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# CONSTRUCTION SITE EMISSIONS: EXPLORING SUSTAINABLE PRACTICES

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## ABSTRACT

Construction and renovation projects generate significant amounts of embodied carbon. However, studies often neglect emissions from the construction phase and focus on operational emissions of building in use. This study examines existing literature and prevalent certification systems, focusing on how they address site activities in relation to sustainability impacts. A comprehensive review of public domain data has been carried out. The current state of the most used certification systems and their approach on embodied carbon emissions from the construction phase has been determined. Interviews with an international panel of experts were held to gather insights. The study contributes to identifying requirements and analyzing incentives for achieving emission-free sites. Findings can serve as a roadmap for operating with less emissions for different construction supply chain actors and policymakers.

## KEYWORDS

Sustainable construction, emission-free construction sites, construction site emissions.

## INTRODUCTION

The European Climate Law aims at achieving climate neutrality by 2050 as a mandatory goal (European Environment Agency, 2024a). Accounting for 37% of global greenhouse gas emissions, the building sector is one of the largest contributors to climate change. (UN Environment Programme, 2023). Thus, the construction industry has a pivotal role in achieving greenhouse gas reduction targets.

Construction in-flows include materials, energy, labor, and water, while outflows encompass excess materials, emissions, material waste, reusable materials, and discharged water. Monitoring these flows is crucial for accurately assessing the sustainability impacts of sites. Lean construction in the context of sustainability means eliminating material waste and adding value to the customer through minimizing resource depletion and pollution (Huovila & Koskela, 1998). Effective management of in- and out-flows on a site begins with creating value and ensuring smooth process flow, in line with lean construction principles.

Due to the many physical flows required in projects and multiple stakeholders' involvement, construction supply chains are inherently complex. Large amounts of materials and equipment need to be transported, and tools and machinery are operated on sites. There are other activities performed that generate emissions such as constructing temporary structures, internal transport

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on-site, lighting and heating. Consequently, considerable amounts of emissions are released from the sites.

Efforts to establish zero-emission construction sites are gaining popularity. European Green Deal (2021) proposes that all new public buildings must be zero-emission already as of 2027 in Europe. It includes both new buildings and renovation efforts, mentioning also that on-site emissions from fossil fuels should be eliminated. Thus, it requires using electricity from a clean energy grid, which do not emit carbon dioxide ($CO_2$), nitrogen oxides ($NO_X$) or hazardous solid or liquid particles suspending on air (C40 Cities, 2020).

Emission reduction efforts tend to focus on reducing the operational phase emissions, leaving the embodied carbon out (United Nations Environment Programme, 2023). It is necessary to consider the embodied carbon generated by construction operations to improve the environmental impact of projects (Pikas et al., 2024). Current literature on emission-free construction sites is limited to individual countries or regions and does not fully cover the direct emissions from sites, often overlooking emissions from construction machinery and transportation (Høyli et al., 2023). To meet climate goals, a coordinated and efficient overarching strategy is essential, underscoring the need to assess current practices that reduce embodied carbon. It is important to examine how these practices are addressed in common certification programs to identify gaps, guide the next steps and support more comprehensive sustainability strategies.

This study examines how sustainability impacts, particularly emissions are addressed in common certification systems and Level(s) framework both of which incorporate Life cycle assessment (LCA) as a key methodological component. The aim is to identify the best practices in construction based on interviews with industry experts. The research questions are:

1. What are the requirements and trends in achieving emission-free construction sites?
2. How and what do the common certification systems take site-emissions into account?
3. What are the remaining gaps in achieving emission-free construction sites?

To answer these questions, the study employs an integrative literature review (Toracco, 2005) to critically analyze how certification systems consider site activities and trends toward emission-free construction. The paper is organized as follows: first, a review of literature on emission-free construction sites, current-best practices and commonly used certification programs, focusing on their approaches on embodied emissions, are presented for background. Next, the method that was employed in the study is outlined, followed by findings on challenges and requirements to achieve emission-free construction sites. Finally, discussion and conclusions are provided.

# LITERATURE REVIEW

Literature from two research streams was reviewed: a) Emission-free construction sites and b) Certification programs' approach to site emissions.

## EMISSION-FREE CONSTRUCTION SITES

Emission-free construction sites do not produce airborne emissions from fuel combustion within its system boundary (Ólafsson et al., 2023). Instead, machines can be powered by alternative energy sources such as batteries or hydrogen. A broad system boundary includes all emissions from construction, driving reductions but complicating implementation. However, there are different perspectives on what exactly an emission-free construction site includes (Wiik et al., 2021), as there are in- and outflows of materials and waste besides on-site material handling, and upstream emissions related to materials themselves. For instance, the production of prefabricated elements such as wall panels and modules is considered part of A1–A3, their transport to the site falls under A4, and their on-site installation is part of A5 (Song, 2024). Moreover, efforts toward emission-free construction are not harmonized and differ across countries (Ólafsson et al., 2023) and lack of international standardization poses a significant challenge in achieving consistent and effective emission reduction practices.

Recent studies indicate that carbon emissions monitoring in construction is still in its early stages (Lõhmus, 2023), with a few best practices emerging from pilot projects aiming for emission-free sites. The City of Oslo in Norway requires municipal projects to use biofuel to reduce embodied emissions from construction activities (Omland & Andresen, 2022). Similarly, the city of Copenhagen in Denmark has piloted a couple of emission-free construction projects (City of Copenhagen, 2024). The city of Stockholm in Sweden prioritizes retrofit projects and promotes reusable materials to reduce the climate impact of construction (C40 Cities, 2019).

In Finland, a voluntary Green Deal agreement on emission-free sites was signed in 2020 by the Ministry of the Environment, and the major cities (Finnish Government, 2023). Electrification of construction machinery is the key activity in achieving this agreement's targets. Unavailability of these machines was identified as a main challenge (Finnish Government, 2023), for example, an electric truck with a crane attached was reported as rare in Finland (Konepörssi, 2024). In urban planning, allocating space for materials and waste management, and infrastructure for charging are essential to improve $CO_2$ efficiency for both long-haul and inner-city heavy-duty transport (Tetik et al., 2024b).

Budget restrictions, market supply availability of heavy site machinery and transport equipment affects achieving the goals, and current uncertain market impacts changing the fleets (Björk, 2023). While purchasing electric vehicles would initially cost twice as much, based on the calculator developed by Nordic Sustainable Construction (2024) for the lifetime cost of electric and diesel construction machinery, it currently takes eight years for the accumulated cost of ownership of a diesel one to exceed the electric one due to operational costs.

Effective data management and integration across the supply chain are pivotal for achieving emission-free construction sites. To manage data for planning emission-free construction sites and monitoring outcomes, strategies such as combining BIM and IoT sensors can be used to manage and visualize data related to construction activities and environmental conditions (Lee et al., 2019). Moreover, automated data acquisition methods like RFID, 3D laser scanning, and photogrammetry can collect data on construction progress and emissions (El-Omari & Moselhi, 2011). However, integrating these technologies requires advanced expertise (Zhao et al., 2019), which many construction actors lack. Furthermore, poor data quality and lack of standardization hinder the effective use of digital technologies (Morewood, 2023).

On-site construction time can be reduced by utilizing prefabricated components (Lihtmaa & Kalamees, 2024), which minimizes the need for continuous operation of machinery and overhead services, such as site office energy consumption, lighting, security and other activities (Pikas et al., 2024). It may facilitate efficient logistics and material handling (Fufa et al., 2023), further improving environmental performance. Thus, adopting prefabrication could aid in mitigating emissions of construction activities.

Consolidated shipment of materials and waste can help decrease emissions (Lundesjö et al., 2015). Logistics solutions can be used for coordination and improved flow of materials and information (Tetik et al., 2022). Efficient planning of material movement on- and off-site, with higher delivery fill rates, can reduce emissions from vehicles and machinery (Tetik et al., 2025). The transition to zero-emissions is urgent, and the sector needs to achieve significant emission cuts to align with this objective, yet current regulations not imposing any limits on new buildings in the Nordic countries risk falling short on targets (Ólafsson et al., 2023). Thus, higher regulatory standards are essential. Stakeholders often lack both awareness and incentives to adopt lower-emission practices (Fredriksson et al., 2022). Moreover, contractors need to adopt higher standards for achieving emission-free construction sites (Wiik et al., 2021). Establishing on-site systems to collect, share, and regularly evaluate data on energy use, resource consumption and waste while involving key project stakeholders can help drive progress toward sustainable practices (Ólafsson et al., 2024).

### COMMON CERTIFICATION PROGRAMS AND METHODS, AND THEIR APPROACH TO SITE EMISSIONS

One of the widely used certification programs in the building sector is Building Research Establishment's Environmental Assessment Method (BREEAM). The certification takes embodied carbon into account by focusing on materials using LCA (BRE Group, 2024). Sustainability is considered through the selection of building materials, taking their longevity, durability and impact during the maintenance phase. The construction phase, which typically includes A4 and A5 (transportation and construction processes in LCA), is covered through the LCA. However, the BREEAM International New Construction scope does not explicitly address other site-related aspects.

Another certification program for assessing building environmental performance is Leadership in Energy and Environmental Design (LEED), a comprehensive system that considers factors such as soil erosion and light pollution (U.S. Green Building Council, 2019). LEED requires projects to implement an Erosion and Sedimentation Control plan during construction which aims to control airborne dust and particulate matter (BuildingGreen, 2024).

The Level(s) framework is a comprehensive European Union initiative designed to assess and enhance the sustainability performance of buildings throughout their life cycle (Dodd, Donatello, & Cordella, 2021). It considers on-site emissions during construction, but not in a detailed or direct way. An interesting observation is the special emphasis given to potential trade-offs between embodied and operational emissions during the use phase, aiming to minimize total greenhouse gas emissions (Dodd et al., 2021). Moreover, electrifying machinery, using renewable energy and minimizing waste and maximizing recycling and reuse are highlighted (European Commission, 2025).

LCA method is defined as “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 14040:2006). It is an analytical method to evaluate and quantify environmental impacts of products by assessing material and energy usage, waste and emission generation, and ways to reduce these impacts (European Environment Agency, 2024b). The term “embodied” in LCA context in construction refers to environmental impacts of materials and processes that occur before operational phase, including those that are not immediately apparent (Röck et al., 2018).

## METHOD

Public domain data from certification programs’ technical documentation and guidelines, and scientific articles from Scopus database have been critically analyzed to determine the current approach on site emissions. Integrative literature analysis (Torraco, 2005) has been used to illustrate the interrelationships in the construction system to address site emissions from a comprehensive perspective. Figure 1 illustrates the research method followed in this study.

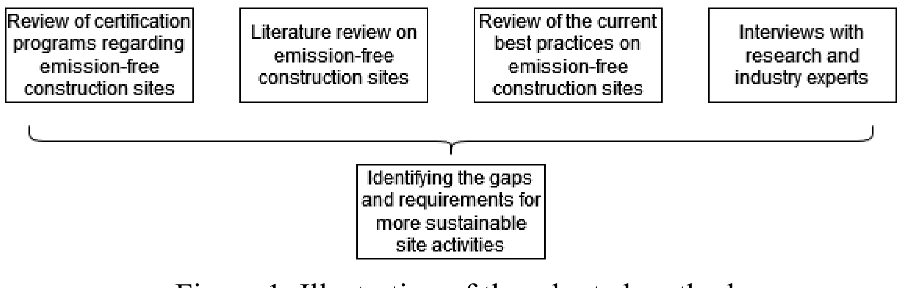


Figure 1: Illustration of the adopted method

LEED and BREEAM certification programs, LCA method and Level(s) framework were reviewed, because these are among the most well-known and widely recognized certifications and methods in the field. Moreover, interviews were conducted with academic and industry experts from different countries (Estonia, Finland, Sweden and Luxembourg) working in the construction supply chain, to capture diverse international views. Semi-structured interviews (Brinkmann, 2014) were used. Overall aim of the interviews was to understand how sustainability is being implemented and measured in current practices, with particular emphasis on carbon emissions, regulations, design decisions, and the potential role of digital technologies. The details regarding data collection are shown in Table 1.

Table 1. Interview details

| Interviewees | Interview details |
|---|---|
| Project Manager, General contractor, Estonia | December 2024, online interview |
| R&D Engineer, Research institution, Luxembourg | December 2024, online interview |
| Logistics Manager, Construction machine rental company, Sweden | March 2024, on-site interview |
| Construction Manager, Joint interest organization, Finland | January 2025, online interview |
| Chief Technology Officer, Contractor, Finland | March 2025, online interview |

# RESULTS

This section presents findings from a review of the literature on emission-free construction sites and commonly used certification systems, followed by insights from expert interviews. A table then summarizes and compares these findings across different regions.

## RESULTS FROM THE REVIEW OF LITERATURE AND COMMONLY USED CERTIFICATION PROGRAMS AND METHODS

A review of certification programs LEED and BREEAM, the LCA method, and the Level(s) framework, along with recent literature, shows that sustainability and environmental impact of buildings has become increasingly important over the past decade. Yet, further improvements are needed to better account for the construction phase in certifications, guide developers on their sustainability journey and educate future practitioners on process emissions.

The lack of biofuel distribution network, especially in northern Finland, was reported as an obstacle to achieve the climate goals (Björk, 2023). Thus, addressing the accessibility and feasibility of biofuels and other logistics solutions is essential to overcome these operational challenges. Attempts to reach sustainability in the industry involve utilizing practices such as applying lean construction principles (Tetik et al., 2024a), LCA (European Environment Agency, 2024b), and design optimization (Gan et al., 2017).

A few requirements were mentioned to reach emission-free sites in the literature. Client demand was identified as a key driver (Lõhmus, 2023). Cities started to set requirements in tendering phases to use emission-free machinery (C40 Cities, 2019). Infrastructure readiness, long-term contracts and demands on using electrified transports from developer to contractor and increased efforts for transports planning are required (Tetik et al., 2024b).

The analyses of the certification programs revealed that their approach on site emissions is limited. The certification systems' scopes are broad, taking building quality and impacts of buildings on their surroundings into account. Yet, site emissions are largely overlooked, and further development of guidelines is required. The construction process aspect is ignored in the sense that it is possible to obtain the certifications after the construction phase is over and no site visits are necessary during the construction phase (Whole Building Design Guide, 2024).

Currently there are a couple of pilot projects identified in the literature which try to reach zero-emissions during projects such as in the Nordic countries. For these examples to become widespread, benchmarking environmentally friendly methods to improve overall standards of sustainable on-site methods are needed. Achieving emission-free construction sites face challenges such as the need for international standardization and energy supply issues. Improved data collection, evaluation systems and higher regulatory standards are needed.

## RESULTS FROM THE INTERVIEW ANALYSIS

The interviews reveal that emissions from construction activities are often overlooked during the planning phase. Stakeholders, especially those not involved in certified projects, tend to neglect these impacts. For instance, a project manager in Estonia noted that sustainability and zero-emission thinking are still in the early stages of planning and implementation and are usually only considered when clients request certifications like ISO 14001 or BREEAM, which primarily focus on specific sustainability aspects, not covering all site-related activities.

A key barrier identified across regions is the lack of clear standards for managing site emissions, especially related to non-renewable energy use. While some sites offer zero-emission electricity contracts, contractors often have limited control if the client chooses the provider. Moreover, many sites, particularly large-scale projects like road construction, are not equipped to run heavy machinery on renewable energy.

In Sweden, a logistics manager mentions growing demand for renewable energy in transporting construction materials and waste. However, sustainability efforts in logistics remain limited, as unplanned deliveries frequently lead to additional emissions. Poor planning of site work and material flows often results in short-notice, inefficient deliveries that further increase emissions.

In Finland, recent legislation requires the calculation of emissions from the construction phase for new buildings. A construction manager emphasized that using renewable energy sources, such as biofuels for material delivery, is one of the most effective ways to reduce site emissions. Digitalization was identified as a key enabler for improving sustainability. A Chief Technology Officer in Finland highlighted the importance of using accurate, digital design models enriched with emissions data to better assess and reduce site emissions. However, despite technological advances, gaps remain in available data, particularly regarding the environmental impacts of material transport and on-site construction activities.

In Luxembourg, the expert pointed out significant gaps in data for project execution phase, particularly regarding material transport (A4), on-site construction (A5), and waste processing (C3) in LCA. Reliance on Environmental Product Declarations (EPD) which covers only A1 and A3 to assess environmental impact is seen as insufficient, as it does not capture the full picture of site-specific emissions. Also, poorly planned and coordinated deliveries cause unnecessary emissions. Rework due to missing data on material dimensions and equipment weights was also identified as a major challenge. Without this detailed information, on-site production is often poorly planned, leading to delays that increase emissions, for example, extended machinery use and longer periods of site illumination or heating. Also, it was highlighted that LCA is currently applied in a top-down manner and has not been fully internalized across all organizational levels, which limits its effectiveness in reducing emissions.

Regional variations in practices and policy implications can influence the implementation of sustainable construction methods. Based on the findings from both the interviews and the literature review, Table 2 provides a breakdown of the comparison for the different regions. The table outlines factors such as available resources, regulatory frameworks, and logistical constraints that shape construction projects in each region.

Table 2. Comparison of region-specific findings and impact areas

| Region | Challenges | Sustainability requirements |
|---|---|---|
| Estonia | Lack of stakeholder awareness and early-stage sustainability thinking. No established guidelines for non-renewable energy and emissions, lack of energy infrastructure for heavy machinery. | Increased awareness and established mandatory sustainability goals. Infrastructure for sustainable energy is needed. |
| Finland | The lack of biofuel distribution network for material transport. Incomplete digital design information to assess sustainability. Logistical and operational challenges in transporting materials. High costs for sustainable transport. | Compliance with new emissions regulations and adoption of biofuels for sites. Supply Chain digitalization for emissions. Improved distribution networks for biofuels |
| Luxembourg | Lack of data on execution phase environmental impacts and limitations in certification systems. | Need for comprehensive data collection to complete datasets and better impact assessment for execution phases. |
| Sweden | Lack of concrete steps for sustainability in logistics and supply chain. Unplanned material deliveries lead to inefficiencies and emissions. Challenges in renewable energy adoption | Improved planning for material deliveries and increased renewable energy adoption. |

Finally, the industry professionals suggest that civil engineering education should incorporate more emphasis on emissions management to provide future professionals with a comprehensive understanding of sustainability in site processes. Adopting a holistic approach, which considers the full life cycle of materials, energy, and emissions, would help graduates to understand the various stages of the project regarding waste reduction and environmental impacts.

# DISCUSSION

This study investigated the requirements and gaps on achieving emission-free construction sites. Requirements include infrastructure readiness, renewable energy access and incentives for contractors. While common certification systems primarily focus on operational energy use, some are beginning to address site emissions during construction phase, although these are often less emphasized. This highlights a gap in existing frameworks which need to more clearly address emissions from machinery, transport and logistics activities.

Fredriksson et al. (2022) suggest that limited incentives for environmentally friendly practices in material transport stem from low client demand and lack of focus on environmental concerns. This reduces pressure on contractors and suppliers to adopt greener alternatives, leading to meeting only the minimum standards instead of ambitious sustainability goals. Stronger policy interventions, greater client awareness and clearer certification guidelines are needed, especially as banks are required to follow sustainability taxonomies in lending and are incentivized to provide green loans over non-sustainable ones. Infrastructure readiness issues as in Björk (2023) and Tetik et al., (2024b), pose barriers to effective reduction of on-site emissions. The capacity of electricity grid to power all machinery on sites and source of electricity, whether it is renewable or not, were mentioned in interviews. These need to be considered when setting sustainability targets of projects.

Current examples, such as use of renewable fuels in Oslo, Stockholm and Copenhagen, and development of LCA tools in Stockholm, show site emission reduction efforts. While public sources reflect strong commitment to zero-emissions, it remains unclear whether these pledges have been realized, highlighting the need for follow-up efforts and emission measurements.

An important highlight from the analyses was the need to have complete digital design models which is in line with the previous study on directing value-adding operations throughout the building's life cycle via complete digital design models (Tetik et al., 2019). Complete and well-structured model enables seamless data flow across the supply chain, supporting automation in areas like $CO_2$ reduction calculations. It aligns well with Alhava et al. (2024) on demonstrating the feasibility of establishing end-to-end information transfer from MEP BIM models to electronic handover and as-built $CO_2$ reporting, automating information flow.

Lean construction emphasizes minimizing material waste. Yet, there is a need to broaden its scope by incorporating site emissions as a critical dimension of waste. This would help reduce both environmental and operational inefficiencies. This study calls on the lean construction community to recognize site emissions, particularly from transportation and machinery, as a key area of concern. To advance sustainable site practices, emission targets should be considered during the design phase. Sustainability requirements must be embedded into early decision-making, ensuring that among functionally equivalent options, those with lower emissions are prioritized.

Follow-up studies and carbon measurements are needed to verify the effectiveness of efforts to reduce emissions. Adopting prefabrication and logistics solutions, integrating lean construction principles, digitalization of construction supply chains, considering the circularity of materials and setting sustainability targets in the design phase are crucial steps towards achieving emission-free construction sites.

# CONCLUSIONS

This paper reviewed literature, certification systems, and expert insights to examine how site activities are addressed in efforts to achieve emission-free construction. Lean thinking emphasizes waste reduction which is inherent in sustainable practices. Findings highlight a growing need for coordinated action across the construction supply chain. Currently, certification programs tend not to take on-site emissions into account. Their scopes can be extended to cover also the embodied carbon emissions generated by site activities. The identified challenges and requirements on having zero-emission sites are:

- Low level of detail in planning the execution of work causes rework, increasing project duration which increases emissions. Projects are not planned with future stages in mind. Poorly planned site deliveries must be addressed. Lean approaches can help minimize rework and improving efficiency of logistics and coordination.
- Lack of awareness regarding site emissions and zero-emission understanding by construction parties. Lean construction principles can help establish awareness as part of the efforts to reduce waste and aim for continuous improvement.
- Certification programs focus more on energy performance of buildings after construction, neglecting direct site emissions. They must include embodied carbon emissions from all project phases.
- Additionally, whole life carbon assessments should ensure that reductions in construction emissions are not counterbalanced by operational emissions.
- Infrastructure readiness problems such as distribution network of biofuels to support renewable energy sources for heavy construction machinery need to be addressed.
- Most project stakeholders lack an understanding of the actual emissions generated by construction processes, and many find measuring these emissions overly complex.

Comprehensive guidelines and regulations to address energy use and consistent evaluation systems for site practices are required.

- Incomplete data sets for LCA phases and EPDs cause insufficient understanding of actual emissions from construction processes which impacts effective and sustainable decision-making for construction production and transportation.
- Lack of established emission limits and guidelines from the policymakers create ambiguity in reduction efforts. Regulations requiring emission calculations and set limits are needed.
- Lack of sustainability thinking integrated in civil engineering education. There is a need for improved knowledge dissemination toward curriculum development.

While this study offers insights, the limited number of interviews may restrict the range of perspectives. The focus on a few certifications was necessary to keep the scope manageable, though it covered the most common systems in Europe. Future research with larger sample sizes could improve the generalizability of the findings, and examining long-term zero-emission practices beyond pilot projects would be beneficial.

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