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CARBON EMISSIONS OF CONSTRUCTION OPERATIONS IN A COLD CLIMATE

Ergo Pikas[1], Rauno Lõhmus[2], Lauri Koskela[3], Müge Tetik[4] and Kädi-Riin Vendel[5]

TABSTRACT

This study focuses on the energy use of construction operations and explores the associated greenhouse gas (GHG) emissions. The case study methodology is used in this exploratory investigation to assess the energy consumption and GHG of eight construction projects in Estonia. The findings highlight the need to account for heating and illumination emissions, underlining the importance of including construction phase emissions in building lifecycle carbon assessments. No strong correlation between building size and energy consumption is found, but there seems to be a connection between project duration, use function, and emissions. It suggests that addressing the embodied carbon of construction operations, particularly when heating is required, is crucial for reducing the overall carbon footprint. This study develops and invites the lean community to establish a baseline for construction operations' energy use and related GHG emissions. A baseline is needed to facilitate the continuous improvement of construction processes from the sustainability viewpoint.

KEYWORDS

Sustainable construction, energy consumption of construction operations, greenhouse gas emissions, winter heating and illumination.

INTRODUCTION

The need to address the effects of climate change has highlighted the urgency of reducing carbon emissions globally (European Commission 2020a). The United Nations Environment Programme estimated that the greenhouse gases (GHG) from construction materials and operational energy emissions of buildings constituted 37% of worldwide emissions (United Nations Environment Programme 2022). Addressing the construction sector and the built environment emissions is deemed a key strategy for decarbonizing the European economy by 2050 (European Commission 2020b).

However, the construction and built environment status report published in 2022 revealed that the gap between actual and target performance is growing (United Nations Environment Programme 2022). The building and construction industry is behind in its efforts to meet the 2050 decarbonization target, which is the key objective of the Paris Agreement (Paris Agreement 2015). It is becoming clear that incremental changes are insufficient; substantial

[1] Assistant Professor, Department of Civil Engineering and Architecture, Tallinn University of Technology, Estonia, ergo.pikas@taltech.ee, orcid.org/0000-0001-5691-685X.
[2] Project Manager, Maru Ehitus AS, Tallinn, Estonia.
[3] Adjunct Professor, Department of Civil Engineering and Architecture, Tallinn University of Technology, Estonia, lauri.koskela@taltech.ee, orcid.org/0000-0003-4449-2281.
[4] Post-Doctoral Researcher, LUT School of Engineering Sciences, muge.tetik@lut.fi, orcid.org/0000-0002-4013-0577.
[5] Project Expert, Department of Civil Engineering and Architecture, Tallinn University of Technology, Estonia, kadiriin.vendel@taltech.ee, orcid.org/0009-0004-1702-1817.

strategic and structural reforms are necessary to face the escalating challenge of realizing a net-zero-carbon built environment (Council of the European Union 2023; Kibert 2022).

Thus far, the focus has been on reducing operational emissions from buildings, but emissions from construction operations remain underexplored (Tang et al. 2013; Weigert et al. 2022). The whole life cycle approach is needed (Kibert 2022). All embodied carbon emissions associated with construction products, transportation, and processes must be tackled to avoid undermining the carbon reductions achieved from energy efficiency and saving measures. The construction phase is expected to become increasingly significant as operational carbon emissions decrease due to enhanced energy efficiency in both new and existing buildings (Bahramian and Yetilmezsoy 2020). However, the baseline for construction operations' energy use and related GHG emissions is not well established.

This research addresses the greenhouse gas emissions associated with construction site processes and activities, with a specific focus on the energy use of construction operations during winter and summer seasons. The case study methodology is used for this exploratory investigation (Yin 2018). Data from eight construction projects of an Estonian building company were gathered, analyzed, and compared. Finally, ideas to reduce the emissions of construction operations are discussed.

RESEARCH BACKGROUND

Lean construction focuses on improving construction processes by eliminating or reducing waste (Koskela 2020), including among others unnecessary consumption of material and energy resources. Systematic literature reviews (e.g., (Moradi and Sormunen 2023)) and detailed studies (Osorio-Gómez et al. 2020; Wandahl et al. 2021) on synergies between lean construction (and lean in general) and sustainability have been conducted.

Osorio-Gómez et al. (2020) evaluated the influence of Lean Construction techniques on the environmental footprint of construction projects through a comparative case study of two projects, one employing Lean principles and the other using traditional methods. The study highlighted an 18–24% reduction in categories like acidification, ecotoxicity, eutrophication, global warming, and ozone depletion for the Lean Construction project. Wandahl et al. (2021) explored the impact of Construction Labour Productivity (CLP) improvements by adopting Lean tools and methods on the EU's renovation wave's energy efficiency targets. The study demonstrated a link between construction process improvement and reduced energy consumption.

While these studies present evidence of the direct relationship between Lean process improvement and environmental impact, most building codes and regulations tend to address operational energy carbon for heating, cooling, and lighting the indoor environment but do not account sufficiently for embodied carbon (United Nations Environment Programme 2022). The studies that address embodied carbon tend to be limited to the extraction, manufacturing, and transportation of construction products, emphasizing the design phase, including selection, methods, and tools (Joseph and Mustaffa 2021), and neglecting construction operations related emissions (Weigert et al. 2022).

A recent comprehensive systematic literature review on carbon assessment of construction operations identified the following themes as significant when considering construction-phase carbon emissions: (1) time and country trends, (2) carbon assessment methods, (3) construction stage-related carbon factors, (4) construction equipment classification, and (5) recommendations for reducing carbon emissions (Joseph and Mustaffa 2021).

Three research focus periods for carbon assessment were identified (Joseph and Mustaffa 2021). In the first period before 2010, there were a few studies focused on isolated aspects of buildings and carbon-related emissions. In the second period between 2010 and 2015, different Life Cycle Assessment (LCA) methods surfaced, including additional aspects and factors of carbon emissions. However, the scope and system boundaries for assessment varied significantly (Tang et al. 2013). That is, no standardized method was used for the LCA (Mastrucci et al. 2017). In the third period after 2015, standardized LCA methods and phases based on the ISO14040 began to be used (Arvanitoyannis 2008), including the different types of construction projects, phases, and construction methods (e.g., prefabricated versus on-site construction) (Bahramian and Yetilmezsoy 2020). This phase also incorporated modeling, simulation, and sensitivity analysis (Joseph and Mustaffa 2021).

The same studies revealed that the carbon emissions of construction operations are typically assessed using (1) LCA, (2) optimization method (3), simulation, and (4) on-site observations (Joseph and Mustaffa 2021). The two main approaches for LCA include the process-based LCA (the bottom-up approach) and input-output-based (I-O) LCA (the top-down approach) (Mastrucci et al. 2017). The selection of the LCA method depended on the main aim of the research (Mastrucci et al. 2017). Optimization methods focus on maximizing or minimizing the chosen function or parameter, such as the carbon impact of construction equipment or selecting the most appropriate construction method (Avetisyan et al. 2012; Szamocki et al. 2019). In simulation-based studies, discrete event simulation, for example, has been used to model and analyze construction operations (Liu et al. 2021). On-site field studies/observations are used to collect emissions data and to study carbon emissions management practices (Joseph and Mustaffa 2021). Also, remote monitoring to measure construction equipment emissions has become more broadly used.

The embodied construction phase-related assessment of different sources of carbon emissions typically includes (1) materials (including also auxiliary products), (2) transportation to and on the site, (3) machinery and equipment, (4) site accommodation and welfare, (5) building operation or energy use, and (6) construction waste (Joseph and Mustaffa 2021). Most studies have focused on construction machinery and equipment, materials, and transportation (Joseph and Mustaffa 2021), which comprise the largest proportion of embodied carbon (Weigert et al. 2022). Regarding construction equipment, the following are typically addressed (Joseph and Mustaffa 2021): (1) lifting and transportation machinery, (2) earthwork machinery, (3) concrete and mortar machinery, (4) processing machinery, (5) piling machinery, (6) welding machinery, (7) road construction machinery, and (8) pump machinery.

The LCA calculation in Europe follows the standard EN 15978:2011 (Van Gulck et al. 2022). In the A5 "construction phase", all carbon emission sources need to be considered. In addition to the carbon sources listed above, the standard includes also heating and cooling of temporary spaces and the building during construction activities (e.g., during cast-in-place concrete or interior works), auxiliary works, materials and products, re-work, and water requirements on the construction site. However, these aspects are often neglected in the LCA studies (Joseph and Mustaffa 2021) or are addressed to a limited extent.

Estonia is situated in a cold climate zone, which means that construction operations carried out in the winter require heating and additional illumination. However, studies addressing the impact of construction operations that need heating and illumination during the winter period could not be found. This gap will be addressed in this study.

RESEARCH METHOD

This exploratory case study research aims to determine the carbon footprint of the energy consumption of construction site operations. The EN 15978:2011 standard was followed and the 2022 CO_2 emissions data for Estonian electricity production was used for all sites to ensure a common basis for comparison.

INITIAL DATA AND LCA CALCULATIONS

While EN 15978:2011 for LCA helps to classify life cycle phases and to categorize carbon emission sources, there is no detailed method for scoping (system boundary) and calculating the carbon footprint of construction operations. This has been addressed differently in various studies utilizing LCA calculations. In this study, for comparing different construction projects, the energy consumption of construction operations was converted into carbon footprint equivalent ($kgCO_2e$), and the total carbon footprint of energy consumption was divided by building net area ($kgCO_2e/m^2$).

For calculating the electricity consumption and district heating carbon emissions, the GHG factor 0.636 ($kgCO_2e$ /kWh) for 2022 from the main Estonian utility company (Elering 2024) and the Estonian Environmental Research Centre (Eesti Keskkonnauuringute Keskus 2024) were used. For district heating, the district heating factor 0.200 ($kgCO_2e/kWh$) from the Estonian Environmental Research Centre (Eesti Keskkonnauuringute Keskus 2024) was used. The carbon emissions for the combustion of fuels for heat energy are calculated by multiplying the burned fuel volume with the fuel factor ($kgCO_2e/kWh$). For the comparison of electricity and heating energy intensity of different construction sites, the diesel and natural gas/propane energy density factors were also used. For the natural gas/propane, the average of the two was used in calculations. The initial values for calculations are summarized in Table 1.

Table 1. Carbon emission factors for the Estonian energy carriers in 2022 (Elering 2024; European Environment Agency 2023).

Energy Carriers/Sources	CO_2e Factor	Energy Density
Electricity (Estonia)	0.636 ($kgCO_2/kWh$)	
Diesel	0.250 ($kgCO_2/kWh$)	10.74 (kWh/l)
Natural Gas/Propane (Gas)	0.140 ($kgCO_2e/kWh$)	15.4/13.8 (kWh/kg) (average 14.6)
District Heating (DH)	0.200 ($kgCO_2e/kWh$)	

SELECTED CASE PROJECTS

The study included construction projects conducted between 2015 and 2023 where energy consumed during construction activities was available. Data on eight construction projects of an Estonian private sector building company were collected. All investigated sites were managed by different site teams and were organized according to ISO 9001, 14001, and 45001 requirements.

The electricity consumption data were obtained in two ways, including (1) monthly electricity meter data, and (2) the recordings of the initial and final meter readings. Meter data on electricity consumption came from the meters installed by the general contractor. For heating in the winter period, the fuel or district heating supplied by the general contractor was considered. Consumption data for the fuel and district heating energy were collected from invoices. Fuels consumed by subcontractors for construction machinery and equipment were excluded from the study.

Table 2 summarizes the main information about construction projects, including the project number (PR), building use function, net area of the building, construction start and end months and years, the duration of the construction project, and consumption of electricity, fuels, and district heating. On projects PR 1 – 3, no heating during construction was used. Different sources for heating were used on PR 4-8. For diesel and natural gas/propane, two energy consumption values are presented, including the natural unit and the equivalent in kWh. Most observed projects were industrial or office buildings, including the residential and warehouse buildings as exceptions. The building sites under investigation varied in size, ranging from 500 to 9000 m², and in construction durations ranging from 4 to 19 months.

Table 2. Information on selected construction sites (* the intended use is not available).

PR	Building Use Function	Net Area (m²)	Construction Duration: Start and End	Electricity (kWh)	Diesel (liters/kWh)	Gas (kg)	District Heating (kWh)
PR 1	Industrial Building; Office Building	1430	6 Months: July 2022 -January 2023	7278			
PR 2	Other Industrial Building; Office Building	500	4 Months: July – November 2022	3896			
PR 3	Other Warehouse Building	2170	10 Months: September 2021 – July 2022	25016			
PR 4	Other Industrial Building	1900	5 Months: October 2022 – March 2023	29894	2842/ 30535		
PR 5	Office Building	9000	9 Months: September 2015 – June 2016	133566	24000/ 257861		
PR 6	Other Industrial Building	1380	7 Months: December 2020 – June 2021	25721		731/ 10673	
PR 7	Residential Building with Three or More Apartments; Office Building	8150	19 Months: September 2020 – April 2022	161845		11551/ 168645	
PR 8	*	1280	15 Months: November 2020 – February 2022	29434			56280

RESULTS

In this section, the energy consumption and carbon emissions for construction operations with and without heating are presented. In the last subsection, the impact of future decarbonization scenarios for electricity and district heating production on construction operations is discussed.

ENERGY CONSUMPTION IN CONSTRUCTION PROJECTS

Table 3 depicts the electricity and heating energy consumption for the studied projects in kWh. The average electricity consumption for projects without heating was 12 063 (kWh), for projects with heating 76 092 (kWh), and across both categories 52 081 (kWh). The average heating energy consumption was 104 799 (kWh). When normalized by net area, the electricity across all sites was 14.56 (kWh/m^2) and heating 23.42 (kWh/m^2), which are 38% and 62% of the total energy consumption, respectively. The overall average per net area for projects without heating is 8.14 (kWh/m^2) and for projects with electricity and heating 41.84 (kWh/m^2).

The best-fit linear regression trendlines were calculated for the building size and energy consumption and between project duration and energy consumption. The trendline y=0.0024x+21.495 for the building size and energy consumption is characterized by a small slope (0.0024) and an R^2 value of 0.1429. This suggests a weak positive correlation, indicating a limited predictive capacity of the linear model. In contrast, the trendline y=2.6177x+4.6584 for the project duration and energy consumption exhibits a steeper slope (2.6177) with a moderate R^2 value of 0.4162, reflecting a stronger relationship and a moderate explanatory power. That is, while the connection between building size and energy consumption is minimal, there is a moderate relationship between project duration and energy consumption. The reason could be that projects with longer duration typically have higher construction scope and likely involve works in the winter season that may need heating. This requires further validation.

Projects with heating have a larger share of electricity consumption per net area. This could be because of the building use functions (see Table 2). Projects PR 4-8 with heating are buildings with residential and office functions, while projects PR 1-3 are mainly industrial. When compared to industrial buildings, residential and office buildings have a higher share of construction operations, mainly interior works, which typically require more electrical machinery, equipment, and heating.

Table 3. Energy consumption on construction projects by energy type.

PR	Net Area (m^2)	Duration (months)	Electricity (kWh)	Heating (kWh)	Electricity (kWh/m^2)	Heating (kWh/m^2)	Average per Category (kWh/m^2)
PR 1	1430	6	7278		5.09		
PR 2	500	4	3896		7.79		8.14
PR 3	2170	10	25016		11.53		
PR 4	1900	5	29894	30535	15.73	16.07	
PR 5	9000	9	133566	257861	14.84	28.65	
PR 6	1380	7	25721	10673	18.64	7.73	41.84
PR 7	8150	19	161845	168645	19.86	20.69	
PR 8	1280	15	29434	56280	23.00	43.97	
AVERAGE	3226	9	52081	104799	14.56	23.42	24.99

CO_2 EMISSIONS IN CONSTRUCTION PROJECTS

Table 4 depicts GHG emissions of consumed energy during construction operations for the studied projects. The average GHG emissions for projects without heating was 7 672 ($kgCO_2e$) and for projects with heating 26 646 ($kgCO_2e$). The average electricity emissions across all projects was 33 124 ($kgCO_2e$) and the average heating emissions across all fuels was 19 953 ($kgCO_2e$), which make up 62% and 38% of carbon emissions respectively. The largest share of carbon emissions comes from electricity consumption in construction projects. This high carbon footprint from electricity consumption is because electricity is the primary energy source on construction sites and Estonian electricity has high carbon intensity when compared to the other EU countries (European Environment Agency 2023). Results are in alignment with the carbon emission factors for the Estonian energy carriers in Table 1.

Table 4. CO_2 emissions of construction sites with and without heating.

PR	Net Area (m^2)	Electricity ($kgCO_2e$)	Diesel ($kgCO_2e$)	Natural Gas/Propane ($kgCO_2e$)	District Heating ($kgCO_2e$)	Total Emissions ($kgCO_2e$)	Average Emissions ($kgCO_2e$)	Average Emissions ($kgCO_2e/m^2$)
PR 1	1430	4629				4629		3.2
PR 2	500	2478				2478	7672.3	5.0
PR 3	2170	15910				15910		7.3
PR 4	1900	19013	7634			26646		14.0
PR 5	9000	84948	64465			149413		16.6
PR 6	1380	16359		1494		17853	26646.3	13.0
PR 7	8150	102933		23610		126544		15.5
PR 8	1280	18720			11256	29976		23.4
AVERAGE	3226	33124	36049	12552	11256	53076	17159	16.5

Figure 1 presents the GHG footprint per net area. The emissions are divided into two categories, including electricity (blue bars) and heating (red bars) emissions (CO_2e kg/m^2). Total carbon emissions per net area range from 3.2 to 23.4 ($kgCO_2e/m^2$), with an average of 5.2 ($kgCO_2e/m^2$) for projects without heating and 16.5 ($kgCO_2e/m^2$) for project with heating. The values for electricity emissions vary across different projects, ranging from as low as 3.2 ($kgCO_2e/m^2$) to as high as 14.6 ($kgCO_2e/m^2$). The heating emissions are lower than the electricity emissions, with values from 1.1 to 8.8 ($kgCO_2e/m^2$).

The chart also depicts an "AVERAGE" column for construction sites with electricity only and sites with electricity in addition to heating emissions, showing the average electricity and heating emissions per net area. For sites with electricity only, the average electricity emissions are 5.2 ($kgCO_2e/m^2$). For sites with electricity and heating consumption, the average electricity emissions are 11.7 ($kgCO_2e/m^2$) and the average for heating emissions is 4.8 ($kgCO_2e/m^2$). Again, these results seem to align with the observations above that building projects with longer duration and use functions related to more interior works tend to have much higher energy consumption. Also, electricity usage is responsible for most of the emissions on construction projects when compared to heating, with electricity making up 66% and heating 34% of the total construction operation emissions.

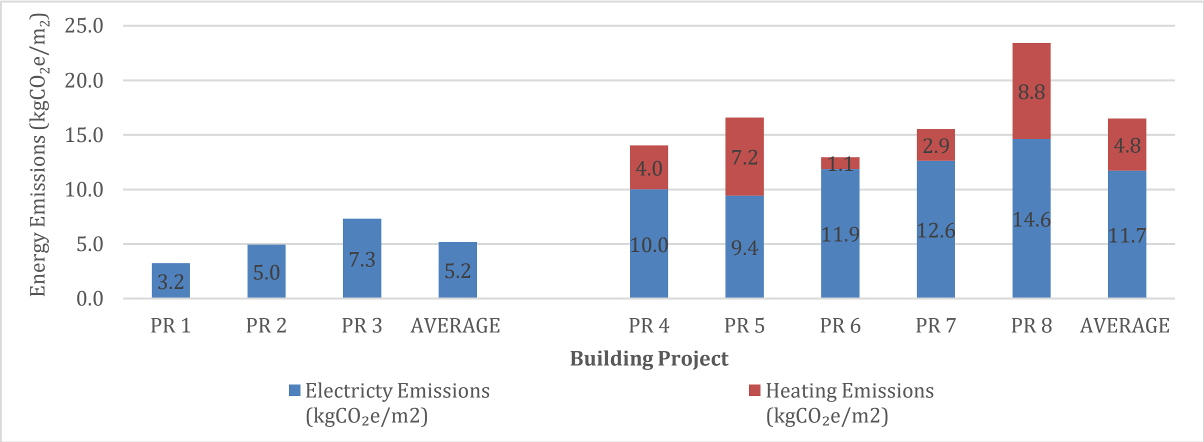

Figure 1. Electricity and heating energy consumption emissions per net area.

IMPACT OF ENERGY DECARBONIZATION ON CONSTRUCTION OPERATIONS

The European energy sector is expected to be the main contributor to the decarbonization of the European economy by 2050 (European Commission 2020a). The Estonian Ministry of Climate has developed a decarbonization strategy for the Estonian energy sector and the Estonian Environmental Research Centre (Eesti Keskkonnauuringute Keskus 2024) has estimated the projected GHG factors for electricity and district heating. In Table 5, the electricity and district heating emission factors are presented for the period from 2024 until 2050 with higher frequency in the early years.

Table 5. Future decarbonization scenarios for the construction operations.

Description	2024	2025	2026	2027	2028	2029	2030	2035	2040	2045	2050
Electricity Emission Factors (kgCO2e/kWh)	0.56	0.55	0.47	0.39	0.31	0.22	0.14	0.06	0.05	0.00	0.00
District Heating Emission Factors (kgCO2e/kWh)	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.05	0.04	0.04

Based on the new emission factors, the average electricity 14.56 (kWh/m^2) and heating 23.42 (kWh/m^2) emissions per net area, and average net building area 3226 (m^2) of the projects studied above, three future scenarios for carbon emissions of construction operations were generated: (1) electricity emissions + heating emissions with 25% share of district heating; (2) electricity emissions + heating emissions with 50% share of district heating; and (3) electricity emissions + heating emissions with 75% share of district heating. Different proportions of district heating are used to visualize the potential impact of heating sites with the combustion of fossil fuels versus district heating.

Figure 2 presents the three scenarios for construction operations with electricity emissions and the district heating share of 25%, 50%, and 75% of total heating. Currently, the electricity carbon emissions dominate. This is because Estonian electricity production has one of the highest carbon intensities in Europe (European Environment Agency 2023). However, if the national electricity decarbonization strategy goes as planned, the heating carbon emissions of construction operations become equal to electricity emissions around 2030 and continue to dominate afterward. From thereon, the combustion of fossil fuels becomes dominant, influencing the embodied carbon of buildings. For example, by 2050, in the scenario of a construction site, where half of the heating comes from the combustion of fossil fuels and the other half from district heating, the heating emission with 50% district heating is expected to be around 2.76 ($kgCO_2e/m^2$), while electricity emissions will be near carbon neutral.

This shows that when electricity production and operational carbon are reduced due to the increased renewable energy sources and energy efficiency of new and existing buildings (Bahramian and Yetilmezsoy 2020), the construction phase is expected to start playing a more important role. The execution of construction operations requiring heating and illumination in the winter season could become a major factor influencing the embodied carbon of buildings in the Estonian cold climate.

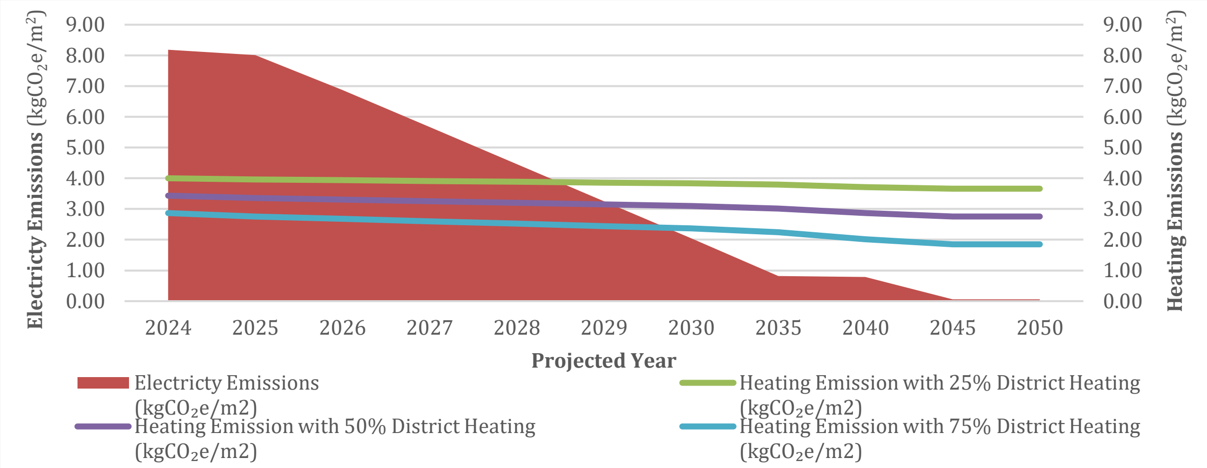

Figure 2. Electricity and heating emission scenarios.

DISCUSSION

To meet global climate objectives, it is necessary to decarbonize the construction and built environment sectors. The construction industry is lagging behind its climate goals. Much emphasis has been placed on enhancing the energy efficiency of buildings, considering the substantial carbon footprint of electricity and heating over their 50 to 60-year lifespan (Joseph and Mustaffa 2021; Weigert et al. 2022). This study highlights the importance of addressing the carbon emissions of construction operations, especially given the illumination and heating demands of winter months in Estonia.

While no direct correlation could be observed between a building's size and construction operations' energy consumption and GHG, a relationship seems to exist between the project's duration, its use function, and its energy consumption and emissions. Industrial projects without additional heating averaged electricity emissions at 5.2 $kgCO_2e/m^2$, while those with extensive interior work and additional heating saw a substantial increase, with average electricity emissions at 11.7 $kgCO_2e/m^2$ and heating emissions at 4.8 $kgCO_2e/m^2$. This means a threefold increase in total emissions, provided that in Estonia, electricity and heating are emissions-intensive.

This study, although limited to one company, offers insights that could contribute to the development of a more generalized approach. Findings demonstrate the great impact of the winter period on the carbon emissions of construction operations, especially regarding heating and illumination during colder months. This becomes increasingly crucial as Estonia moves towards decarbonizing its energy sector. A baseline and parameters for such assessments need to be established and standardized to consider and plan alternative improvement scenarios.

For a thorough assessment of construction activities' carbon footprint, more detailed case studies need to be made, looking at energy use in different types of work. Furthermore, action research for project-wise reduction of construction carbon emissions, as well as for continuous improvement at the construction company level, is needed. Establishing industry-wide methods and developing practical guidelines for reducing carbon emissions in construction operations across different climates and building types are important steps forward.

CONCLUSIONS

This study on carbon emissions from construction operations in Estonia's cold climate has demonstrated that winter demands for heating and illumination significantly contribute to GHG, with heating-required projects averaging 16.5 $kgCO_2e/m^2$ in emissions versus 5.2 $kgCO_2e/m^2$

for those without. While no strong correlation between building size and energy consumption was identified, a connection between project duration and emissions was observed. This emphasizes that it is important not to neglect the embodied carbon of construction operations in lifecycle assessments. The research suggests that significant emission reductions can be achieved through targeted improvements in construction processes, particularly in projects necessitating heating. The implementation of lean principles – prioritizing process improvement and waste reduction – emerges as a natural strategy in the pursuit of carbon footprint reduction in construction as well as of the broader objectives of sustainable construction.

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