Location	Type	2012	2013	2014	2015	2016	2017
Capital	Commercial	3,505	6,101	2,577	8,091	13,171	7,118
	Residential	7,028	14,590	22,265	19,456	28,017	30,275
	Other	665	1,302	1,498	2,509	2,474	2,683
Rural	Commercial	3,903	9,297	7,919	8,483	15,256	15,332
	Residential	3,542	2,749	4,271	4,654	7,936	11,687
	Other	3,335	3,949	3,970	3,349	7,239	6,840

Table 3. Total area (m^2) of new buildings by location, type and year built.

Location	Type	2012	2013	2014	2015	2016	2017
Capital	Commercial	23,280	35,398	12,900	36,239	62,506	33,230
	Residential	37,053	74,377	114,942	102,611	137,699	127,094
	Other	4,772	3,898	5,485	3,624	9,963	5,909
Rural	Commercial	26,992	41,190	40,778	39,012	91,512	71,630
	Residential	19,630	14,940	22,108	22,626	39,225	50,780
	Other	20,976	28,166	22,375	20,773	37,20	40,043

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2.2. Method
The emissions were estimated using a life cycle analysis (LCA) approach, which enables capturing the emissions from the production and delivery chains [17]. The assessment includes only the GHG emissions, and the result can thus be called carbon footprint [18].

The LCA was conducted using an input-output (IO) approach, which utilizes monetary transaction values and IO tables to estimate the emissions [19]. IO LCA greatly simplifies the assessment since the information the practitioner would have to gather from all the processes of the supply chain is now included in the input-output tables. IO LCA is also a comprehensive method including the full production and supply chains without cutoffs. Säynäjoki et al. [20] have shown that the cutoffs can be tens of percentages in the building sector. At the same time, IO approach is average based and suffers from several other problems as well, discussed further in the discussion section. In general, the method is efficient for first screening assessment, such as conducted in this study, to understand the rough magnitudes, but cannot be used for detailed analyses.

2.3. Assessment model
The U.S. economy-based IO model of the Carnegie Mellon University Green Design Institute, called the 2007 U.S. Benchmark Producer Price Economic Input-Output Life-Cycle Assessment model (EIO LCA) [21], adjusted with Icelandic data for some key local activities. The EIO LCA is among the most disaggregated models available with 388 economic sectors, which provides better sectoral fit between the model and the data than the majority of other existing models. Being a purchaser price model, the emission outputs are adjusted to the final end-user market prices. The classification follows the North American Industry Classification System (NAICS), but the fit is relatively good with the Classification of individual consumption by purpose (COICOP) system as well. The adjustments to the model are explained below and the uncertainties discussed in the discussion section.

2.4. The assessment
Table 4 shows the EIO LCA sectors utilized in the assessment and the matching with the input data. The second column uses the terminology of the input data. To enhance the match between the US economy based model and Icelandic data, the GHG intensities of the utilized sectors were adjusted with inflation between the model year 2007 and the data years 2013-2017 utilizing US sectoral inflation rates for different construction sectors [22]. The adjusted intensities were then converted to Icelandic kronor according to the annual average currency exchange rates for 2013-2017 [23].

Table 4. The EIO LCA sectors utilized in the assessment and the matching with the input data building types.

EIO LCA sector	**Input data**
Highways, Streets, And Bridges	Infrastructure
Manufacturing Buildings	Industrial buildings
Commercial Structures, Including Farm Structures	Shops and offices, specialized buildings
Single-Family Homes	Detached houses, summer houses
Multifamily Homes	Semi-detached houses, apartment buildings
Other Nonresidential Structures	Warehouses

3. Results

Over the five-year time span of the study the GHGs from built environment development in Iceland sum up to 1.2 million tons of carbon dioxide equivalents (tCO2e), meaning 240,000 t per annum and close to 0.8 t per capita (Figure 1). Significant growth was also detected, likely relating to Iceland's recovery after a major economic recession in the beginning of the decade. In 2013 the annual load was 180,000 t, whereas in 2017 it had surpassed 300,000 t and 1.0 t per capita. Buildings occupy a share of approximately 70% with some annual fluctuation, and infrastructure around 30%. The share of buildings includes the immediate infrastructure to the buildings, such as parking lots and yards and playgrounds, which could also be allocated to infrastructure, but could not be separated with the data in use.

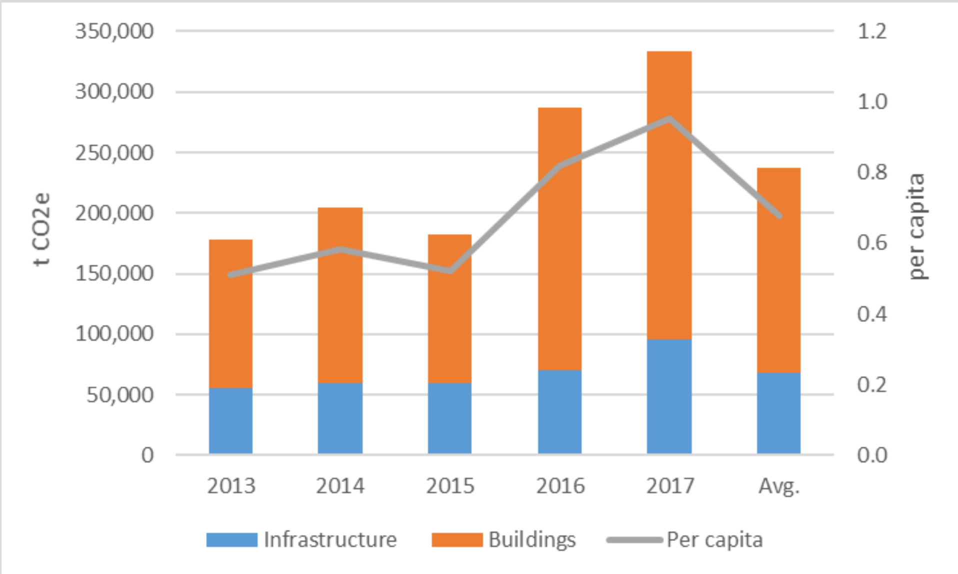

Figure 1. The GHGs from built environment development in Iceland from buildings and infrastructure in 2013-2017.

When looking at the emissions from building construction more closely, it appears rather surprisingly that the capital region does not drive the emissions as strongly as was expected (Figure 2). Due to the

Figure 2. Average annual GHGs from building construction in the capital region and other parts of the country.

strong concentration of the population of Iceland to the capital region (about two thirds of the population living in the capital region), in absolute terms the capital region drives the emissions, but on per capita terms the emissions are even somewhat higher outside the capital region (the orange triangles in Figure 2). In the capital region it is the emissions from residential building construction which dominate, driven by the ongoing migration from other parts of the country, and abroad, to the capital region. 15 to 20% of the residential building construction in the other parts of the country are also due to summer house construction, which is likely to a large extent driven by the residents of the capital region.

4. Discussion

The study was set to assess a rough estimate for the GHG emissions from built environment development in Iceland. Typically building and infrastructure system assessments are done over the lifetime of the assessment object and to one object at a time, which gives little information about the overall annual GHG load from all building and infrastructure construction activities. This study thus provides one case example, which can in the future be used as a benchmark and complemented with other studies.

What was found is that the GHGs from built environment development should be taken into account when designing GHG mitigation strategies in the context of the built environment, such as building energy efficiency regulations and infrastructure development projects to facilitate low-carbon transport. Otherwise it may happen that the "carbon investment" in the development phase is never paid back or the payback is longer than would be acceptable. E.g. Säynäjoki et al. [8] and Chester et al. [15] have showed case examples of long payback times related to building construction and public transport infrastructure development. In addition, Kyrö et al. [24] show how building energy efficiency improvement might not be enough to payback the construction phase emissions on a city-level.

As noticed above, this study has several limitations and should only be taken as indication of what the GHGs from built environment development might be. First, the data for infrastructure is restricted to the part in the responsibility of the main road and other civil infrastructure authority Vegagerdin, thus lacking the streets and roads under the responsibility of municipalities. Second, there is no applicable IO model for Iceland, and thus the US economy based EIO LCA model was selected. To the knowledge of the authors, Iceland is only included in one multi-region IO model, Eora [25], and this model only includes 26 sectors which is too few for a one-sector study such as this [26]. The selected US model includes 388 sectors and several for different construction sector sub-sectors. The match was thus found as the best possible with the inflation and currency exchange rate corrections presented in the method section. However, Iceland is in many ways a special case. With very low population density, difficult conditions and relatively long distances it might be that particularly the infrastructure component of our assessment appears different from that in many other locations.

The IO LCA method itself has also several limitations. Because the emissions factor for each IO sector is based on the weighted average of the emissions of several actual economic sectors, with different emissions per unit of output, there is an aggregation error in the total estimated emissions [27,28]. In addition, there are concerns regarding the validity of the homogeneity and linearity assumptions. While emissions from the production of different goods in a factory can vary considerably, based on the homogeneity assumption, an IO LCA considers that the IO table's averages signify all the products manufactured under a certain sector. Moreover, according to the linearity assumption, there is a linear correlation between the market price and the environmental impacts [27].

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