Nordic Innovation

Emission-free Construction Sites

Definitions, boundaries, and terminology – Current status in the Nordic countries

Contents

This publication is also available online in a web-accessible version at https://pub.norden.org/us2023-424

Preface

This project is part of the Nordic Sustainable Construction programme initiated by the Nordic ministers for construction and housing and funded by Nordic Innovation. The programme contributes to the Nordic Council of Ministers' Vision 2030 by supporting the Nordics in becoming the leading region in sustainable and competitive construction and housing with minimal impact on the environment and climate.

The programme supports the green transition of the Nordic construction sector by creating and sharing new knowledge, initiating debates in the sector, creating networks, workshops, and best practice cases, and helping to harmonise Nordic regulations on the climate impact of buildings.

The programme runs from 2021 to 2024 and consists of the following focus areas:

WP1 – Nordic Harmonisation of Life Cycle Assessment
WP2 – Circular Business Models and Procurement
WP3 – Sustainable Construction Materials and Architecture
WP4 – Emission-free Construction Sites
WP5 – Programme Secretariat and Capacity- building Activities for Increased Reuse of Construction Materials

This report is one of the WP4 deliverables.

The work has been carried out by a multidisciplinary working group with participants from Green Building Council in Iceland in collaboration with the Icelandic Ministry of Infrastructure, the Housing and Construction Authority of Iceland, and the University of Iceland. The Icelandic Ministry of Infrastructure is the responsible party.

Nordic Sustainable Construction

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Summary

The objective of the Nordics to take the lead in a sustainable and competitive construction and building sector comes with the aspiration to reduce the environmental and climate impact of construction. Key to reaching this objective is working with procurement and sustainable construction requirements. To facilitate this, it is essential to engage the entire value chain and promote new and innovative solutions and business models.

The building and construction industry is responsible for an estimated 39% of total energy and process-related greenhouse gas emissions, while the construction of new buildings may represent up to 5% of the total emissions across all sectors. New construction is bound to increase due to growing populations and affluence, which further highlights the need for addressing these emissions.

The environmental impact of construction is being addressed in a number of ways. There are legislative and voluntary measures, such as limits on permitted emissions and environmental certifications. Meanwhile, emission-free construction sites, sometimes termed zero-emission construction sites, are emerging as a means to focus on the construction process. Projects aimed at reducing construction emissions generally have different system boundaries and aspirations. Further development in the field would benefit from a unified framework. This can be based on the well-known standards and approaches that are used in life cycle assessments of buildings.

During construction, most of the greenhouse gas emissions relate to transport, machinery, and other energy use. Construction waste also contributes to emissions and this should therefore be considered. The use of fossil fuels on construction sites can be replaced by either fossil-free alternatives or emission-free energy carriers. Fossil-free biofuels are already available and can be used in existing machinery fleets. Further development in biofuels and electrofuels can be expected. Emission-free alternatives such as batteries and fuel-cells have the extra advantage of eliminating other airborne pollution. Although battery electric solutions are currently at the forefront of this, hydrogen is expected to be used in long-range applications.

Emission-free construction in the Nordic countries has mostly been propelled by way of public procurement. Cities and municipalities have awarded contracts based on environmental award criteria. The results are promising, and a growing number of building projects are implementing emission-free construction sites. The level of ambition ranges from fossil-free machinery to emission-free transport and machinery and the low-emission management of waste.

1. Introduction

Global climate change driven by greenhouse gas (GHG) emissions has become an existential threat to modern civilisation.[1 2] The building and construction sector is one of the main emitters of greenhouse gases and has been estimated to be responsible for about 39% of the world's energy process and energy-related CO_2 emissions.[3 4] The construction sector is therefore one of the most relevant sectors when planning reduction strategies.

Estimates show that new building construction may represent 5% of total GHG emissions.[5] These emissions are significant considering that they occur over a short period of time during the early stages of a building's life cycle.[6] In Oslo, GHG emissions related to construction sites account for approximately 7% of the city's total emissions, while in Copenhagen 5% of the municipality's total CO_2 footprint can be attributed to machines from construction sites.[7] Construction also causes emissions of other pollutants such as particulate matter, noise, and waterborne pollution. Here, the focus is on climate effects and the general term "emission" is used for greenhouse gas emissions in this text.

Many Nordic cities are already working towards lowering emissions at the city level with clear goals, and have committed to clean construction as part of their city climate strategies. The municipality of Copenhagen has a goal of becoming CO_2

1. I. Karlsson, J. Rootzén, F. Johnsson, and M. Erlandsson, 'Achieving net-zero carbon emissions in construction supply chains – A multidimensional analysis of residential building systems,' *Dev. Built Environ.*, vol. 8, p. 100059, Sep. 2021, doi: 10.1016/j.dibe.2021.100059.
2. A. Säynäjoki, J. Heinonen, and S. Junnila, 'A scenario analysis of the life cycle greenhouse gas emissions of a new residential area,' *Environ. Res. Lett.*, vol. 7, no. 3, p. 034037, Sep. 2012, doi: 10.1088/1748-9326/7/3/034037.
3. J. H. Andersen, N. L. Rasmussen, and M. W. Ryberg, 'Comparative life cycle assessment of cross laminated timber building and concrete building with special focus on biogenic carbon,' *Energy Build.*, vol. 254, p. 111604, Jan. 2022, doi: 10.1016/j.enbuild.2021.111604.
4. A. Hafner and S. Schäfer, 'Environmental aspects of material efficiency versus carbon storage in timber buildings,' *Eur. J. Wood Wood Prod.*, vol. 76, no. 3, pp. 1045–1059, May 2018, doi: 10.1007/s00107-017-1273-9.
5. J. L. Blanco, H. Engel, F. Imhorst, M. J. Ribeirinho, and E. Sjödin, 'Call for action: Seizing the decarbonization opportunity in construction,' McKinsey, 2021.
6. S. M. Fufa, M. K. Wiik, S. Mellegård, and I. Andresen, 'Lessons learnt from the design and construction strategies of two Norwegian low emission construction sites,' *IOP Conf. Ser. Earth Environ. Sci.*, vol. 352, no. 1, p. 012021, Oct. 2019, doi: 10.1088/1755-1315/352/1/012021.
7. Regeringens Klimapartnerskaber, 'Klimapartnerskab for bygge og anlæg,' 2021. Accessed: Feb. 03, 2023. [Online]. Available: https://em.dk/media/14288/sektorkoereplan-for-klimapartnerskab-for-bygge-og-anlaeg.pdf

-neutral by 2025, which requires all construction sites to be fossil and emission-free by 2025.[8] Oslo's target is for all construction sites to have zero emissions by 2025.

The main contributors to direct emissions from construction sites are heavy transport, construction machinery, and activities such as heating and drying.[9] [10]

Construction and demolition waste (CDW) is steadily increasing globally and causing serious ecological problems.[11] Large quantities of materials are discarded during the construction of a building, such as material off-cuts, packaging, and excavated material. Emissions from the production of materials that are wasted during construction can be assigned to the construction site. Emissions from waste processing and disposal can also be assigned to the site as indirect emissions.

Emissions from a construction site may be high enough to question whether new construction hinders ambitions in reaching GHG emission goals, no matter how energy-efficient the buildings are during their operation.[12] As the energy and climate performance of the use phase of the built environment keeps improving, the impact of the construction process is increasingly coming being drawn into focus.[13] Most embodied emissions occur before the building is occupied and therefore reducing embodied emissions of construction products is critical.[14]

Due to growing populations and increasing affluence, the construction industry is growing rapidly.[15] Estimates suggest that more than half of the buildings and infrastructure expected to exist in 2050 is yet to be built.[16] Any type of construction-related activity is likely to contribute to global warming,[17] and we must therefore set the same sustainability requirements for the work process on construction sites as for the buildings themselves.[18] [19] To mitigate climate change, there is a need to reduce construction phase emissions, which include the construction process itself, as these dominate the lifecycle emissions profile and can be immediately influenced in building design as well as by policy.[20] Reducing emissions from construction

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8. 'Regeringens klimapartnerskaber - Danmarks største brainstorm,' DI. Accessed: Feb. 03, 2023. [Online]. Available: https://www.danskindustri.dk/politik-og-analyser/klimapartnerskaber/
9. M. Maniak-Huesser, L. G. F. Tellnes, and E. Zea Escamilla, 'Mind the Gap: A Policy Gap Analysis of Programmes Promoting Timber Construction in Nordic Countries,' *Sustainability*, vol. 13, no. 21, p. 11876, Oct. 2021, doi: 10.3390/su132111876.
10. M. Akhlaq, 'Emission Free Construction Site-Thermal Overloading of the Charging System,' University of South-Eastern Norway, 2022.
11. S. Mamo Fufa, C. Venås, and M. Kjendseth Wiik, 'Is it possible to achieve waste free construction sites in Norway?' *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1196, no. 1, p. 012018, Oct. 2021, doi: 10.1088/1757-899X/1196/1/012018.
12. M. Akhlaq, 'Emission Free Construction Site-Thermal Overloading of the Charging System,' University of South-Eastern Norway, 2022.
13. I. Karlsson, J. Rootzén, A. Toktarova, M. Odenberger, F. Johnsson, and L. Göransson, 'Roadmap for Decarbonization of the Building and Construction Industry—A Supply Chain Analysis Including Primary Production of Steel and Cement,' *Energies*, vol. 13, no. 16, p. 4136, Aug. 2020, doi: 10.3390/en13164136.
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15. C. Venås *et al.*, 'No or low emissions from construction logistics – Just a dream or future reality?' *IOP Conf. Ser. Earth Environ. Sci.*, vol. 588, no. 4, p. 042003, Nov. 2020, doi: 10.1088/1755-1315/588/4/042003.
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17. W. Hawkins, S. Cooper, S. Allen, J. Roynon, and T. Ibell, 'Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure,' *Structures*, vol. 33, pp. 90–98, Oct. 2021, doi: 10.1016/j.istruc.2020.12.013.
18. M. Maniak-Huesser, L. G. F. Tellnes, and E. Zea Escamilla, 'Mind the Gap: A Policy Gap Analysis of Programmes Promoting Timber Construction in Nordic Countries,' *Sustainability*, vol. 13, no. 21, p. 11876, Oct. 2021, doi: 10.3390/su132111876.
19. W. Hawkins, S. Cooper, S. Allen, J. Roynon, and T. Ibell, 'Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure,' *Structures*, vol. 33, pp. 90–98, Oct. 2021, doi: 10.1016/j.istruc.2020.12.013.
20. E. Resch, I. Andresen, F. Cherubini, and H. Brattebø, 'Estimating dynamic climate change effects of material use in buildings—Timing, uncertainty, and emission sources,' *Build. Environ.*, vol. 187, p. 107399, Jan. 2021, doi: 10.1016/j.buildenv.2020.107399.

activities will not only require technological innovation but also efforts to develop new means of co-operation between stakeholders in the supply chain.[21]

1.1. Background

The reduction of GHG emissions from the construction industry is addressed in different ways and contexts. The construction site or process is generally not presented on its own but as part of a larger scheme. Here are some examples of the carbon-reducing concepts that are currently being applied, either directly or indirectly.

Sustainable building certifications are used to rate the environmental performance of buildings. There are many variations to these labels and many are specific to individual countries.[22] [23] In the Nordic countries, **BREEAM**, **LEED**, and the **Nordic Swan** are popular systems. The European Commission has presented the **Level(s)** system for assessing and reporting on the sustainability performance of buildings.[24] The objective of using certification is to measure and show environmental performance with the ultimate goal of reducing the negative impact.[25] [26]

Similar to the voluntary certifications above, authorities in the Nordic countries are developing legislation requiring a **Life Cycle Assessment** (LCA) of new buildings. Sweden, Finland, and Denmark are at the forefront of this work but other countries are following suit. The general aim is to develop baseline emission values and set normative carbon limits for allowable emissions in building projects.[27] [28] [29] [30]

The **EU taxonomy** is a new tool established by the European Parliament and is being applied in stages from 2021.[31] The EU taxonomy is a framework for defining and classifying sustainable economic businesses and activities. The idea is to clearly define what can be seen as sustainable and thus prevent greenwashing, support green public procurement, and help to shift investment in a more "green" direction.

Public procurement can be used to actively encourage environmentally friendly activities and production. This applies also to buildings and sometimes to

21. I. Karlsson, J. Rootzén, A. Toktarova, M. Odenberger, F. Johnsson, and L. Göransson, 'Roadmap for Decarbonization of the Building and Construction Industry—A Supply Chain Analysis Including Primary Production of Steel and Cement,' *Energies*, vol. 13, no. 16, p. 4136, Aug. 2020, doi: 10.3390/en13164136.
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23. M. Braulio-Gonzalo, A. Jorge-Ortiz, and M. D. Bovea, 'How are indicators in Green Building Rating Systems addressing sustainability dimensions and life cycle frameworks in residential buildings?' *Environ. Impact Assess. Rev.*, vol. 95, p. 106793, Jul. 2022, doi: 10.1016/j.eiar.2022.106793.
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26. K. G. Jensen and H. Birgisdóttir, *Guide to Sustainable Building Certifications*. Statens Byggeforskningsinstitut, SBi, 2018.
27. Nordic Sustainable Construction, *Nordic Sustainable Construction*. Accessed: Aug. 10, 2022. [Online]. Available: http://nordicsustainableconstruction.com/
28. 'VCBK - Videncenter om Bygningers Klimapåvirkninger,' VCBK. Accessed: Jan. 22, 2023. [Online]. Available: https://byggeriogklima.dk/
29. 'Regulation on climate declarations for buildings,' Boverket, Sweden, 2020:28, 2020. [Online]. Available: https://www.boverket.se/en/start/publications/publications/2020/regulation-on-climate-declarations-for-buildings/
30. M. Kuittinen and T. Häkkinen, 'Reduced carbon footprints of buildings: new Finnish standards and assessments,' *Build. Cities*, vol. 1, no. 1, pp. 182–197, Jun. 2020, doi: 10.5334/bc.30.
31. 'Details, Guides and News about the EU Taxonomy,' EU Taxonomy Info. Accessed: Feb. 3, 2023. [Online]. Available: https://eu-taxonomy.info/

construction sites. The EU as well as the Nordic countries are making use of this method.

A **Zero -Energy Building** (ZEB) has net -zero energy consumption. The term is sometimes defined as a Zero -Emission Building as the goal is to avoid greenhouse gas emissions. There are variations in the definition in terms of how and when consumption is measured. The terminology differs slightly and terms such as Zero -Carbon Building and Net -Zero Energy Building are also used. A similar term is Nearly Zero-Energy Building, where energy efficiency is very high. The focus is on energy use in the operational phase of the building. There are, however, more ambitious definitions that take into account emissions related to building materials as well as construction and end-of-life.[32] [33] [34] [35] [36] [37]

A carbon tax on GHG emissions is a tool for reducing carbon emissions as well as creating a revenue stream for public finances. This taxation supports the energy transition and has an effect on energy-related emissions on construction sites.

Poor **air quality** is a public health issue, especially in modern cities.[38] [39] Harmful gases and particulate matter are huge environmental health risks in Europe. A large part of this pollution stems from combustion engines in the transport and construction sectors. This emphasises that construction sites in densely populated urban areas should strive to reduce not only carbon emissions but also other harmful airborne pollutants.

The concept of the emission-free construction site is emerging and is still not very well known or developed. It is related to all of the above in various ways as it concerns the reduction of emissions from the construction process. In the following, a basis for discussion will be presented and definitions of the main concepts will be investigated further.

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32. A. J. Marszal *et al.*, 'Zero Energy Building – A review of definitions and calculation methodologies,' *Energy Build.*, vol. 43, no. 4, pp. 971–979, Apr. 2011, doi: 10.1016/j.enbuild.2010.12.022.
33. 'Nearly zero-energy buildings,' European Commission. Accessed: Sep. 28, 2022. [Online]. Available: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-buildings_en
34. A. J. Marszal and P. Heiselberg, 'A Literature Review of Zero Energy Buildings (ZEB) Definitions,' Department of Civil Engineering, Aalborg University, 2009. [Online]. Available: https://vbn.aau.dk/ws/portalfiles/portal/18915080/A_Literature_Review_of_Zero_Energy_Buildings__ZEB__Definitions
35. W. Wu and H. M. Skye, 'Residential net-zero energy buildings: Review and perspective,' *Renew. Sustain. Energy Rev.*, vol. 142, p. 110859, May 2021, doi: 10.1016/j.rser.2021.110859.
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37. S. M. Fufa, R. D. Schlanbusch, K. Sørnes, M. Inman, and I. Andresen, 'A Norwegian ZEB Definition Guideline,' SINTEF, 2016. [Online]. Available: https://www.sintefbok.no/book/index/1092
38. 'Air quality in Europe 2022 — European Environment Agency,' European Environment Agency. Accessed: Jan. 24, 2023. [Online]. Available: https://www.eea.europa.eu/publications/air-quality-in-europe-2022
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2. Definitions

There are different terms used for construction where emissions are systematically controlled and minimised. The name that is used here – emission-free construction sites – is interchangeable with other similar names. Emission-free and zero-emission are the most common with either construction or construction sites added at the end. Also used is Zero -Carbon Construction or Net -Zero Carbon Construction.[40] [41] [42] [43]

The basic definitions for emission types related to the construction process are already in use in this context.[44]

> A **fossil-free construction** site does not make use of any fossil fuels, such as diesel or propane, within the system boundary. Construction machinery and vehicles powered by combustion engines using fuels containing carbon are permitted, provided the carbon does not increase the net amount of atmospheric carbon. Examples are sustainably sourced biofuels and electro-fuels.
>
> An **emission-free construction** site has no airborne emissions from fuel combustion within the system boundary. Energy sources such as batteries or hydrogen can be used as energy sources for machines.

Emission-free also means fossil-free, i.e. the energy sources used may not be derived offsite from fossil fuels. Implementing emission-free solutions also reduces other types of harmful environmental emissions such as nitrogen oxides (NOx), sulphur oxides (SOx), particulate matter (PM5, PM10), and audible noise which affect local

40. I. Andresen, M. K. Wiik, S. M. Fufa, and A. Gustavsen, 'The Norwegian ZEB definition and lessons learnt from nine pilot zero emission building projects,' *IOP Conf. Ser. Earth Environ. Sci.*, vol. 352, no. 1, p. 012026, Oct. 2019, doi: 10.1088/1755-1315/352/1/012026.
41. 'Towards a zero carbon construction site,' Balfour Beatty plc. Accessed: Jun. 29, 2022. [Online]. Available: https://balfourbeatty.com/sustainability/cop26/towards-a-zero-carbon-construction-site/
42. 'Net Zero Carbon Buildings Framework,' UKGBC - UK Green Building Council. Accessed: Jan. 24, 2023. [Online]. Available: https://www.ukgbc.org/ukgbc-work/net-zero-carbon-buildings-framework/
43. 'Net Zero Carbon Construction,' WSP. 2021. Accessed: Jan. 25, 2023. [Online]. Available: https://www.wsp.com/en-au/insights/net-zero-carbon-construction
44. S. Davidson, A. O. Lie, and M. J. Rustad, 'Guide to arranging fossil- and emission-free solutions on building sites,' DNV GL AS, Oslo, 2018–0418, Rev. 2-ENG, 2018. [Online]. Available: https://www.klimaoslo.no/wp-content/uploads/sites/88/2018/06/Veileder-Utslippsfrie-byggeplasser-ENG.pdf

air quality and human health.[45]

These definitions are strongly related to energy use and are not directly relevant to construction waste. According to the widely accepted practice of life cycle assessment, the waste generated during construction is to be taken into account in emission calculations. The addition of one more definition may be necessary.[46]

> **Waste-free construction sites** support the development of emission-free construction sites. These are construction sites that do not generate waste in any of their construction site activities (including the production of the materials).[47]
>
> The terms emission-free and zero-emission are somewhat optimistic as indirect emissions should also be taken into account. **The greenhouse gas emission intensity** of renewable electricity generation is low but not zero. Construction powered by electricity or hydrogen from electrolysis powered by a renewable source still has an off-site emission due to the lifetime carbon emissions from power plant operations. The same applies if other upstream emissions are considered, such as the production of machinery. Things get even more complicated when off-site emissions from waste are included.

Carbon dioxide equivalent (CO_2eq) is a unit often used to standardise the global warming effect of different gas emissions.

Greenhouse gases (GHG) are gases in the atmosphere that absorb thermal radiation, mostly water vapour, carbon dioxide, methane, ozone, and nitrous oxide. The increased amount of these gases in the atmosphere disrupts the balance between incoming radiation from the sun and radiation from the surface of the earth emitted back into space. The greenhouse gases form a thermal shield like a blanket that raises the surface temperature and causes global warming. Carbon dioxide (CO_2) is responsible for about 70% of warming, methane (CH_4) for about 24%, and nitrous oxide (N2O) for 6%.[48]

Global Warming Potential (GWP) is an index used to compare the radiative forcing of different gases. GWP is a measure of cumulative warming over a given fixed period of time.[49] The GWP of carbon dioxide is defined as 1 regardless of the time period considered. Methane has a GWP of about 27 over a period of 100 years. Consequently, a kilo of methane released into the atmosphere has the same 100-year warming effect as 27 kilos of carbon dioxide.

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45. S. M. Fufa, M. K. Wiik, S. Mellegård, and I. Andresen, 'Lessons learnt from the design and construction strategies of two Norwegian low emission construction sites,' *IOP Conf. Ser. Earth Environ. Sci.*, vol. 352, no. 1, p. 012021, Oct. 2019, doi: 10.1088/1755-1315/352/1/012021.
46. S. Mamo Fufa, C. Venås, and M. Kjendseth Wiik, 'Is it possible to achieve waste free construction sites in Norway?' *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1196, no. 1, p. 012018, Oct. 2021, doi: 10.1088/1757-899X/1196/1/012018.
47. S. Mamo Fufa, C. Venås, and M. Kjendseth Wiik, 'Is it possible to achieve waste free construction sites in Norway?' *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1196, no. 1, p. 012018, Oct. 2021, doi: 10.1088/1757-899X/1196/1/012018.
48. J. Houghton, 'Global warming,' *Rep. Prog. Phys.*, vol. 68, no. 6, pp. 1343–1403, Jun. 2005, doi: 10.1088/0034-4885/68/6/R02.
49. W. Hawkins, S. Cooper, S. Allen, J. Roynon, and T. Ibell, 'Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure,' *Structures*, vol. 33, pp. 90–98, Oct. 2021, doi: 10.1016/j.istruc.2020.12.013.

2.1. System boundaries of the construction site

The definition of "construction site" in this context has been evolving over the past few years. Work on emission-free construction is not harmonised and varies between countries. Published life cycle assessments of building construction define system boundaries in different ways. What is generally included are energy-consuming activities onsite, whereas transport and waste can be excluded.

Municipalities and industry in Norway have gained experience in this field through several emission and fossil-free projects. At first, the focus was on on-site construction machinery and energy use, but later transport and waste were included in some projects.[50 51 52] This Norwegian approach is becoming closely aligned with the European standard for the LCA of buildings - EN 15798.[53] Other publications also define boundaries as a variation on this theme.[54 55] The general consensus is to focus on energy use while waste is peripheral.

Although the zero-emission building (ZEB) is an older and more developed concept, definitions also vary. Operational emissions are traditionally within the scope of ZEB while construction is sometimes included.[56 57 58]

It is beneficial for the ongoing work on emission-free construction sites to create a harmonised framework, at least in the Nordics. The discussion and analysis of emission-free construction sites could then be based on a clear definition of the boundaries of the construction site and what emissions are included, facilitating a comparison between projects.

2.2. Considerations in boundary development

The definition of a construction site should consider all relevant stakeholders and how included activities align with their interests. The main stakeholders that use or are directly impacted by the boundaries can be categorised as follows.

Project owner – Here all the basic decisions are made, such as if the construction should be emission-free.

Designer – This includes all work on conceptualising, planning, and designing the building. These primary phases greatly impact all emissions during

50. S. Davidson, A. O. Lie, and M. J. Rustad, 'Guide to arranging fossil- and emission-free solutions on building sites,' DNV GL AS, Oslo, 2018–0418, Rev. 2-ENG, 2018. [Online]. Available: https://www.klimaoslo.no/wp-content/uploads/sites/88/2018/06/Veileder-Utslippsfrie-byggeplasser-ENG.pdf
51. M. K. Wiik, K. Fjellheim, and R. Gjersvik, 'Erfaringskartlegging av krav til utslippsfrie bygge- og anleggsplasser,' SINTEF, 86, 2022. [Online]. Available: https://hdl.handle.net/11250/2837785
52. S. Mamo Fufa, S. Mellegård, M. Kjendseth Wiik, C. Flyen, and G. Hasle, 'Utslippsfrie byggeplasser State of the art Veileder for innovative anskaffelsesprosesser,' 2018. Accessed: Aug. 03, 2022. [Online]. Available: http://hdl.handle.net/11250/2572024
53. 'EN 15978 Sustainability assessment of construction works – assessment of environmental performance of buildings – calculation method,' CEN. 2011. [Online]. Available: https://standards.cencenelec.eu/
54. 'Zero-Emissions Construction Sites,' Bellona.org. Accessed: Jun. 28, 2022. [Online]. Available: https://bellona.org/projects/zero-emissions-construction-sites
55. M. Weigert, O. Melnyk, L. Winkler, and J. Raab, 'Carbon Emissions of Construction Processes on Urban Construction Sites,' *Sustainability*, vol. 14, no. 19, p. 12947, Oct. 2022, doi: 10.3390/su141912947.
56. I. Andresen, M. K. Wiik, S. M. Fufa, and A. Gustavsen, 'The Norwegian ZEB definition and lessons learnt from nine pilot zero emission building projects,' *IOP Conf. Ser. Earth Environ. Sci.*, vol. 352, no. 1, p. 012026, Oct. 2019, doi: 10.1088/1755-1315/352/1/012026.
57. D. Satola, M. Balouktsi, T. Lützkendorf, A. H. Wiberg, and A. Gustavsen, 'How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC annex 72,' *Build. Environ.*, vol. 192, p. 107619, Apr. 2021, doi: 10.1016/j.buildenv.2021.107619.
58. D. Satola *et al.*, 'Comparative review of international approaches to net-zero buildings: Knowledge-sharing initiative to develop design strategies for greenhouse gas emissions reduction,' *Energy Sustain. Dev.*, vol. 71, pp. 291–306, Dec. 2022, doi: 10.1016/j.esd.2022.10.005.

construction and also what solutions can be chosen during the construction phase.

Government – The building industry is highly regulated and the construction site is no exception. Health and safety is a good example. Emissions are now within the scope of regulation and emission limits are on the horizon.

Contractor/Constructor – The actor that actually controls the construction site and can minimise emissions within the limits set by the design and regulations. In most cases, subcontractors handle specialised tasks under the supervision of the main contractor.

There are a number of aspects to consider about what is included and these can affect what should be included. The effectiveness of the reduction of emissions and ease of practical implementation are two such criteria. The following aspects have been identified as important criteria for construction site boundaries:

Stakeholder responsibility – Boundaries should exclude activities that are not under the control of the contractor, designer, or other stakeholders in the building project.

Effectiveness – Boundaries should promote changes that result in a reduction in emissions. Also, emissions should not be easily moved outside the boundary.

Simplicity – Additional design and management burdens should be kept to a minimum while achieving the goals of the project.

Harmonisation with LCA – Life Cycle Assessment is widely used in the construction industry. It is an important tool in the design phase and is being incorporated into environmental regulations in the Nordics.[59] [60] Aligning with predefined system boundaries from LCA simplifies co-ordination between stakeholders. In addition, monitoring construction site emissions would provide valuable information in LCA-related efforts.

The system boundaries for the construction phase of buildings are defined in the European Standard EN 15978 "Sustainability of construction works - Assessment of environmental performance of buildings - calculation method".[61] The life cycle of a building is divided into stages, starting from the product stage, through the construction process, followed by the use of the building until its end-of-life stage is reached. Figure 1 shows how the stages are further divided into modules.

59. 'Regulation on climate declarations for buildings,' Boverket, Sweden, 2020:28, 2020. [Online]. Available: https://www.boverket.se/en/start/publications/publications/2020/regulation-on-climate-declarations-for-buildings/
60. T. Malmqvist, S. Borgström, J. Brismark, and M. Erlandsson, 'Referensvärden för klimatpåverkan vid uppförande av byggnader,' KTH Royal Institute of Technology, Stockholm, 2021.
61. 'EN 15978 Sustainability assessment of construction works – assessment of environmental performance of buildings – calculation method,' CEN. 2011. [Online]. Available: https://standards.cencenelec.eu/

Building Life Cycle																Additional info
Product			Construction process		Use							End of life				Potential benefits and loads
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport to manufacturing	Manufacturing	Transport to Construction site	Construction installation Process	Use, installed production	Maintenance	Repair	Replacement	Refurbishment	Operational energy	Operational water	Deconstruction	Transport	Waste processing	Disposal	Recovery, reuse and Recycling potential

Figure 1. Construction site in relation to stages in the building lifecycle according to EN 15978. Stages A4-A5 and C1-C2 describe construction and deconstruction by way of similar activities. Stages B3-B5 and C3-C4 are related to construction, but are not considered conventional construction sites.

Figure adapted from: 'EN 15978 Sustainability assessment of construction works – assessment of environmental performance of buildings – calculation method,' CEN. 2011. [Online]. Available: https://standards.cencenelec.eu

The standard describes the construction process as the activities involved in transporting materials from factory to site (A4) and then installing the products until completion of the building (A5). Strictly speaking, module A5 is a description of a construction site, while A4 is a transportation scenario. Other modules also involve construction work, such as the maintenance modules B3 to B5. The end-of-life modules involve activities and processes that are also part of the construction process modules.

The EN 15978 standard describes the activities and processes that are to be taken into account when assessing the impact in modules A4 and A5. The emissions attributed to the construction phase according to the LCA perspective fit into the following categories:

> ***Material transport*** *– This includes the transport of all building materials from the factory gate to the site. Material that is lost during transit should also be included in this category.*
>
> ***Equipment transport*** *to and from the construction site. This includes machinery and all equipment needed for the construction work.*
>
> ***Personnel transport*** *– Transport of all workers to and from the site. This category is currently not part of the LCA standard boundary but is sometimes a considerable emission factor. This category can be used voluntarily here.*
>
> ***Wasted material transport*** *– This includes the transport of all materials that*

are produced, but not used in the construction. The most prominent is excavated ground from the site. Other materials are off-cuts from building materials and packaging.

Construction machinery *– Emissions from the use of machinery are included, but not the manufacturing of the machines. This category includes larger machines such as excavators, wheel loaders, trucks, and cranes. Smaller tools are excluded. On-site transport is included here.*

Energy *– Emissions from energy sources used onsite for tools, heating, ventilation, lighting, etc. This includes the use of fuels for generating electricity on site. Emissions from the off-site generation of electricity are also included.*

Auxiliary material and waste *– This category includes emissions from the production of auxiliary materials that are used for the construction, but not declared in other LCA phases. Production of other materials that will be lost, such as off-cuts and packaging is included here.*

Temporary works *– Emissions from any temporary installations, on or offsite, that are not counted as part of other categories.*

Waste treatment *– Emissions from the waste management of materials that are not reused.*

The standard EN 15978 does not include transport of personnel to and from the site. This activity is usually not managed by the contractor. It is, however, included here as an option for ambitious projects and future use.

Figure 2 depicts the proposed overall boundary of the construction site in visual form.

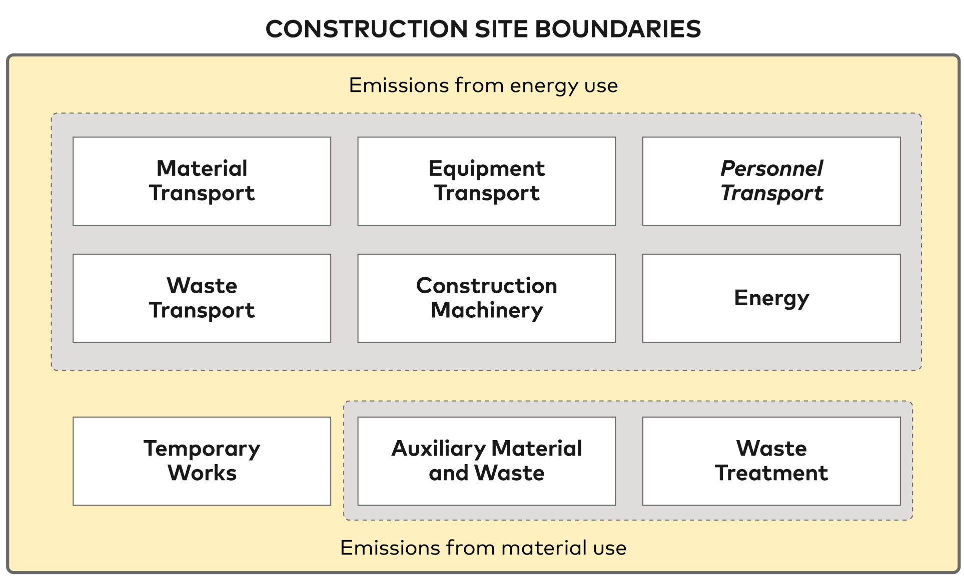

Figure 2. Proposed boundary of a construction site. The primary emission types from the processes are either energy use or material production and waste management.

The activities that emit GHGs within this boundary are primarily energy use and waste of materials.

The direct energy use relates to machinery and transport, which traditionally use diesel fuel. Also, heating and drying often require fossil fuels. These activities are the first emitters that come to mind when considering emission-free construction sites. Other significant emitters are additional material use and waste. According to the standard, emissions from the entire lifecycle of auxiliary building materials, waste, and lost material should be included in the LCA. Auxiliary and temporary building materials have not been accounted for in the impact assessment for the building in material stages A1 to A3. The same applies to waste and lost building materials.

Using the boundaries defined in the standard for the LCA harmonises the regulations and environmental monitoring and control systems. It follows that the boundary definition includes all emissions emanating from the construction and is therefore effective in pushing for emission reductions. Minimising waste and promoting reuse and recycling are important for reducing emissions throughout the value chain. This is not always directly under the control of the contractor, but rather the designer and project owner. The same is true for transport; a large part of material transport is under the control of the contractor, but designers also can choose materials and methods that minimise transport over longer distances.

2.3. Practical implementation

The downside of having such a broad boundary definition is the complexity of implementation. Although managing the energy use of machinery and heating is relatively simple, calculating the environmental impact of waste and lost material is more complicated. Therefore, it is virtually impossible for the construction industry to implement emission-free construction sites from the outset, according to the proposed boundaries. Implementation in stages is necessary.

In the implementation of emission-free construction sites in stages, the objectives and primary environmental focus (or focuses) should be defined before starting the individual work on each project. Generally, an accessible starting point at this point in time is fossil-free construction machinery and energy, leaving other categories as in conventional construction. However, in the case of more ambitious environmental objectives, waste reduction can be also chosen as an additional focus point, as well as the categories of auxiliary material and waste, and waste treatment.

What has to be noted, however, is the fact that even when following the recommendations described above, the emission-free construction site will never be fully emission-free. As mentioned above in point 2, the terms emission-free and zero-emission are somewhat optimistic because of indirect emissions related to electricity or materials production, for instance. However, it is important that project owners can “label” their projects as sustainable, even if only part of the activities are fossil-free or nearly emission-free.

This approach provides flexibility for implementation while maintaining harmonisation with the widely used EN 15798 standard.

3. Emissions from construction activities

Buildings and construction account for a large share of global GHG emissions, but the exact proportion across the value chain of the building industry is difficult to estimate. Recent reports estimate that about 25% of GHG emissions stem from construction and buildings. The sector is responsible for up to 40% of total process and energy-related emissions, with 30% from the use phase and about 10% from the initial construction phase.[62 63 64] The term embodied carbon is generally used for the emissions from construction. This is defined as the sum of all GHG emissions relating to a building's construction and building materials. This includes the entire lifecycle of the building, except for the emissions from operational energy use. Embodied carbon is closely related to embodied energy as most emissions stem from energy use.[65 66]

Historically, the magnitude of operational carbon emissions has been greater than **embodied carbon**, and the focus of emission reductions has therefore been on the operational phase. This has started to shift in recent years, as new energy-efficient buildings can have embodied carbon equal to their operational carbon emissions.[67]

The amount of embodied carbon in a building varies based on many factors such as material, size, and functional type. Based on studies, an expected value can be

62. J. L. Blanco, H. Engel, F. Imhorst, M. J. Ribeirinho, and E. Sjödin, 'Call for action: Seizing the decarbonization opportunity in construction,' McKinsey, 2021.
63. '2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector,' United Nations Environment Programme, Nairobi, 2022. [Online]. Available: https://globalabc.org/our-work/tracking-progress-global-status-report
64. '2019 global status report for buildings and construction,' International Energy Agency and Global Alliance for Buildings and Construction, Paris. Accessed: Aug. 2, 2022. [Online]. Available: https://globalabc.org/sites/default/files/2020-03/GSR2019.pdf
65. M. Adams, V. Burrows, and S. Richardson, 'Bringing embodied carbon upfront,' WorldGBC, London, 2019. [Online]. Available: https://www.worldgbc.org/sites/default/files/WorldGBC_Bringing_Embodied_Carbon_Upfront.pdf
66. C. De Wolf, F. Pomponi, and A. Moncaster, 'Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice,' *Energy Build.*, vol. 140, pp. 68–80, Apr. 2017, doi: 10.1016/j.enbuild.2017.01.075.
67. M. Röck *et al.*, 'Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation,' *Appl. Energy*, vol. 258, p. 114107, Jan. 2020, doi: 10.1016/j.apenergy.2019.114107.

anywhere from 100 to more than 500 $kgCO_{2eq}/m^2$ of the built area.[68 69 70 71]

The unit $kgCO_{2eq}/m^2$ in the building is the **LCA functional unit for climate change**. The unit $kgCO_{2eq}/m^2$/year is sometimes used where the emissions are averaged over the lifetime of the building, usually 50 years.[72]

The share of construction site activity emissions in embodied carbon also varies. A recent study in Sweden indicated that embodied carbon in new buildings averages 266 $kgCO_{2eq}/m^2$ of which 44 $kgCO_{2eq}/m^2$ (around 17%) are emissions from construction site activities and transport (LCA phases A4 and A5).[73] A small study in Iceland finds embodied carbon in a number of new buildings to be about 340 kgCO2eq/m^2 and about 28% of that stems from construction activities.[74]

3.1. Energy use in transport and construction

Energy use is the main contributor of emissions from the construction phase. Around 95% of emissions directly from the site itself, can be attributed to transportation and machinery while around 5% of the emissions come from the heating and drying of structures during construction.[75 76]

Transport (LCA module A4) is largely based on diesel-powered vehicles. On construction sites, diesel-powered machinery is used for most high-power activities such as earth-moving, piling, and drilling. Diesel or propane is often used for heating and drying and diesel generators are common on work sites. Although the use of energy from fossil fuels creates GHG emissions, there are other harmful effects as the burning of fuels creates a range of harmful gases and substances.

The conventional diesel engine is used in the transport of materials and in the majority of construction machinery. The primary gaseous emissions are CO_2 and water vapour, which have no direct health effects on the local environment in low concentrations. There are however other harmful emissions from these diesel engines. **Particulate matter (PM)** is part of the airborne exhaust. These particles are typically smaller than 1 μm and seriously affect human health and have other environmental impacts such as the degradation of visibility. Other important pollutants include nitrogen oxide (NO) and nitrogen dioxide (NO_2), which are grouped together as **nitrogen oxides (NO_x)**. These gases can have a serious negative effect on the human respiratory system. Nitrogen oxides also contribute to environmental problems such as aquatic nutrient enrichment, acid rain, the formation of ozone, and the formation of photochemical smog. Another type of

68. T. Malmqvist, S. Borgström, J. Brismark, and M. Erlandsson, 'Referensvärden för klimatpåverkan vid uppförande av byggnader,' KTH Royal Institute of Technology, Stockholm, 2021.
69. M. Röck *et al.*, 'Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation,' *Appl. Energy*, vol. 258, p. 114107, Jan. 2020, doi: 10.1016/j.apenergy.2019.114107.
70. K. Simonen, B. X. Rodriguez, and C. De Wolf, 'Benchmarking the Embodied Carbon of Buildings,' *Technol. Des.*, vol. 1, no. 2, pp. 208–218, Nov. 2017, doi: 10.1080/24751448.2017.1354623.
71. S. Ó. Bjarnadóttir and B. Marteinsson, 'Mat á kolefnislosun frá íslenskum byggingariðnaði,' Húsnæðis- og mannvirkjastofnun, 2022. [Online]. Available: https://byggjumgraenniframtid.is/wp-content/uploads/2022/06/Vegvisir-ad-vistvaenni-mannvirkjagerd-I.-hluti.-Losun.pdf
72. A. Grant and R. Ries, 'Impact of building service life models on life cycle assessment,' *Build. Res. Inf.*, vol. 41, no. 2, pp. 168–186, Apr. 2013, doi: 10.1080/09613218.2012.730735.
73. T. Malmqvist, S. Borgström, J. Brismark, and M. Erlandsson, 'Referensvärden för klimatpåverkan vid uppförande av byggnader,' KTH Royal Institute of Technology, Stockholm, 2021.
74. S. Ó. Bjarnadóttir and B. Marteinsson, 'Mat á kolefnislosun frá íslenskum byggingariðnaði,' Húsnæðis- og mannvirkjastofnun, 2022. [Online]. Available: https://byggjumgraenniframtid.is/wp-content/uploads/2022/06/Vegvisir-ad-vistvaenni-mannvirkjagerd-I.-hluti.-Losun.pdf
75. M. Maniak-Huesser, L. G. F. Tellnes, and E. Zea Escamilla, 'Mind the Gap: A Policy Gap Analysis of Programmes Promoting Timber Construction in Nordic Countries,' *Sustainability*, vol. 13, no. 21, p. 11876, Oct. 2021, doi: 10.3390/su132111876.
76. M. Akhlaq, 'Emission Free Construction Site-Thermal Overloading of the Charging System,' University of South-Eastern Norway, 2022.

pollutant emitted from diesel engines is so-called **hydrocarbons (HC)**, which are a group of organic compounds formed mainly due to incomplete fuel combustion. Airborne hydrocarbons may irritate the respiratory system, cause severe health problems, and contribute to ozone-formation. Additionally, due to incomplete fuel combustion, **carbon monoxide (CO)** is formed. CO is odourless and colourless but highly toxic and can pose a risk if engines are operated in enclosed spaces.[77]

The amount of harmful emissions from combustion engines in motor vehicles is regulated in the European Union by the so-called Euro limits, see table 1. The emission limits are gradually being tightened and the current version is Euro VI, introduced in 2014. For construction machinery, there is a similar standard, currently Stage V from 2019.

Table 1. Euro VI standard for heavy-duty vehicles (transient driving cycle) and Stage V standard for non-road engines (130-560kW).

Data from: 'Emission Standards: Europe: Nonroad Engines,' Diesel Net. Accessed: Jan. 31, 2023. [Online]. Available: https://dieselnet.com/standards/eu/nonroad.php
'Emission Standards: Europe: Heavy-Duty Truck and Bus Engines,' Diesel Net. Accessed: Jan. 31, 2023. Available: https://dieselnet.com/standards/eu/hd.php

Emission	Euro VI [g/kWh]	Stage V [g/kWh]
Carbon monoxide (CO)	4	3.5
Hydrocarbons (HC)	0.16	0.19
Nitrogen oxides (NO_x)	0.46	0.4
Particulate matter (PM)	0.01	0.015

To put the numbers in context, a lorry or an excavator with a 100kW engine is allowed to emit 400 grams of carbon monoxide per hour of work, 1 gram of particulate matter and 46 grams of nitrogen oxides.

3.2. Construction and demolition waste (CDW)

Construction and demolition waste (CDW) is another significant contributor to emissions on construction sites. The European List of Wastes (LoW) has defined CDW as a mixture of different materials generated from construction, reconstruction, expansion, conservation, demolition, maintenance, and alteration.[78] [79]

77. İ. A. Reşitoğlu, K. Altinişik, and A. Keskin, 'The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems,' *Clean Technol. Environ. Policy*, vol. 17, no. 1, pp. 15–27, Jan. 2015, doi: 10.1007/s10098-014-0793-9.
78. J.-L. Gálvez-Martos, D. Styles, H. Schoenberger, and B. Zeschmar-Lahl, 'Construction and demolition waste best management practice in Europe,' *Resour. Conserv. Recycl.*, vol. 136, pp. 166–178, Sep. 2018, doi: 10.1016/j.resconrec.2018.04.016.
79. R. Infante Gomes, C. Brazão Farinha, R. Veiga, J. de Brito, P. Faria, and D. Bastos, 'CO2 sequestration by construction and demolition waste aggregates and effect on mortars and concrete performance - An overview,' *Renew. Sustain. Energy Rev.*, vol. 152, p. 111668, Dec. 2021, doi: 10.1016/j.rser.2021.111668.

CDW is one of the largest waste flows in the world, accounting for 30-40% of total global urban waste, and is estimated to increase from 12.7 billion metric tonnes to 27 billion metric tonnes globally by 2050.[80] The quantity of CDW varies between countries which is influenced by a number of internal and external factors such as population growth, construction logistics, regional planning, and construction CDW management.[81]

The top three CDW generators are China (2.4 billion tonnes/ year), the United States (US) (800 million tonnes/ year), and the European Union (EU) (700 million tonnes/ year).[82 83] In the EU, the Waste Framework Directive set a minimum target of 70% by weight for the recycling of non-hazardous CDW by 2020, which has been met by most of the EU countries primarily through backfilling and low-grade recovery applications.[84 85] Some EU Member States have reported a CDW recovery rate in excess of 90%. However, the varying interpretations of waste and waste recovery by each country make it difficult to compare values between countries.[86]

The composition of CDW varies between countries and according to the source, location, and type of site.[87 88] CDW can be divided into two types: non-hazardous waste such as concrete, masonry, and soil; and hazardous waste such as wires, cables, and insulation fixtures which include hazardous substances.[89 90] Wood can also represent a significant fraction of CDW, such as in Sweden or Finland.[91]

Although efforts to recycle and reuse CDW have been increasing, around 35% of all CDW globally is sent directly to landfill without any further treatment.[92 93] The inadequate disposal and management of CDW has resulted in serious ecological

80. J. Xu, Y. Shi, Y. Xie, and S. Zhao, 'A BIM-Based construction and demolition waste information management system for greenhouse gas quantification and reduction,' *J. Clean. Prod.*, vol. 229, pp. 308–324, Aug. 2019, doi: 10.1016/j.jclepro.2019.04.158.
81. M. Menegaki and D. Damigos, 'A review on current situation and challenges of construction and demolition waste management,' *Curr. Opin. Green Sustain. Chem.*, vol. 13, pp. 8–15, Oct. 2018, doi: 10.1016/j.cogsc.2018.02.010.
82. R. Infante Gomes, C. Brazão Farinha, R. Veiga, J. de Brito, P. Faria, and D. Bastos, 'CO^2 sequestration by construction and demolition waste aggregates and effect on mortars and concrete performance - An overview,' *Renew. Sustain. Energy Rev.*, vol. 152, p. 111668, Dec. 2021, doi: 10.1016/j.rser.2021.111668.
83. J. Xu, Y. Shi, Y. Xie, and S. Zhao, 'A BIM-Based construction and demolition waste information management system for greenhouse gas quantification and reduction,' *J. Clean. Prod.*, vol. 229, pp. 308–324, Aug. 2019, doi: 10.1016/j.jclepro.2019.04.158.
84. T. B. Christensen, M. R. Johansen, M. V. Buchard, and C. N. Glarborg, 'Closing the material loops for construction and demolition waste: The circular economy on the island Bornholm, Denmark,' *Resour. Conserv. Recycl. Adv.*, vol. 15, p. 200104, Nov. 2022, doi: 10.1016/j.rcradv.2022.200104.
85. B. Galán, J. R. Viguri, E. Cifrian, E. Dosal, and A. Andres, 'Influence of input streams on the construction and demolition waste (CDW) recycling performance of basic and advanced treatment plants,' *J. Clean. Prod.*, vol. 236, p. 117523, Nov. 2019, doi: 10.1016/j.jclepro.2019.06.354.
86. B. Galán, J. R. Viguri, E. Cifrian, E. Dosal, and A. Andres, 'Influence of input streams on the construction and demolition waste (CDW) recycling performance of basic and advanced treatment plants,' *J. Clean. Prod.*, vol. 236, p. 117523, Nov. 2019, doi: 10.1016/j.jclepro.2019.06.354.
87. J.-L. Gálvez-Martos, D. Styles, H. Schoenberger, and B. Zeschmar-Lahl, 'Construction and demolition waste best management practice in Europe,' *Resour. Conserv. Recycl.*, vol. 136, pp. 166–178, Sep. 2018, doi: 10.1016/j.resconrec.2018.04.016.
88. R. P. Waskow, V. L. G. dos Santos, W. M. Ambrós, C. H. Sampaio, A. Passuello, and R. M. C. Tubino, 'Optimization and dust emissions analysis of the air jigging technology applied to the recycling of construction and demolition waste,' *J. Environ. Manage.*, vol. 266, p. 110614, Jul. 2020, doi: 10.1016/j.jenvman.2020.110614.
89. Y. Shi and J. Xu, 'BIM-based information system for econo-enviro-friendly end-of-life disposal of construction and demolition waste,' *Autom. Constr.*, vol. 125, p. 103611, May 2021, doi: 10.1016/j.autcon.2021.103611.
90. M. A. T. Alsheyab, 'Recycling of construction and demolition waste and its impact on climate change and sustainable development,' *Int. J. Environ. Sci. Technol.*, vol. 19, no. 3, pp. 2129–2138, Mar. 2022, doi: 10.1007/s13762-021-03217-1.
91. R. P. Waskow, V. L. G. dos Santos, W. M. Ambrós, C. H. Sampaio, A. Passuello, and R. M. C. Tubino, 'Optimization and dust emissions analysis of the air jigging technology applied to the recycling of construction and demolition waste,' *J. Environ. Manage.*, vol. 266, p. 110614, Jul. 2020, doi: 10.1016/j.jenvman.2020.110614.
92. M. Menegaki and D. Damigos, 'A review on current situation and challenges of construction and demolition waste management,' *Curr. Opin. Green Sustain. Chem.*, vol. 13, pp. 8–15, Oct. 2018, doi: 10.1016/j.cogsc.2018.02.010.
93. Y. Shi, Y. Huang, and J. Xu, 'Technological paradigm-based construction and demolition waste supply chain optimization with carbon policy,' *J. Clean. Prod.*, vol. 277, p. 123331, Dec. 2020, doi: 10.1016/j.jclepro.2020.123331.

problems such as air pollution, landslides, and soil and water pollution.[94][95] The main CDW disposal GHG emissions are CO_2, CH_4, and N_2O, where N_2O emissions contribute most to the greenhouse gas effect.[96]

Given the above, when compared to landfill disposal or incineration, recycling and reuse are the most environmentally friendly methods of treating CDW.[97][98] However, preventing waste by using fewer materials in design and manufacturing should always be a top priority.[99] Although plastic, paper, glass, and wood have well-established recycling markets, recycled concrete aggregates face many restrictions. CDW is generally mixed material and therefore their potential reuse is typically limited to road coverings, concrete blocks, concrete pavements, and the like.[100]

3.3. Sustainability of resource use

The construction industry is classified as the world's largest consumer of raw materials.[101] With increasing demand for construction materials,[102] resource efficiency is critical to providing resource security.[103] On a typical construction site, 33% of the waste can be attributed to failures to prevent waste during the design phase.[104] Material efficiency deserves more attention in policy and climate mitigation as it is a key abatement measure for all construction materials.[105]

The circular economy has increasingly been seen as a framework for recycling within the construction sector where increased reuse and improved recycling could capture a higher economic value from CDW.[106]

Along with these measures, we should explore alternatives and other strategies such as avoiding building when possible by repurposing assets and increasing shared spaces.

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94. Y. Shi and J. Xu, 'BIM-based information system for econo-enviro-friendly end-of-life disposal of construction and demolition waste,' *Autom. Constr.*, vol. 125, p. 103611, May 2021, doi: 10.1016/j.autcon.2021.103611.
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97. B. Galán, J. R. Viguri, E. Cifrian, E. Dosal, and A. Andres, 'Influence of input streams on the construction and demolition waste (CDW) recycling performance of basic and advanced treatment plants,' *J. Clean. Prod.*, vol. 236, p. 117523, Nov. 2019, doi: 10.1016/j.jclepro.2019.06.354.
98. Y. Shi and J. Xu, 'BIM-based information system for econo-enviro-friendly end-of-life disposal of construction and demolition waste,' *Autom. Constr.*, vol. 125, p. 103611, May 2021, doi: 10.1016/j.autcon.2021.103611.
99. M. A. T. Alsheyab, 'Recycling of construction and demolition waste and its impact on climate change and sustainable development,' *Int. J. Environ. Sci. Technol.*, vol. 19, no. 3, pp. 2129–2138, Mar. 2022, doi: 10.1007/s13762-021-03217-1.
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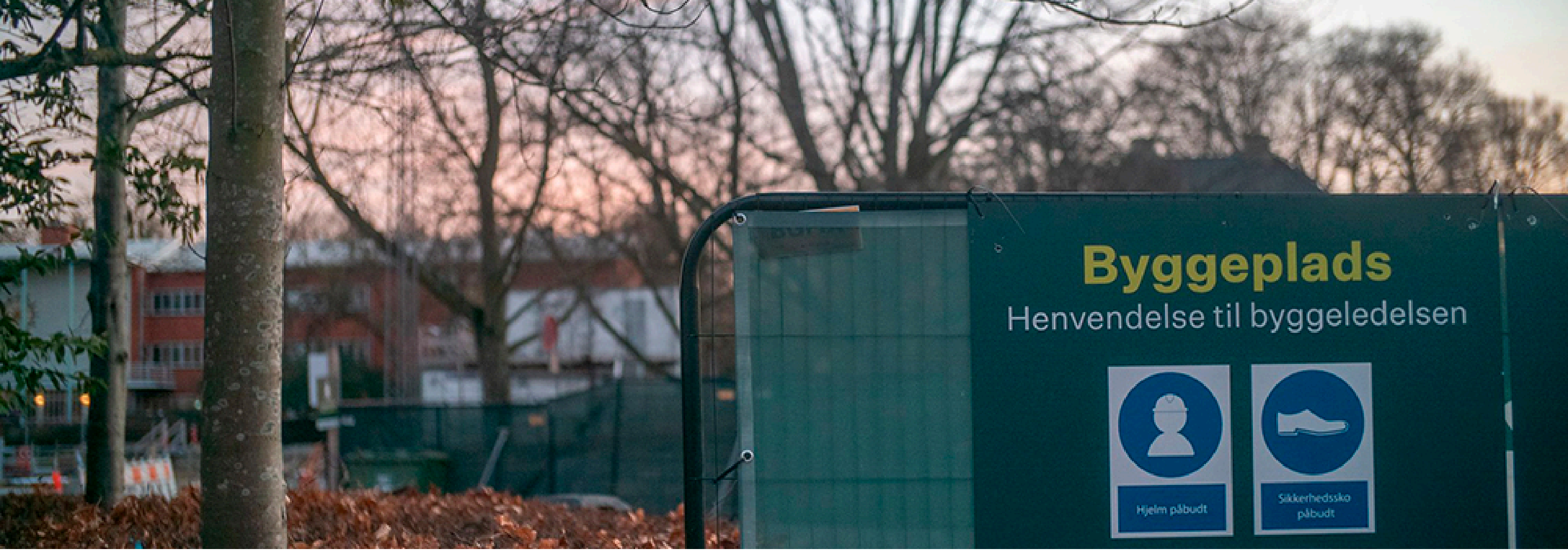
104. J.-L. Gálvez-Martos, D. Styles, H. Schoenberger, and B. Zeschmar-Lahl, 'Construction and demolition waste best management practice in Europe,' *Resour. Conserv. Recycl.*, vol. 136, pp. 166–178, Sep. 2018, doi: 10.1016/j.resconrec.2018.04.016.
105. I. Karlsson, J. Rootzén, A. Toktarova, M. Odenberger, F. Johnsson, and L. Göransson, 'Roadmap for Decarbonization of the Building and Construction Industry—A Supply Chain Analysis Including Primary Production of Steel and Cement,' *Energies*, vol. 13, no. 16, p. 4136, Aug. 2020, doi: 10.3390/en13164136.
106. T. B. Christensen, M. R. Johansen, M. V. Buchard, and C. N. Glarborg, 'Closing the material loops for construction and demolition waste: The circular economy on the island Bornholm, Denmark,' *Resour. Conserv. Recycl. Adv.*, vol. 15, p. 200104, Nov. 2022, doi: 10.1016/j.rcradv.2022.200104.



4. Energy carriers for construction activities

When fossil fuels such as diesel and propane are removed from construction sites, some clean energy sources must be introduced. This is truly a part of the global **energy transition**, where the aim is to phase out fossil fuel-based energy systems and introduce renewable energy. Methods proposed for the energy transition in transportation and heating can be applied to construction sites.

The energy sources to replace fossil oil, coal, and natural gas are electricity from sources such as wind, solar power, geothermal, and hydropower. Biomass is an indirect utilisation of solar power and may be used to provide biofuels, heating, and electric power generation.

The climate crisis shows that the extensive use of fossil fuels is not sustainable. Renewable energy sources come with their own climate impacts as well as other negative impacts on the environment and society. Renewable does not automatically mean sustainable.[107] [108] Although reducing GHG emissions is an important goal, resource use and other sustainability aspects must also be considered. This is why reducing energy use during construction in general should be a part of the emission-free mindset.

4.1. Overview of energy carriers

The term **energy carrier** is often used for the array of methods that replace traditional liquid fuels. The renewable energy carriers used to substitute fossil transportation fuels are biofuels, batteries and hydrogen. Direct electrification is also used but is essentially limited to rail transport.[109] Electrofuels are an emerging

107. O. Ortiz, F. Castells, and G. Sonnemann, 'Sustainability in the construction industry: A review of recent developments based on LCA,' *Constr. Build. Mater.*, vol. 23, no. 1, pp. 28–39, Jan. 2009, doi: 10.1016/j.conbuildmat.2007.11.012.
108. M. J. B. Kabeyi and O. A. Olanrewaju, 'Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply,' *Front. Energy Res.*, vol. 9, p. 743114, Mar. 2022, doi: 10.3389/fenrg.2021.743114.
109. C. Cunanan, M.-K. Tran, Y. Lee, S. Kwok, V. Leung, and M. Fowler, 'A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles,' *Clean*

energy carrier of electricity and can be used in conventional combustion engines. Their production to date is, however, limited.

All these technologies may be used at construction sites and for the transportation of building materials. The trend in usage is also similar. Biofuels are now common on construction sites, while battery-powered machinery is rapidly becoming available. Hydrogen remains a promising technology seen as a considerable part of the energy transition.[110]

- **Biofuel** is derived from biomass. It is used in conventional combustion engines, usually as a drop-in fuel. Ethanol, biodiesel, and HVO are the most commonly used biofuels in engines. Their energy density is high, especially for liquid biofuels, which equates to long range and/or run times.
- **Hydrogen** is a promising energy carrier in construction. Although hydrogen can be used in combustion engines, fuel cells offer better efficiency and zero emissions. The primary production paths of clean hydrogen are electrolysis and the gasification of biomass.
- **Batteries** are the most energy-efficient energy carrier. The charging and discharging cycle retains up to 95% of the initial energy. The energy density is very low, resulting in a short range and/or run time.
- **Electrofuel** is a method to store electricity in liquid fuel and use it in conventional combustion engines. Electricity is used to produce hydrogen, which is then combined with carbon dioxide. Methanol is now produced commercially, and diesel or its substitutes can also be produced.[111]

Table 2 shows some key properties of these energy carriers.

Table 2. A simple comparison of renewable energy carriers for construction activities. Hydrogen is assumed to be used in fuel cells. Electrofuels also include hydrogen when used in combustion engines.

Energy carrier	Advantages	Disadvantages
Biofuel	Drop-in fuel Long range Low vehicle cost	Pollution from combustion Low efficiency
Hydrogen	Emission free Medium efficiency	Medium range High vehicle cost
Batteries	Emission free High efficiency	Short range High vehicle cost
Electrofuel	Drop-in fuel Long range Low vehicle cost	Pollution from combustion Low efficiency

Technol., vol. 3, no. 2, pp. 474–489, Jun. 2021, doi: 10.3390/cleantechnol3020028.
110. 'Zero-Emissions Construction Sites,' Bellona.org. Accessed: Jun. 28, 2022. [Online]. Available: https://bellona.org/projects/zero-emissions-construction-sites
111. S. Brynolf, M. Taljegard, M. Grahn, and J. Hansson, 'Electrofuels for the transport sector: A review of production costs,' *Renew. Sustain. Energy Rev.*, vol. 81, pp. 1887–1905, Jan. 2018, doi: 10.1016/j.rser.2017.05.288.

The energy efficiency of battery-powered electric machines is about three times greater than diesel-powered machines. Hydrogen fuel cell machines are somewhere in between due to the medium efficiency of the fuel cell.[112] This can be put into context with a simple example of a car.[113]

- Popular electric car - energy efficiency ~ 22 kWh/100km
- Comparable diesel car - fuel economy ~ 6 L/100km
- Comparable diesel car - energy efficiency ~ 68 kWh/100km

Diesel fuel has an energy density of about 11.4 kWh/L.[114] The energy in six litres of diesel is, therefore, 68 kWh.

4.2. Battery-electric machinery

The two main advantages of battery-operated vehicles and machinery are very high efficiency and no tail-pipe emissions. The typical drivetrain in electric cars has energy efficiency in the range of 60-80%, depending on design and use. It is generally assumed that the efficiency is less than about 30% for drivetrains based on diesel engines.[115]

Electric motors are well-suited for all vehicles and hydraulic systems. Modern electric drivetrains use electronic inverters to control the motor, and such systems have superior performance over combustion engines with mechanical gearboxes or transmissions.

The battery pack is the main weakness of the system. The rechargeable electrochemical battery stores energy in the form of chemicals. This means that the battery has to convert electrical energy into chemical compounds, store all the chemical compounds needed and then convert the energy back into electricity. The result is very low specific energy, around 0.5 MJ/kg (0.14 kWh/kg), considering a battery pack with the container, cooling, and management systems. For comparison, the specific energy of diesel fuel is around 43 MJ/kg. The weight of batteries for vehicles and machinery is, therefore, in the range of several hundred kilos. Such a large and complex component is inevitably very expensive. The weight and price of battery packs limit the practical range and run time of electric vehicles and machinery.[116]

4.3. Fuel cell machinery

The hydrogen fuel cell is an established technology and has been used in electric vehicles for many years. The range of fuel cell machinery is limited only by the size of the hydrogen tanks on board. Although the specific energy of hydrogen is extremely

112. C. Cunanan, M.-K. Tran, Y. Lee, S. Kwok, V. Leung, and M. Fowler, 'A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles,' *Clean Technol.*, vol. 3, no. 2, pp. 474–489, Jun. 2021, doi: 10.3390/cleantechnol3020028.
113. 'Jaguarisland,' Jaguar Iceland, 2023. Accessed: Feb. 2, 2023. [Online]. Available: https://www.jaguarisland.is/
114. 'Technology Data – Renewable fuels,' Danish Energy Agency, Copenhagen, 2017. [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf
115. C. Cunanan, M.-K. Tran, Y. Lee, S. Kwok, V. Leung, and M. Fowler, 'A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles,' *Clean Technol.*, vol. 3, no. 2, pp. 474–489, Jun. 2021, doi: 10.3390/cleantechnol3020028.
116. 'Technology Data – Renewable fuels,' Danish Energy Agency, Copenhagen, 2017. [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf

high at 119 MJ/kg, it is difficult to compress and store. Pressurised tanks are used in production vehicles today, with pressures ranging from 35-70 MPa (350-700 bar). Even under this high pressure, the energy density is only about 7 MJ/kg. This is still more than ten times better than batteries. Furthermore, the energy is stored separately in tanks, and the range is therefore not limited by the size of the electrochemical cells, as in the case of batteries. The conversion efficiency from hydrogen to electricity is about 60%. In comparison, electrochemical batteries can have a discharge efficiency above 95%. Fuel cell machinery uses high-efficiency electric motors, and the system energy efficiency is far greater than in systems with combustion engines. The development of fuelling infrastructure has halted the introduction of hydrogen vehicles. Hydrogen is generally more difficult to handle than more common natural gas and methane as its high working pressure requires specialised compressors and containers.[117] [118]

4.4. Biofuels

The compression-ignited internal combustion engine is normally referred to as a diesel engine. It is the standard for heavy equipment due to its relatively high efficiency, durability, and robustness. This engine will be in service on construction sites for many years, both on fossil-free sites and also while phasing out fossil diesel. On fossil-free construction sites, biofuels can be used as a direct replacement for conventional diesel or used in modified engines. Biomass resources are needed for production, and some of the Nordic countries can exploit this option for harnessing energy.[119]

Biodiesel and HVO are widely used biofuels in construction and heavy-duty transport. They are commonly based on vegetable oils with varying degrees of processing. Simple engines can run on straight vegetable oils and even oils derived from fish. Vegetable oils are processed to make better fuel, and biodiesel and HVO are two of these products. These are first -generation biofuels and large-scale production is not considered sustainable. The feedstock is vegetable oil, which competes with food production and is fairly resource -intensive. Although second-generation drop-in diesel biofuels are being developed, price is the main limiting factor for commercialisation. In this case the feedstock is organic waste, unused by-products or energy crops grown with very low resource use and with minimal impact on food production and the environment.[120] Biomass can also be a feedstock for production of almost any chemical fuel, such as hydrogen, diesel, petrol, jet fuel, methanol, and methane. Here are some of the biofuels that are relevant for the construction industry.[121]

- **Biodiesel** is a popular name for fatty-acid methyl-esters (FAME). The conversion from vegetable oil is fairly simple. FAME does not conform to quality standards

117. 'Technology Data – Renewable fuels,' Danish Energy Agency, Copenhagen, 2017. [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf
118. M. Balat, 'Potential importance of hydrogen as a future solution to environmental and transportation problems,' *Int. J. Hydrog. Energy*, vol. 33, no. 15, pp. 4013–4029, Aug. 2008, doi: 10.1016/j.ijhydene.2008.05.047.
119. K. Refsgaard, M. Kull, E. Slätmo, and M. W. Meijer, 'Bioeconomy – A driver for regional development in the Nordic countries,' *New Biotechnol.*, vol. 60, pp. 130–137, Jan. 2021, doi: 10.1016/j.nbt.2020.10.001.
120. 'Technology Data – Renewable fuels,' Danish Energy Agency, Copenhagen, 2017. [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf
121. 'Technology Data – Renewable fuels,' Danish Energy Agency, Copenhagen, 2017. [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf

for diesel fuel and is typically only used as a blend in fossil diesel.

- **HVO** is an abbreviation for hydrotreated vegetable oil. The substance is also known as hydro-processed esters and fatty acids (HEFA). Like biodiesel, it is derived from vegetable oil. HVO is a high -quality diesel fuel and can fully replace conventional diesel fuel.
- **Renewable diesel** is one of many terms for fuel that is chemically very similar to, or identical to diesel, but produced from second-generation biomass such as organic waste.
- **Bio-hydrogen** is produced via the gasification of biomass where hydrocarbons are separated into carbon and hydrogen in a closed process. This hydrogen is chemically identical to any other hydrogen.
- **Methane** is easily produced via the anaerobic digestion of organic matter. Methane can be used directly in machinery designed for natural gas, either compressed or liquefied as CNG or LNG respectively.
- **Ethanol** is usually produced through the fermentation of biomass and is extensively used as blended to petrol. Ethanol is rarely used in diesel engines.

4.5. Electrofuels

Fuels for combustion engines may also be produced synthetically from hydrogen and carbon dioxide, where carbon dioxide is used to convert hydrogen into a more accessible fuel. As electrolysis is used for hydrogen production, such fuels are often named electrofuels, but the term synthetic fuel can also be used. Usually, the unconverted hydrogen is not considered an electrofuel. However, as it can be used in combustion-engine machinery, it is categorised here as a type of electrofuel. Here are some examples of electrofuels.[122]

- **Hydrogen** is the simplest electro fuel. Electrolysis uses electric current to split water molecules into hydrogen and oxygen. Hydrogen can be combusted in modified diesel and petrol engines.
- **Methanol** is a liquid fuel with similar properties to ethanol. It is typically used to replace petrol with minimal modifications to the engine. Methanol can be used in diesel engines with pilot ignition and lubricant additives.
- **DME** (di-methyl-ether) is a derivative of methanol. DME is suitable as fuel for diesel engines. DME is gaseous at normal conditions but liquefies at low pressure. Due to its chemical properties (ether), its combustion is related to no -soot formation.
- **OME** (oxy-methyl-ether) is also a derivative of methanol. OME molecules of a certain chain length are excellent liquid fuel for diesel engines. Like DME, it is more clean-burning than conventional diesel.
- **F-T diesel** (Fischer-Tropsch diesel) is identical to conventional diesel. A certain catalyst system is used to form the correct length of hydrocarbon chains. The process is inefficient and is likely not commercially viable.

122. 'Technology Data – Renewable fuels,' Danish Energy Agency, Copenhagen, 2017. [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf

5. Procurement is a powerful tool

In the EU, all medium and higher-value contracts with users of public funds or other entities operating in non-competitive, specific conditions have to legally be awarded through competitive procedures (tenders). As large sums and considerable demand are behind public procurement, it has great potential for contributing to the low-carbon transition of the construction sector.[123]

Government agencies, municipalities, and county councils play an important role as drivers by setting examples with their significant purchasing powers[124] by demanding more environmentally sustainable solutions and thus facilitating the development of corresponding market solutions. Such a procurement process would be both green and innovative.[125] Examples of green methods have been found in many procurement processes around the Nordics in the last few years. What is often seen is that contracts are awarded based on both environmental and quality-related factors, where the latter accounts for 70-90% in the scoring system. Oslo Municipality has used procurement guidelines with an award system for fossil-free and emission-free construction since 2020.[126] In September 2020, the City of Helsinki, together with the Finnish Ministry of the Environment, Senate Properties, and the cities of Espoo, Turku, and Vantaa, signed the Green Deal. The goal of the agreement is that the sites of the participating municipalities will be fossil-free by the end of 2025.[127]

123. Fossil Free Sweden, 'Roadmap for Fossil-free Competitiveness - Construction and Civil Engineering Sector,' 2018. [Online]. Available: https://www.skanska.se/4ae1fd/siteassets/om-skanska/hallbarhet/gront-byggande/klimatneutralitet/fardplan-fossilfritt-kampanj/ffs-the-construction-and-civil-engineering-sectorpdf.pdf
124. I. Karlsson, J. Rootzén, and F. Johnsson, 'Reaching net-zero carbon emissions in construction supply chains – Analysis of a Swedish road construction project,' *Renew. Sustain. Energy Rev.*, vol. 120, p. 109651, Mar. 2020, doi: 10.1016/j.rser.2019.109651.
125. R. Stokke, X. Qiu, M. Sparrevik, S. Truloff, I. Borge, and L. de Boer, 'Procurement for zero-emission construction sites: a comparative study of four European cities,' *Environ. Syst. Decis.*, Sep. 2022, doi: 10.1007/s10669-022-09879-7.
126. M. R. K. Wiik, K. Fjellheim, and R. Gjersvik, 'A survey of the requirements for emission-free building and construction sites,' 86 E, 2021. [Online]. Available: https://hdl.handle.net/11250/2980064
127. 'Pilot of an emission-free construction site: Kulosaari park road contract - Case City of Helsinki Hankintakeino.fi,' KEINO. Accessed: Feb. 1, 2023. [Online]. Available: https://www.hankintakeino.fi/en/materialbank/pilot-emission-free-construction-site-kulosaari-park-road-contract-case-city-helsinki

5.1. Examples of green procurement methods

An innovative use of procurement was introduced for Oslo Municipality's building projects in 2019. The criteria for awarding contracts for construction work are divided into price, quality, and environment. Points are awarded for each main criteria and the bidder with the highest score wins the contract. The weight of the environmental awarding criteria shall be at least 20% versus price and quality. It is recommended that the environment sub-criteria are mainly emission-free machinery and reduced emissions in bulk transport.[128] [129] This has enabled the rapid development and implementation of new market-oriented fossil and emission-free solutions.

Keino, a competence centre for sustainable and innovative public procurement, has published a booklet on the worksites concept for the green deal for zero-emission worksites. There are environmental criteria for equipment at zero-emission worksites. The minimum requirement applied as procurement criteria for machinery and energy consumption is, for example, that at least 30% of the machinery used must use electricity, hydrogen, or biogas. The other machinery at the worksite should use non-fossil fuels. There is also an example of a bonus applied in procurement where a certain amount is paid for each hour of active use of emission-free or low-emission machinery.[130]

5.2. Environmental sustainability criteria

Sustainability criteria are a recurring theme in sustainable procurement and are compatible with the protection of the environment. Sustainability criteria can function as a tool to promote and safeguard sustainable products and their sustainable production. It can set an upper limit to the use of natural resources and provide institutional guidance.[131]

There are different forms of sustainability criteria and requirements that can be used in procurements to push towards emission-free construction sites. For instance, a carbon -neutral rating, where a percentage of the total rating of a tender is for the use of emission-free or fossil-free machinery, has been used across the board.

The minimum procurement requirements are called selection criteria and the emphasis is on the bidder. The emphasis of award criteria, on the other hand, is on the bid.[132] Using the award criteria, it is possible to go beyond the minimum requirements and encourage providers to come up with innovative solutions.[133]

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128. M. R. K. Wiik, K. Fjellheim, and R. Gjersvik, 'A survey of the requirements for emission-free building and construction sites,' 86 E, 2021. [Online]. Available: https://hdl.handle.net/11250/2980064
129. 'Climate and environmental requirements for the City of Oslo's construction sites,' Klima Oslo, Oslo, 2019. [Online]. Available: https://www.klimaoslo.no/wp-content/uploads/sites/88/2019/11/Climate-and-enviromental-requirements.pdf
130. 'Emission-free construction sites – green deal agreement for sustainable procurement,' HNRY. Accessed: Feb. 1, 2023. [Online]. Available: https://hnry.fi/en/emission-free-construction-sites-green-deal-agreement-for-sustainable-procurement/
131. E. Pavlovskaia, 'Sustainability criteria: their indicators, control, and monitoring (with examples from the biofuel sector),' *Environ. Sci. Eur.*, vol. 26, no. 1, p. 17, Dec. 2014, doi: 10.1186/s12302-014-0017-2.
132. 'Emission-free construction sites – green deal agreement for sustainable procurement,' HNRY. Accessed: Feb. 1, 2023. [Online]. Available: https://hnry.fi/en/emission-free-construction-sites-green-deal-agreement-for-sustainable-procurement/
133. 'Utslippsfri byggeplass - eksempler på krav og tildelingskriterier Anskaffelser.no,' DFØ. Accessed: Feb. 3, 2023. [Online]. Available: https://anskaffelser.no/verktoy/eksempler/utslippsfri-byggeplass-eksempler-pa-krav-og-tildelingskriterier.

The Swedish procurement authority has a bank of sustainability criteria for procurement with an emphasis on environmental and social sustainability (criteria service). The Swedish criteria bank mentions four different forms of criteria:

- Qualification requirements
- Technical specifications
- Award criteria
- Special contract conditions

These criteria consist of fully formulated requirements and are more far-reaching than the legislation introducing them. The user of the criteria can make a decision based on available market information, ambition, resources and needs, with up to three levels: basic, advanced, and cutting edge.[134]

Kriterieveiviseren is a Norwegian guide to sustainable public procurement with requirements and criteria for procurement, including both technical specifications and award criteria, also divided into three levels. Part of the procedure is filling the table with information on the estimated use of fossil fuels for construction machinery on site, heating, and drying as well as the degree of waste sorting.[135]

Landsvirkjun is a public power company in Iceland with a large portfolio of construction projects. Landsvirkjun has three ways to promote the green energy transition and reduction in the use of fossil fuels in construction works:

- Carbon -neutral rating (award criteria)
- Payment system
- Maximum emission requirements (special contract conditions)

They specify that it would be possible to combine these methods e.g., it would be possible to have requirements for maximum GHG emissions but also pay for emissions savings in excess of these requirements. It would also be possible to give contractors a carbon -neutral rating yet still pay them for GHG emissions savings. The chosen route must be well presented to the contractors and other stakeholders.[136]

134. 'Hitta hållbarhetskriterier,' Upphandlingsmyndigheten, 2022. Accessed: Jan. 24, 2023. [Online]. Available: https://www.upphandlingsmyndigheten.se/kriterier/
135. 'Kriterieveiviseren Veiviser for bærekraftige offentlige anskaffelser.' Accessed Feb. 1, 2023. [Online]. Available: https://kriterieveiviseren.difi.no/nb
136. Mannvit, 'Orkuskipti í framkvæmdum,' Landsvirkjun, 2021. [Online]. Available: http://gogn.lv.is/files/2021/2021-044.pdf

6. Case studies

There are several case studies in the Nordic countries with different ambitions and that document a variety of construction activities:

- Lia Nursery School, Norway
- Campus Evenstad, Norway
- Hoppet preschool, Sweden
- Kulosaari park road, Finland
- Lukutori site plan, Finland
- Strøget pilot project, Denmark
- UN17 Eco Village, Denmark
- Mundi daycare, Denmark

These cases provide insight into emission-free and zero-emission construction site logistics, learning, and impact. Many Nordic cities are already working towards lowering emissions at the city level with clear goal -setting and have committed to clean construction as part of their city climate strategies. The sharing of case studies, best practices, and knowledge development can contribute to better understanding and help to identify solutions in real-world situations.

6.1. Lessons learnt from the case studies

The requirements for emission-free building and construction sites came mainly from the municipalities. Hoppet, for example, was part of Gothenburg's climate strategy programme with the aim of achieving sustainable and fair GHG emission levels by 2050. The focus of the Hoppet preschool project was to investigate the possibilities of building a completely fossil-free preschool, whereas Gothenburg's goal is for all preschools to be built fossil-free by 2030.[137]

137. R. Calderon, P. Löfås, and A. Larsson, 'Klimatarbete Hoppet Delrapportering 2 Byggskede,' Derome AB, Gothenburg, 2022. [Online]. Available: https://goteborg.se/wps/wcm/connect/2709251d-233c-4362-8439-1ea67a66ac7b/Klimatarbete+Hoppet-Delrapportering+Byggskede.pdf?MOD=AJPERES

Better planning

Good planning in the early design phases and close co-operation between stakeholders where ambitions, concepts, and challenges were discussed resulted in a shorter construction phase, and better transport logistics.[138] In Lia nursery school, various subcontractors were given the opportunity to give input to create an efficient and productive workflow.

The most significant emission reduction in the life cycle of infrastructure projects can be solved in the tendering phase.[139] Performing an LCA in the early design-making process phase can help evaluate and compare GHG emission reduction measures to make informed choices concerning the building envelope, technical facilities, and on-site renewable energy generation, as is discussed in[140] for example.

The greatest opportunities for contractors to influence emission-free construction sites are related to the selection of work machines and the optimisation of working methods and transport equipment. However, in some cases, contractors have limited opportunities to influence the project's environmental impact when looking at the entire life cycle of a project.[141]

Choice of construction system

The choice of construction solutions was a combination of prefabricated, locally produced, and ready-made external wall elements. By choosing prefabricated solutions, the number of journeys and use of machinery can be reduced.

Training

Training was carried out for various groups:

- Eco-driving for machine operators
- Training on key resources in respect of building/ heating/drying
- Waste training courses were held to improve knowledge of waste management and to increase the participation of subcontractors.

Building design

In Lia nursery school, prefabricated construction solutions reduced the transport of materials and personnel to the site. In Campus Evenstad, the contractor selected locally produced building materials to reduce embodied emissions related to the transport distance.[142]

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138. S. M. Fufa, M. K. Wiik, S. Mellegård, and I. Andresen, 'Lessons learnt from the design and construction strategies of two Norwegian low emission construction sites,' *IOP Conf. Ser. Earth Environ. Sci.*, vol. 352, no. 1, p. 012021, Oct. 2019, doi: 10.1088/1755-1315/352/1/012021.
139. A. Tuusjärvi, 'Ympäristövaikutusten kartoitus ja päästöjen vähentäminen infrahankkeessa,' Metropolia, Helsinki, 2021.
140. S. M. Fufa, M. K. Wiik, S. Mellegård, and I. Andresen, 'Lessons learnt from the design and construction strategies of two Norwegian low emission construction sites,' *IOP Conf. Ser. Earth Environ. Sci.*, vol. 352, no. 1, p. 012021, Oct. 2019, doi: 10.1088/1755-1315/352/1/012021.
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142. S. M. Fufa, M. K. Wiik, S. Mellegård, and I. Andresen, 'Lessons learnt from the design and construction strategies of two Norwegian low emission construction sites,' *IOP Conf. Ser. Earth Environ. Sci.*, vol. 352, no. 1, p. 012021, Oct. 2019, doi: 10.1088/1755-1315/352/1/012021.

Optimising logistics

The selection of construction materials with low embodied emissions that also meet fire safety, sound, and ventilation requirements.[143]

Seasons can be exploited to further reduce on-site energy demands. As an example, installing concrete foundations during the summer months reduces the need for thawing the ground in northern climes.

Waste

In Hoppet preschool, waste signs were produced and adapted based on the languages spoken by the various stakeholders who worked on the construction site.[144]

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143. S. Mamo Fufa, S. Mellegård, M. Kjendseth Wiik, C. Flyen, and G. Hasle, 'Utslippsfrie byggeplasser State of the art Veileder for innovative anskaffelsesprosesser,' 2018. Accessed: Aug. 03, 2022. [Online]. Available: http://hdl.handle.net/11250/2572024
144. R. Calderon, P. Löfås, and A. Larsson, 'Klimatarbete Hoppet Delrapportering 2 Byggskede,' Derome AB, Gothenburg, 2022. [Online]. Available: https://goteborg.se/wps/wcm/connect/2709251d-233c-4362-8439-1ea67a66ac7b/Klimatarbete+Hoppet-Delrapportering+Byggskede.pdf?MOD=AJPERES

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J. H. Andersen, N. L. Rasmussen, and M. W. Ryberg, 'Comparative life cycle assessment of cross laminated timber building and concrete building with special focus on biogenic carbon,' *Energy Build.*, vol. 254, p. 111604, Jan. 2022, doi: 10.1016/j.enbuild.2021.111604.

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About this publication

Emission-free Construction Sites
Definitions, boundaries, and terminology - Current status in the Nordic countries

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US2023:424
Published: 16.03.2023
Layout: Erling Lynder
Coverphoto: Anders Vestergaard Jensen/norden.org
Other photos in the publication from the authors.

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