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Assessment of embodied emissions of road infrastructure in the Capital Region and those created in future development to 2040

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Þetta verkefni er styrkt af rannsóknarsjóði Vegagerðarinnar. Höfundar skýrslunnar bera ábyrgð á innihaldi hennar. Niðurstöður hennar ber ekki að túlka sem yfirlýsta stefnu Vegagerðarinnar eða álit þeirra stofnana eða fyrirtækja sem höfundar starfa hjá.

Abstract

A fair amount of development is planned in the Capital Region in the coming decade due to increased population growth. The municipalities within the region have dedicated themselves to build 37,159 new apartments in total before 2032 and the City of Reykjavík estimates to build additional 1200 apartments annually from there on to 2040. Additionally, some infrastructure development is tied to these new apartments and neighbourhoods as well as large scale traffic infrastructure development like Borgarlínan and Sundabraut are planned in the coming decade. This development in the Capital Region will cause a great amount GHG emissions to be released into the atmosphere. There is an abundance of research on buildings and green spaces, but less on the environmental impact of road infrastructure. This study aims to quantify the carbon embodied in the Capital Region's current traffic infrastructure and estimate the emissions from future development. The results show that the carbon embodied in the Capital Region is 441,091 tCO₂eq. In total the carbon embodied in the Capital Region in 2040 will be between 715,031-779,057 tCO₂eq.

Útdráttur

Umfangsmikil uppbygging er fyrirhuguð á Höfuðborgarsvæðinu næsta áratuginn og til ársins 2040 vegna aukinnar fjólksfjölgunar á svæðinu. Til að bregðast við því hafa yfirvöld einsett sér að byggja 37.159 íbúðir til ársins 2032 og Reykjavíkurborg stefnir á að byggja 1200 íbúðir á ári aukalega til ársins 2040 eftir það. Auk þess er nokkur innviðauppbbygging bundin við þessar framkvæmdir og þar fyrir utan eru yfirgripsmiklar vegaframkvæmdir á borð við Borgarlínu og Sundabraut á dagskrá á komandi áratug. Vegna umhverfisáhrifa byggða umhverfis mun þessi uppbygging valda mikilli losun gróðurhúsalofttegunda. Rannsóknir á umhverfisáhrifum bygginga og grænna svæða hafa verið framkvæmdar í miklum mæli síðusta áratuginn eða svo en skortur virðist vera á rannsóknum tengdum veginnviðum, þótt þær hafi færest í aukana á síðustu árum. Þessi rannsókn áætlar innbyggt kolefni í núverandi veginnviðum á Höfuðborgarsvæðinu og áætlar losun frá fyrirhuguðum framkvæmdum og viðhaldi til ársins 2040. Niðurstöðurnar leiða í ljós að innbyggt kolefni í Höfuðborginni er 441.091 tonn CO₂íg og að losun frá fyrirhuguðum framkvæmdum og viðhaldi mun nema allt frá 715.031-779.057 tonnum CO₂íg.

1 Introduction

The world is becoming more urbanised. According to the UN (2018) 68% of the world population will live in cities by 2050. This urbanisation will call for an increase in development of housing and infrastructure on a large scale which will produce an unknown amount of greenhouse-gas (GHG) emissions. According to the IPCC (2023) fossil fuels and industry are one of the main sources of CO₂ emissions globally where the built environment places the greatest pressure on the natural environment (Pomponi & Moncaster, 2016). Although built-up areas (e. cities, towns, villages and human infrastructure) only cover around 1% of Earth's surface (Ritchie, 2018) the global human-made mass has exceeded all living biomass on Earth (Elhacham et al., 2020). With current consumption patterns, urban material consumption will double to 89 billion tonnes by 2050 with the estimated population projections (UNEP, 2018).

Buildings alone account for 30-40% of global GHG emissions with operational emissions accounting for 40% of global energy-related CO₂ emissions (Nwodo & Anumba, 2019). The research on the carbon footprint of buildings and green spaces is extensive while assessments addressing the environmental impact of traffic infrastructure is not as abundant. However, infrastructure will play an important role in the quest for an environmentally sustainable built environment. In 2013, Muller et al. estimated that if the developing countries would catch up with the developed countries with the amount of infrastructure per capita, the GHG emissions from that development would be similar to the carbon budget remaining in order to not exceed the current 1.5 degree warming target. The global average temperatures are on the rise and have increased by 1 degree since the pre-industrial era (IPCC, 2018). We only have a carbon budget of around 400 Gt CO₂ that can be emitted for the 1.5 degree target which, at this rate, will be spent by the end of 2030 (IPCC, 2021). Therefore, addressing all domains of the built environment is important for a truly sustainable city.

In Iceland the embodied carbon of buildings has been quantified by a working group, Byggjum grænni framtíð (BGF), a project initiated by the Government of Iceland and stakeholders in the construction industry. According to their research the carbon embodied in the Icelandic building stock is 12,708,373 tCO₂-eq (BGF, 2022). This has yet to be done for infrastructure. This study aims to quantify the carbon embodied in the Reykjavík Capital Region's traffic infrastructure and estimate emissions from future infrastructure development in the Region. There are some large scale development projects planned in the next decade in the Region, such as Sundabraut, Miklabraut í stokk and Sæbraut í stokk. Additionally, the Capital Region is following the global urban population trend (Table 1) and has, according to their 2023- 2032 housing plans, committed to building 37,159 new apartments for future residents (HMS, 2024) who are estimated to be around 275,000 (Borgarlínan, 2018). At the same time the Capital Region is following a denser-upward policy which makes buildable land limited to certain growth limits. Infrastructure development is tied to these development plans additionally. In the City of Reykjavík, it is estimated that an additional 1200 apartments will be built per year from 2032-2040, in total 8400 apartments additionally. Table 1 summarizes the expected population increase until 2032 along with forecasted new apartments built.

Table 1 *Current population in the Capital Region and population and apartment forecast to 2032*

Municipality	Population 2024	Estimated population increase forecast 2024-32	New apartments 2024-2032
Reykjavík	136,824	18.3%	22,813
Hafnarfjörður	30,616	40.2%	6,441
Kópavogur	39,335	21.9%	3,821
Garðabær	19,088	28.8%	3,543
Mosfellsbær	13,403	34.4%	343
Kjósarhreppur	269	60.6%	73
Seltjarnarnes	4,572	8.5%	125
Total	244,107		37,159

Note. Current population, population forecast to 2032 and apartment development plans to 2032 in the Capital Region. Source: HMS (2024).

To further extrapolate this data to 2040, the rate of development from up until 2040 was estimated based on the statement from Reykjavik City, that 1200 new apartments will be built annually. This is just under half of what is expected in those 9 years from 2024-2032, 2,535 apartments annually in Reykjavík City. $1200 / 2535$ is 0.4734, which will be used here as the multiplication factor (Table 2).

Table 2 *Estimation of new apartments from 2033-2040*

Municipality	New apartments 2024-2032	New apartments annually 2024-2032	New apartments annually 2033-2040
Reykjavík	22,813	2535	1200
Hafnarfjörður	6,441	716	339
Kópavogur	3,821	425	201
Garðabær	3,543	394	186
Mosfellsbær	343	38	18
Kjósarhreppur	73	8	4
Seltjarnarnes	125	14	7
Total	37,159	4,129	1,955

Note. New apartments estimated from HMS (2024) are divided by number of years (9) and extrapolated based on the ratio of estimated new apartments from 2024-2032 vs 2033-2040 from Reykjavik City.

The total of new apartments by 2040 in the Capital Region is therefore estimated as $37,159 + (1,955 * 8) = 52,799$.

1.1 The Capital Region case study and city-level climate accounting

The Capital Region has committed to reduce GHG emissions and become carbon neutral by 2040 (SSH, 2022). For this purpose, it is important to know the material load on current human infrastructure systems as well as get an overview of how future development in built-up areas will add to the mass and emissions of the Capital Region. In city-level climate accounting, GHG emissions are divided into three sources; those created within city boundaries (Source 1), those related to grid-supplied electricity, heating and/or cooling (Scope 2), and GHG emissions related to city activities occurring outside of the city boundary (Scope 3) (C40, 2018). The majority of the emissions from the built environment in the Capital are outsourced emissions occurring outside the country. These emissions are tied to the upfront emissions of resource extraction related to the manufacturing and transportation of the building materials, also known as the embodied emissions. Additionally, the maintenance during the operation of the structures as well as demolition and waste processing during its end-of-life are included in the embodied emissions. These emissions might account for the majority of the lifecycle emissions from the structure, especially when use phase energy is low-carbon or buildings highly energy efficient. Given how these embodied GHG emissions are emitted in a short period of time before the use phase even begins, it causes a carbon spike which is more harmful than those emissions occurring over a longer period during the building lifetime (Säynäjoki et al., 2012). A recent study (Wiedmann et al., 2020) shows that cities that outsource these emissions in their accounting miss mitigation targets by 41% of their territorial emissions. Therefore, including source 3 emissions in the inventory is an important factor of a successful mitigation path for cities in their path towards zero emissions by 2040.

2 Materials and methods

When assessing the current and future GHG emissions from infrastructure in the Capital Region the following methods and materials were utilised:

2.1 Environmental assessment of infrastructure using the life-cycle assessment (LCA) approach

Life-cycle assessment (LCA) can assess emissions from the whole life-cycle of a product or process from cradle to grave and has become the dominant method of assessing the environmental impact of the construction sector (Säynäjoki et al., 2017).

2.1.1 Goal and scope

This study will assess the carbon emissions related to upfront emissions of current roads in the Capital Region, emissions related to future development of new traffic infrastructure within the neighbourhoods, and the emissions of road maintenance. Emissions related to traffic or other uses are excluded from the study.

2.1.2 Functional unit (FU)

According to Arshad et al. (2021) the selection of FU should be based on the goal and scope and spatial features or local design codes and practices. According to Jing et al (2020) the most accurate results will be from assessing road length, width, and depth. This study will use m^2 as the FU and will include depth when possible.

2.2 Assessing the carbon embodied in the Capital Region's roads and streets

2.2.1 Data on the extent of roads and streets in the Capital Region

When assessing the carbon embodied in the Capital's road infrastructures the municipalities were contacted in search for data on the extent of roads and streets existing within their jurisdiction (Table 3). The City of Reykjavík had information on road infrastructure in m^2 and km available, and Hafnarfjörður only km. Other municipalities in the region had no such data readily available. For highways, Vegagerðin provided m^2 for roads under their jurisdiction within the growth limits of the Capital Region. In order to estimate the total extent of traffic infrastructure in the Capital Region, estimations had to be made for those municipalities who did not have data available. This was done by conducting a per capita extrapolation using data from the City of Reykjavík as the point of reference. The extent (m^2) of roads and streets in Reykjavík is 5,536,786 m^2 and divided by the population estimates that the m^2 per capita of roads and streets is 40,47 m^2 (see Table 3). This number is then simply multiplied by the population in each municipality.

Table 3 *Estimations on extent of traffic infrastructure in the Capital Region*

Municipality	Area km²	Population	Roads km	Roads m²	m² est.
Reykjavík	273	136,824	1272.15	5,536,786	
Hafnarfjörður	143	30,616	315		1,239,030
Kópavogur	80	39,335			1,591,887
Garðabær	76	19,088			772,491
Mosfellsbær	185	13,403			542,419
Kjósarhreppur	288	269			10,886
Seltjarnarnes	2	4,572			185,029
Vegagerðin roads				1,431,500	
Total	1047	244,107		6,968,286	4,341,742

Note. The size of the municipalities, population, and extent of traffic infrastructure in each of the municipalities as well as roads under Vegagerðin jurisdiction within the growth limits of the Capital Region. m² estimates based on m² road per capita extrapolated from road m² within the City of Reykjavík.

11,310,028 m² total of roads and streets estimated in the Capital Region.

2.2.2 Assumption on m² per km

The FU in this present study is m² but some data that was utilised was only available in km. A m² per km was therefore estimated by using the data from the City of Reykjavík which had both data on km and m² within the municipality:

$$5,536,786 / 1,272.15 = 4,352 \text{ m}^2 \text{ in one km of road.}$$

In an LCA on a typical Icelandic road (Bjarnadóttir, 2013), the FU was 1 km of a 8.5 metre wide road, or 8500 m² in one km. However, the roads in City of Reykjavík vary in width since the values are both for streets, pathways and roads. The assumption of 4352.31 will therefore be used in this study since the roads assessed will have similar properties.

2.3 Future projections on road development in the Capital Region

When estimating future projections of traffic infrastructure development in the Capital Region hard data was utilised where data was available. This was the case for large scale projects such as the Borgarlína and Sundabraut. For estimations on road maintenance and other development within the Capital Region, data from the City of Reykjavík on road maintenance were used. For new infrastructure related to neighbourhood development and new apartments, data provided by the City of Reykjavík and utilised by Sigurðardóttir et al. (2023) was used to estimate the extent of traffic infrastructure per apartment. This number was then adapted to HMS's apartment development by 2032.

2.3.1 Streets and pathways

For streets and pathways within neighbourhoods a paper by Sigurðardóttir et al. (2023) was the main source. The paper is an LCA on phase 1 (of 2) in a new neighbourhood in the City of Reykjavík consisting of 685 new apartments and a parking house. It presents data from the City on the future neighbourhood which consists of the extent of roads, streets, parking house, green spaces, and a school playground, referred to as other spaces (OS) in the study, in total 79,905 m². This data was used as a reference to estimate the emissions from traffic infrastructure tied to new neighbourhoods and apartments in the coming years.

2.3.2 Artery roads

For this part of the study two large development projects that are planned in the Capital Region were included, Borgarlínan and Sundabraut (Table 4). Borgarlínan (2021) provided data on the first 6 phases to be constructed in the coming years which is in total 44 km. A project consultant from the Sundabraut development provided data on total km of roads, bridges, and tunnels in a private email.

Table 4 Future development on Sundabraut and Borgarlína in the Capital Region to 2040

Road type	Km	m2 est.*	Source
Borgarlína phase 1	14.5	63,105	Borgarlínan, 2021
Borgarlína phase 2	4	17,408	Borgarlínan, 2021
Borgarlína phase 3	4	17,408	Borgarlínan, 2021
Borgarlína phase 4	8	34,816	Borgarlínan, 2021
Borgarlína phase 5	5	21,760	Borgarlínan, 2021
Borgarlína phase 6	8.5	36,992	Borgarlínan, 2021
Sundabraut	23.4	101,837	Project consultant, 2024
Total		293,326	

Note. * By dividing km by m² of roads and streets in the City of Reykjavík (Table 3) it was estimated that in 1 km of road there are 4,352 m². Using these estimates, m² was quantified for future construction.

2.3.3. Maintenance

According to a summary of construction from Reykjavik City (2018), equilibrium in maintenance is achieved when 6% of road surfaces are resurfaced with asphalt every year. Therefore, maintenance is assumed as new asphalt on 6% of the total road surface in Reykjavik every year. It is assumed that new development in the next 17 years does not need resurfacing during this timeframe. We therefore assume:

$$\begin{aligned} & \underline{11,310,028 \text{ m}^2 \text{ total of roads and streets today} * 0.06 * 17 \text{ years} =} \\ & \underline{11,536,229 \text{ m}^2 \text{ resurfaced in total}} \end{aligned}$$

2.4 Estimating CO₂eq/m² for traffic infrastructure

When estimating a CO₂eq/m² for road infrastructure various data was reviewed and compared. With the aim to find detailed sources to compare to, previous LCA studies

were reviewed. These studies used various LCA approaches (e. i/o LCA, process LCA, and hybrid LCA) and methods. Additionally, EPD's on asphalt and cement used in Iceland were reviewed and compared. In the end, one Icelandic LCA was chosen as reference for embodied carbon and new construction in the Capital Region and EPD's conducted for Icelandic asphalt was used to compare for carbon footprint of road maintenance.

2.4.1 Results from an road LCA of a typical Icelandic road

In 2012 Bjarnadóttir conducted an LCA on 1 Km typical Icelandic road to estimate where the highest environmental impact occurs within its lifetime. The width of the road assessed is 8.5 m and total depth of 930 mm. The environmental footprint of the road according to the study is 707 tCO₂eq/km of which 47% is allocated to the upfront emissions of the road construction, or 332 tCO₂eq/km which results in 39 kgCO₂eq/m² of new road with the depth of 930 mm.

2.4.2 Asphalt EPD's

Colas Ísland ehf., asphalt manufacturer in Iceland, conducted LCA's for EPD's on four of their products in collaboration with EFLA engineering firm (Colas, 2024). The FU is one tonne of asphalt of: 1. Traditional hot-mix asphalt (HMA) for pedestrian pathways and light traffic roads with reclaimed asphalt pavement (RAP); 2. Traditional hot-mix asphalt for heavy traffic; 3. Cold-mix asphalt (CMA) for pedestrian pathways and light traffic roads; 4. Cold-mix asphalt with cement for pedestrian pathways, light traffic roads, and upper base course for high traffic roads. Since the FU of this present study is 1m², a tonnage calculator provided by Heidelberg Materials (n.d.) was used to estimate a tonne of asphalt used per m². The depth of asphalt in Icelandic conditions is between 3.5-5.5 cm (Vegagerðin, 2021). It is estimated that 0.1 tonnes of asphalt is needed for 1m² of road with a depth of 4.5 cm. However, it is important to address the fact these results do not include the total depth of road. This data could therefore be useful when estimating the carbon footprint of road maintenance. Table 5 shows estimates on kgCO₂eq using these assumptions on 1m² of road surface.

Table 5 Results from Colas Ísland (2024) EPD's quantified to a kgCO₂eq/m²

Asphalt type	kg CO ₂ eq/tonne	est. kgCO ₂ eq per m ² *
Hólabrú, Traditional HMA, 30% RAP	50.8	5.08
Durasplitt, Traditional HMA, 30% RAP	74.8	7.48
74000 CMA	19.3	1.93
CMA with cement	38.6	3.86

Note. Results from Icelandic asphalt EPD's. Source: Colas Ísland (2023).* It is estimated that 0.1 tonne of asphalt is needed for 1m² of road with depth of 4.5 cm.

2.4.3 Carbon footprint of traffic infrastructure in new neighbourhoods

The data from Sigurðardóttir et al. (2023) paper was used as a reference to estimate the emissions from traffic infrastructure tied to new neighbourhoods and apartments in the coming years. It presents data from the City of Reykjavik on a future neighbourhood

which consists of the extent of roads, streets, parking house, green spaces, and a school playground, referred to as other spaces (OS) in the study, in total 79,905 m². The study found that OS were responsible for 39 kgCO₂eq per square meter. This information was used to assess the extent of emissions from traffic infrastructure development per apartment:

$$39 \text{ kgCO}_2\text{eq} * 79905 \text{ m}^2 / 685 \text{ apartments} = 4.55 \text{ tons CO}_2\text{eq per apartment}$$

As we can expect 52,799 new apartments by 2040, we calculate:

$$4.55 \text{ tonsCO}_2\text{eq} * 52,799 \text{ new apartments} = 240,235 \text{ tonsCO}_2\text{eq} \\ \text{connected to neighbourhood development by 2040.}$$

Summary

To estimate the extent of traffic infrastructure needed for future neighbourhood development, it was first assessed how many new apartments would be needed in the Capital Region by 2040. An LCA study on the carbon footprint of infrastructure connected to neighbourhood development in Iceland (Sigurðardóttir et. al, 2023) was used to assess future emissions from apartments-related infrastructure development.

To estimate the extent of current road infrastructure in the Capital Region, data from Reykjavík City was extrapolated to other municipalities based on population. Data from Vegagerðin was added to the total. To assess the embodied carbon footprint of the current road infrastructure stock, an LCA from Bjarnadóttir (2013) was used.

The extent of future road maintenance needed in the Capital Region was assessed based on documents from Reykjavík City, which assume 6% asphalt resurfacing annually. Emissions from future maintenance were estimated based on EPDs from Colas Ísland (2023).

Two future development projects were assessed and included in the study; Sundabraut and Borgarlína. There is high uncertainty within this particular assessment, as it will use the same emission factor per m² as regular roads within the city.

3 Results

The goal of this study was to quantify the GHG emissions embodied in the Capital Region's traffic infrastructure and estimate emissions from future construction development to 2040. In total the GHG emissions that will be tied to the Capital Region's traffic infrastructure systems will be between 715,031-779,057tCO₂eq (Figure 1) The carbon currently embodied in the Capital Region's roads and streets, including roads under Vegagerðin's jurisdiction, is estimated to be 441,091 tCO₂eq (Table 6). GHG emissions from new road development within the Capital Region such as Borgarlínan, Sundabraut is estimated around 11,440 tCO₂eq, and roads and streets within new neighbourhood development result in 240,235 tCO₂eq (Table 7). When it comes to estimating GHG emissions tied to maintenance need from 2024-2040 the results are estimated to be between 22,265-86,290 tCO₂eq, depending on type of asphalt mix used in the construction (Table 8). In section 3.4 four different scenarios of the carbon footprint of traffic infrastructure are presented in more detail.

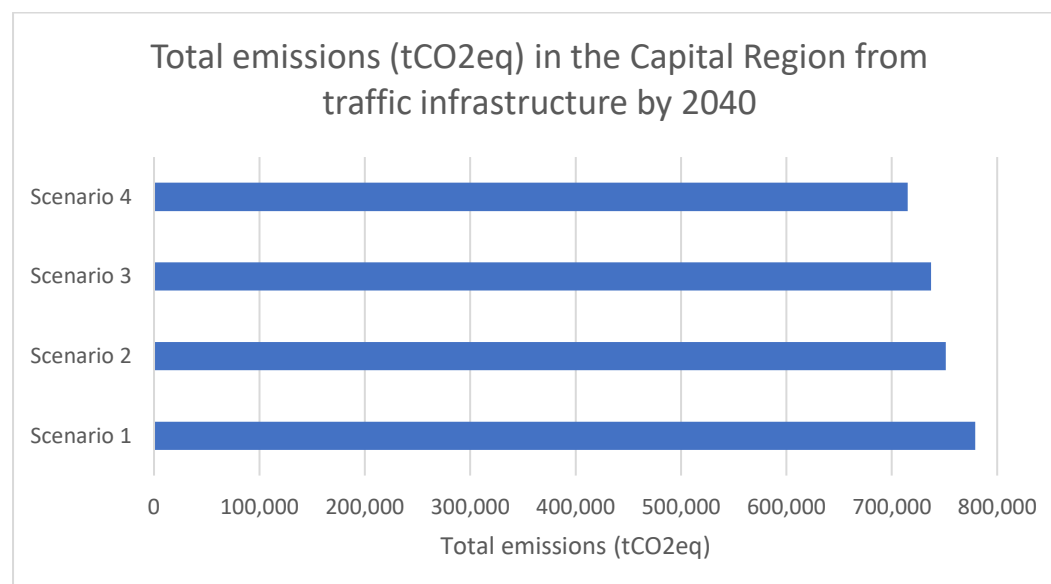


Figure 1 GHG emissions tied to traffic infrastructure in the Capital Region in 2040

Note. The results are shown in four different scenarios. The difference between the scenarios is type of asphalt used during the maintenance phase. Scenario 1 uses Durasplitt, Traditional HMA, 30% RAP, scenario 2 uses Hólabrú, Traditional HMA, 30% RAP, scenario 3 uses CMA with cement, and finally, scenario 4 uses 74000 CMA.

Table 6 Carbon embodied in the Capital Region's current traffic infrastructure

Road	Extent m2	Total tCO ₂ eq
Current roads in the Capital Region	9,878,528	385,263
Vegagerðin roads within Capital growth limits	1,431,500	55,829
Total CO₂ embodied in the Capital Region		441,091

Note. Table 6 shows the carbon embodied in the roads and streets of the Capital Region, and the carbon embodied in roads under Vegagerðin jurisdiction within the growth limits of the Capital Region excluding maintenance. 39 kgCO₂/m² are used to quantify the total tCO₂eq currently embodied in the Capital in 2023.

3.1 Carbon footprint of future traffic infrastructure development

When assessing the carbon footprint from future development, large scale development like Sundabraut and Borgarlína were included along with assumptions on traffic infrastructure that will be constructed alongside new neighbourhood developments, as the Capital Region will construct an estimated 52,799 apartments between 2023-2040. By using a neighbourhood LCA conducted by Sigurðardóttir et al. (2023) estimations were made that infrastructure related to each apartment emitted 4.55 tCO₂eq. Traffic infrastructure for 52,799 apartments is therefore estimated at 240,235 tonsCO₂eq.

Table 7 Carbon footprint from future traffic infrastructure development in the Capital Region

Type	Extent m2	Total tCO ₂ eq
Traffic infrastructure in new neighbourhoods	171,904	240,235
Borgarlínan		7,468
Sundabraut	101,837	3,972
Total		251,675

Note. Table 7 shows the tCO₂eq of future development. New development includes, new neighbourhood and apartment related traffic infrastructure, as well as Borgarlínan and Sundabraut

3.2 Maintenance related CO₂ emissions 2024-2040

The quantification on road maintenance in the Capital Region was based on data from the City of Reykjavík on how much road maintenance is needed for equilibrium. We assumed that 6% of the current road infrastructure in the Capital Region is resurfaced with new asphalt every year. This is likely a good estimate by Reykjavik City, as it means that all of the road surfaces will have been resurfaced in 17 years. Table 8 shows the emissions associated with four different asphalt mixes used for the maintenance. Here the EPD's provided by Colas (2024) were used for reference which could also provide different scenarios of the carbon footprint of different asphalt types. The carbon footprint related to road maintenance in the Capital Region between 2024-2040 is therefore between 22,265 tCO₂eq at the lowest to 86,291 tCO₂eq at the highest depending on scenarios.

Table 8 *The carbon footprint of different asphalt types*

Asphalt type	est. kgCO₂eq per m²*	tCO₂eq total due to maintenance 2024-40
Hólabrú, Traditional HMA, 30% RAP	5.08	58,604
Durasplitt, Traditional HMA, 30% RAP	7.48	86,291
74000 CMA	1.93	22,265
CMA with cement	3.86	44,530

Note. Table 8 shows the maintenance related CO₂eq in the Capital Region between 2024-2040, comparing results from Colas Ísland (2024) EPD's on different asphalt types. This table shows tCO₂eq if 6% of the roads are resurfaced every year for 17 years. Here it is assumed that by maintaining only the top surface was removed and fixed.

3.4 Total CO₂eq in the Capital Region 2024-2040

This section shows four different scenarios on how the carbon footprint of traffic infrastructure might evolve in the Capital Region to 2040. The main differences are in the maintenance emissions, where different asphalt mixes from Colas Ísland (2024) are used for resurfacing. According to this study, the tCO₂eq embodied in the current traffic infrastructure in the Capital Region is 441,091 tCO₂eq. GHG emissions from future development and maintenance in 2024-2040 will be between 273,940-337,966tCO₂eq depending on asphalt type used during maintenance. In total the carbon embodied in the Capital Region in 2040 will be between 715,031-779,057 tCO₂eq (Figure 2).

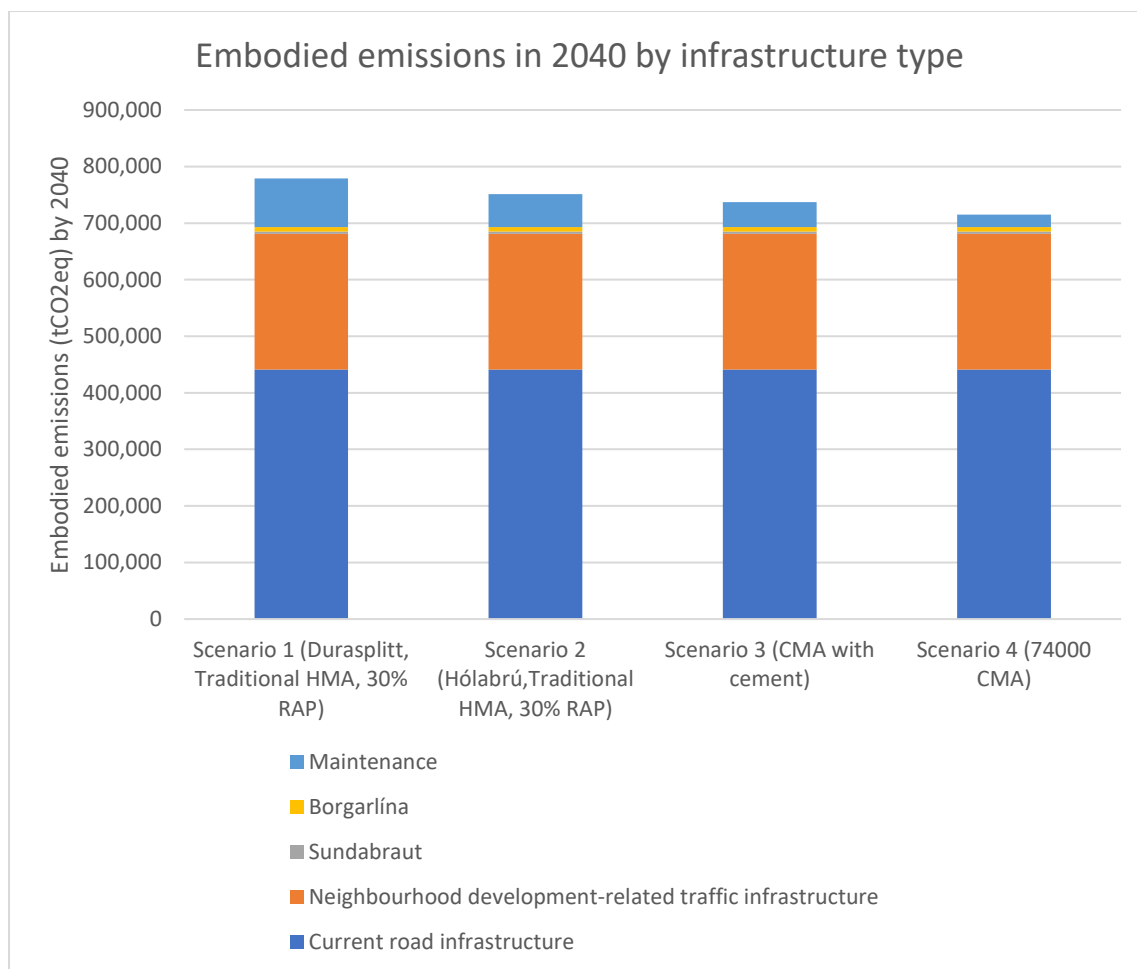


Figure 2 The estimated embodied emissions (tCO_2eq) in the Capital Region by 2040, split by infrastructure category.

Note. The results are shown in four different scenarios. The difference between the scenarios is type of asphalt used during the maintenance phase. Scenario 1 uses Durasplitt, Traditional HMA, 30% RAP, scenario 2 uses Hólabrú, Traditional HMA, 30% RAP, scenario 3 uses CMA with cement, and finally, scenario 4 uses 74000 CMA.

4 Discussions & Conclusion

The world is becoming more urbanised with estimations from the UN (2018) that 68% of the global population will live in cities by 2050. Iceland is following this global population trend and is expecting an increase in the local population with the highest increase occurring in the Reykjavík Capital Region. To accommodate the current and future population over 50,000 new apartments will need to be constructed by 2040 along with infrastructure to keep up with the population's lifestyles and needs. Recent research has revealed that the environmental impact of the built environment is a great contributor to GHG emissions due to the upfront carbon connected to the resource extraction, transportation and manufacturing of the building materials, and to the operational carbon which varies between countries and their electricity sources. A factor that still needs to be researched more in connection to the carbon footprint of cities is the upfront and embodied carbon of traffic infrastructure. Usually studies on the environmental impact of traffic infrastructure looks at the use phase and traffic. However, as with buildings, the emissions occurring before the road, bridge, or tunnel is operational also need to be accounted for to better understand the carbon footprint of traffic infrastructure and to be able to design truly climate sustainable settlements

This study is twofold and looks to 1. the embodied emissions of current road infrastructure in the Capital Region, and 2. estimates on the extent of future traffic infrastructure development and the carbon footprint of those developments. Various materials were utilised to estimate the CO₂eq of 1m² of traffic infrastructure as well as other sources to give an estimate on the extent of road infrastructure currently in the Capital Region as well as how much m² will be added by the year 2040 with future developments for a growing population. Various traffic infrastructure LCA's and asphalt EPD's were reviewed to create CO₂eq/m² benchmarks for road infrastructure. However, some of the LCA's reviewed were for new construction accounting for the sub-base, base and pavement. There, the carbon footprint of 1 m² was around 40 kgCO₂eq/m². The EPD's reviewed from Colas (2024) only accounted for the top-surface layer with comparison of different types of asphalt mixes. Those were useful to compare how different materials can affect the carbon footprint of infrastructure. There was a great difference between the carbon footprint of hot-mixed asphalt (HMA) and cold-mixed asphalt (CMA) and if there were any recycled aggregates (RAP) or cement in the mixes. For instance, the asphalt mix with the lowest CO₂eq was the 74000 CMA from Colas Ísland (2024) of 1.93 tCO₂eq/m² and the one with the highest CO₂eq was the Durasplitt HMA of 7.48 tCO₂eq/m², also from Colas Ísland. However, the difference between those two was that the CMA mix is to be used for light traffic and pedestrian pathways while the HMA mix is to be used for heavy traffic.

4.1 Limitations and assumptions

To conduct this study, several assumptions had to be made. Uncertainties in the results are related to the following assumptions:

- When assessing the extent of current traffic infrastructure in the Capital Region, only the City of Reykjavík had data on m² and km of roads and streets in the city. To get an estimate for the other municipalities a m² per capita was quantified by using the City of Reykjavík as reference. The value was then

multiplied with the population from the other municipalities. The density of the built environment can greatly affect the amount of infrastructure needed per capita, and therefore there is high uncertainty related to this extrapolation method.

- When estimating the extent of traffic infrastructure in future development assumptions had to be made on traffic infrastructure in the new neighbourhoods. By using a neighbourhood LCA by Sigurðardóttir et al. (2023) data on a new neighbourhood was used to estimate the amount traffic infrastructure needed per apartment. The value was then quantified with the estimated apartment need in the Capital Region to 2040. This neighbourhood LCA used as a benchmark was for a new neighbourhood in Skerjafjörður, which likely needs more new infrastructure than constructing a single apartment block in an older neighbourhood. Therefore, depending on the type of apartment development in the future, this number might be overestimated. On the other hand, the paper mentions that the LCA study likely underestimates the emissions.
- When estimating maintenance need in the Capital Region, it was assumed a rate of 6% resurfacing per year (Reykjavik City, 2018). There are uncertainties associated with this assumption, but in addition, maintenance other than resurfacing was excluded..
- The data on apartment need and population increase was estimated to 2032 but this study aims to estimate the carbon footprint of traffic infrastructure by 2040. Only Reykjavik City had an estimate of new apartments needed after 2032, so there is uncertainty related to how it was extrapolated to account for new apartments in the other municipalities after 2032.
- Only two major traffic infrastructure developments were included in this study (Borgarlína and Sundabraut), but there are also other planned, such as Miklabraut tunnel. In addition, the carbon footprint of each m² of these major developments was assumed to be the same as regular road infrastructure. It is therefore highly underestimated.

Despite these limitations and assumptions the results give a rough estimate on the extent of emissions associated with traffic infrastructure development in the near future.

4.3 Policy recommendations and future research proposal

With global human-made mass already exceeding all living biomass on Earth (Elhacham et al., 2020) and the high carbon footprint of the built environment, humanity needs to be mindful of how future cities will be planned and constructed to create a climate sustainable future. The EPD's by Colas Ísland (2024) utilised for the study clearly show how different materials and processes affect emission reductions which should be taken into account for future development. Additionally, rethinking how cities are designed could also change the need for high emitting building materials like HMA which is mainly used for heavy traffic. The limitations faced in this study on hard data on the material load in Reykjavík Capital Region's current traffic infrastructure systems raise ideas on the importance of having a database accessible that clearly states the current human-made material load in the Capital Region and how future development will add

to that load. Having a unified database that includes values from all sectors, including scope 3 emissions, should indicate clearly if the Capital Region is on track for a 1.5 degree future.

References

- Arshad, H., Thaheem, M. J., Bakhtawar, B., & Shrestha, A. (2021). Evaluation of road infrastructure projects: A life cycle sustainability-based decision-making approach. *Sustainability*, 13(7), 3743.
- Bjarnadóttir, H.J. (2013). Vistferilsgreining fyrir veg – Rannsóknarverkefni Vegagerðarinnar. Vegagerðin og verkfræðistofan EFLA. Reykjavík. Retrieved February 28th, 2023, from [https://www.vegagerdin.is/vefur2.nsf/Files/Vistferilsgreining_fyrir_veg/\\$file/Vistferilsgreining%20fyrir%20veg.pdf](https://www.vegagerdin.is/vefur2.nsf/Files/Vistferilsgreining_fyrir_veg/$file/Vistferilsgreining%20fyrir%20veg.pdf)
- Borgarlínan. (2018). Svæðisskipulag Höfuðborgarsvæðið 2040. Tillaga að breytingu á svæðisskipulagi. Retrieved from: <https://wp.borgarlinan.is/wp-content/uploads/2020/11/svaedisskipulagid-hofudborgarsvaedid-2040.pdf>
- Borgarlínan. (2021). *Borgarlínan 1. lota forsendur og frumdrög*. Kafi C: Framkvæmdir og næstu skref. Retrieved from: <https://www.borgarlinan.is/static/skyrsla/Borgarlina-1lota-forsendur-frumdrog-Jan2021-Kaflic.pdf>
- BGF. (2022). *Mat á kolefnislosun frá íslenskum byggingariðnaði*. Vegvísir að vistvænni mannvirkjagerð: 1. hluti. Retrieved from: <https://byggjumgraenniframtid.is/wp-content/uploads/2022/06/Vegvisir-ad-vistvaenni-mannvirkjagerd-l.-hluti-Losun.pdf>
- C40. (2018). *Consumption-based ghg emissions of C40 cities*. Retrieved from: https://www.c40knowledgehub.org/s/article/Consumption-based-GHG-emissions-of-C40-cities?language=en_US
- Colas. (2024). Sjálfbærni. Retrieved from: <https://colas.is/sjalfbaerni/>
- Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y.M., Milo, R. (2020). Global human-made mass exceeds all living biomass. *Nature*, 588, pp. 442-444.
- Heidelberg Materials. (n.d.). Asphalt Calculator. *Tools*. Retrieved from: <https://www.heidelbergmaterials.co.uk/en/tools/asphalt-calculator>
- HMS. (2024). *Útgefnar húsnæðisáætlanir*. Höfuðborgarsvæðið. 2024-2032. Retrieved from: <https://hms.is/husnaedi/husnaedisaaetlanir/utgefnar-husn%C3%A6%C3%B0isa%C3%A6tlanir-sveitarfelaganna>
- IPCC. (2023). *Synthesis Report of the IPCC Sixth Assessment Report (AR6)*. The Intergovernmental Panel of Climate Change. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf
- Jing, C., Zhang, J., & Song, B. (2020). An innovative evaluation method for performance of in-service asphalt pavement with semi-rigid base. *Construction and Building Materials*, 235, 117376.

- Müller, D. B., Liu, G., Løvik, A. N., Modaresi, R., Pauliuk, S., Steinhoff, F. S., & Brattebø, H. (2013). Carbon emissions of infrastructure development. *Environmental science & technology*, 47(20), 11739-11746.
- Nwodo, M.N., Anumba, C.J. (2019). A review of life cycle assessment of buildings using a systematic approach. *Building and Environment*, 162. 106290.
- Pomponi, F., Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment – What does the evidence say? *Journal of Environmental Management*, 181, pp. 687-700. <https://doi.org/10.1016/j.jenvman.2016.08.036>
- Project consultant. (2024). Private email from Sundabraut's project consultant.
- Reykjavíkurborg. (2018). Malbik – Yfirlit framkvæmda. *Umhverfis- og skipulagssvið*. https://fundur.reykjavik.is/sites/default/files/agenda-items/usk_malbik.pdf
- Reykjavíkurborg. (2017). *Götulisti – Raun útlagnir 2017*. Retrieved from: https://reykjavik.is/sites/default/files/afrit_af_malbik_2017_raunlisti.pdf
- Ritchie, H. (2018). *How urban is the world?* Our World in Data. Retrieved from: <https://ourworldindata.org/how-urban-is-the-world>
- SSH. (2022). *Loftslagsstefna höfuðborgarsvæðisins ásamt greiningu á stöðu málaflössins og tillögum að aðgerðum sem geta leitt til samdráttar í losun gróðurhúsalofttegunda*. Unnið fyrir Samtök sveitarfélaga á höfuðborgarsvæðinu (SSH). Retrieved from: https://www.ssh.is/static/files/storybook/Skjol/Soknaraaetlun/ssh_loftslagsstefna_undirritad.pdf
- UN. (2018). *68% of the world population projected to live in urban areas by 2050, says UN*. News. Retrieved from: <https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html>
- UNEP. (2018). *The weight of cities: Resource requirements of future urbanization*. International Resource Panel.
- Vegagerðin. (2021). *Hvað er malbik? Hvað er klæðning?* Fréttir. Retrieved from: <https://www.vegagerdin.is/upplýsingar-og-utgafa/frettir/hvad-er-malbik-hvad-er-klæding>
- Vegagerðin. (2022). *Viðgerðir á malbikuðum slitlögum 2022-2024, höfuðborgarsvæði og Reykjanes*. Opnun tilboða. Retrieved from: <https://www.vegagerdin.is/framkvaemdir/utbod/nidurstodur-utboda/vidgerdir-a-malbikudum-slitlogum-2022-2024-hofudborgarsvaedi-og-reykjanes-1>
- Wiedmann, T., Chen, G., Owen, A., Lenzen, M., Doust, M., Barrett, J., Steele, K. (2020). Three-scope carbon emission inventories of global cities. *Journal of Industrial Ecology*. Wiley. DOI: 10.1111/jiec.12063