THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Achieving net-zero carbon emissions in construction supply chains

Analysis of pathways towards decarbonization of buildings and transport infrastructure

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Achieving net-zero carbon emissions in construction supply chains -

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Abstract

Sweden has committed to achieving net-zero greenhouse gas emissions by 2045. The construction sector, which accounts for approximately 10-15% of CO_2 emissions, plays a significant role in this commitment. The sector's emissions arise from the manufacture, processing, and transport of construction materials along with activities on the construction site.

This thesis research thoroughly explores CO_2 emission reduction potentials across building and transport infrastructure construction supply chains. Employing scenario analysis, extensive literature reviews, and involving broad stakeholder participation, these studies have identified and analyzed key abatement options throughout the construction supply chain. This culminates in a detailed roadmap, delineating reduction potentials and implementation timelines with increasing ambition over 5-year time steps towards close to zero CO_2 emissions by 2045.

The results indicate that it is possible to halve CO_2 emissions associated with construction already today using currently available technologies and practices. Moreover, it is possible and feasible if all value chain actors do their parts to reach around 70% reduction by 2030 and close-to-zero emissions by 2045. Achieving these levels of reductions nationally necessitates implementation of comprehensive measures across the board, requiring extensive collaboration along the whole value chain.

Key strategies include enhancing resource efficiency and circularity measures besides adopting electrified industrial processes and heavy vehicles. Deep reductions in CO_2 emissions are possible through consideration of resource efficiency and circularity opportunities at all stages of the value chain. Optimization of structures and concrete mixes are emphasized alongside increased reuse and recycling, combined with substitutions to bio-based materials.

For heavy transport and the construction process, progressive electrification is supported by digital and automated processes, strategic machine setups, and transport and on-site logistic optimization.

Policy measures and procurement strategies should be tailored to support the aforementioned measures with a clear supply chain focus. This includes early involvement of contractors and suppliers in planning and design, facilitating balanced risk sharing. The studies also underscore the importance of avoiding pitfalls along the way, such as over-reliance on materials or solutions that cannot be scaled up to the levels required to reach deep emissions reductions on a national or international level.

The studies included in this thesis offer insights for stakeholders to accelerate the climate transition in building and transport infrastructure construction and renewal to advance towards global climate goals. At the core of this is collective efforts, embracing solutions across the supply chain, and prioritizing the climate transition in the development of the built environment.

By assessing supply chains with active involvement from value chain stakeholders and considering the time perspective, technical maturity, and scalability of emissions reduction measures, the research included in this thesis is laying the foundation for actionable roadmaps towards decarbonizing the embodied emissions of buildings and transport infrastructure.

Acknowledgements

I extend my sincerest gratitude to my supervisors, Filip Johnsson and Johan Rootzén, whose encouragement, beneficial discussions, and flexibility has allowed me to navigate through the research process with confidence. I so appreciate your ongoing support in my efforts to utilize the research to further support stakeholders in their decarbonization efforts. Thank you also for the opportunities you have given me to present my work in different forums.

I am also grateful to all the people across the construction supply chain that have provided me with invaluable insights and learnings from the 'real world'. This input really creates this research and takes it to the next level. There are too many names to mention here, but I would like to extend a special thanks to Stefan Uppenberg at WSP whom I have had the privilege of collaborating with since the outset of this thesis research. Your wealth of knowledge and willingness to share it is truly remarkable.

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My deepest appreciation goes to my family and friends around the world. A heartfelt thank you to my dear friends Sophie, Linda, and Minna for your unwavering support. Your friendship has been a constant source of strength and inspiration.

To my parents, I am profoundly grateful for your never-ending support and love. Your constant presence and encouragement are a continued pillar of strength for me.

To Stefan, I am blessed to have you in my life. Your optimism, patience and calm demeanor is a grounding force during challenging times. We sure have not made an easy life choice, but it is anything but boring. I am thrilled about the journey we are on, and I look forward to future adventures together. You have a remarkable talent for turning dreams into reality, and I am lucky to have you by my side.

And to my dear children, you are my sunshine. Your presence fills me with joy and continuously renewed purpose. Everything I do is for you and your future. I promise to remain working tirelessly to create a better, cleaner, and brighter world for you all.

List of publications

The thesis is based on the following appended papers, which are referred to in the text by their Roman numerals:

I. Karlsson, I., Rootzén, J., and Johnsson, F., "Reaching net-zero carbon emissions in construction supply chains – Analysis of a Swedish road construction project," *Renew. Sustain. Energy Rev.*, vol. 120, 2020, https://doi.org/10.1016/j.rser.2019.109651.

II. Karlsson, I., Rootzén, J., Toktarova, A., Odenberger, M., Johnsson, F., and Göransson, L., "Roadmap for Decarbonization of the Building and Construction Industry—A Supply Chain Analysis Including Primary Production of Steel and Cement," *Energies*, Aug. 2020, https://doi.org/10.3390/en13164136.

III. Karlsson, I., Rootzén, J., Johnsson, F., Erlandsson, M., "Achieving net-zero carbon emissions in construction supply chains – multi-dimensional analysis of residential building systems", *Developments in the Built Environment*, Volume 8, 2021, https://doi.org/10.1016/j.dibe.2021.100059.

IV. Karlsson, I. Rootzén, J., Johnsson, F., Uppenberg, S., "Accelerating Carbon Reduction in Transport Infrastructure Construction: Synthesis of Project-level Mitigation Strategies", Submitted for publication in *Renewable and Sustainable Energy Reviews.*

V. Karlsson, I. Rootzén, J., Johnsson, F., "Decarbonizing Transport Infrastructure: A Supply Chain Action Plan towards Net-zero Emissions", To be submitted.

Ida Karlsson is the principal author of Papers I–V and conducted the literature reviews, the modeling, calculations and writing of these papers. Professor Filip Johnsson, who is the main academic supervisor, together with co-supervisor Johan Rootzén, contributed with discussions and the editing of all five papers. Alla Toktarova, Mikael Odenberger and Lisa Göransson contributed with reviewing and discussions as part of the refining of Paper II. Martin Erlandsson contributed data and review of Paper III. Stefan Uppenberg contributed inspiration and material to, and review of, Paper IV and V.

Related publications

VI. Karlsson, I., Toktarova, A., Rootzén, J., and Odenberger, M., "Mistra Carbon Exit Technical Roadmap - Buildings and Transport Infrastructure," 2020. https://www.mistracarbonexit.com/news/2020/5/19/technical-roadmap-buildings-and-transport-infrastructure.

VII. Karlsson, I., Toktarova, A., Rootzén, J., and Odenberger, M., "Mistra Carbon Exit Technical Roadmap - Cement Industry," 2020. https://www.mistracarbonexit.com/news/2020/5/19/technical-roadmap-cement-industry.

VIII. Toktarova, A., Karlsson, I., Rootzén, J., and Odenberger, M., "Mistra Carbon Exit Technical Roadmap - Steel Industry," 2020. https://www.mistracarbonexit.com/news/2020/5/19/technical-roadmap-steel-industry.

IX. Johnsson, F., Karlsson, I., Rootzén, J., Ahlbäck, A., and Gustavsson, M., "The framing of a sustainable development goals assessment in decarbonizing the construction industry – Avoiding 'Greenwashing,'" *Renew. Sustain. Energy Rev.*, vol. 131, no. July, 2020. https://doi.10.1016/j.rser.2020.110029.

X. Toktarova, A., Karlsson, I., Rootzén, J., Göransson, L., Odenberger, M., & Johnsson, F.. "Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study", *Energies*, 13(15), 3840 2020. https://doi.org/10.3390/en13153840.

XI. Morfeldt, J., Larsson, J., Andersson, D., Johansson, D., Rootzén, J., Hult, C., and Karlsson, I. "Emission pathways and mitigation options for achieving consumption-based climate targets in Sweden". *Commun Earth Environ* 4, 342, 2023. https://doi.org/10.1038/s43247-023-01012-z.

Contents

1 Introduction

1.1 Emissions associated with buildings and transport infrastructure

The climate emergency demands immediate and urgent action to accelerate the transformation towards achieving net-zero CO_2 emissions by 2050 and negative emissions thereafter [1]. The built environment sector holds a crucial role in addressing this crisis, as the construction, maintenance, renewal, and operations of built structures account for approximately 40% of global CO_2 emissions, with construction alone contributing around 13% [2]. Despite the need to halve building and infrastructure emissions by 2030 to align with climate targets, implying an 8% reduction per year starting from 2020 [3], global emissions from the sector have remained constant over the past 5 years [4]. This underscores the significant gap between the current state and the necessary decarbonization trajectory [5].

1.2 Operational versus embodied emissions – Current status and future development

Until now, policy initiatives and progress within the building and transport infrastructure sector have primarily targeted CO_2 emissions generated from the operations of built assets - specifically, heating, cooling, and lighting [6–8]. This focus is substantiated by the significant contribution of energy use in building to global and European Union (EU) emissions, as depicted in Figure 1.

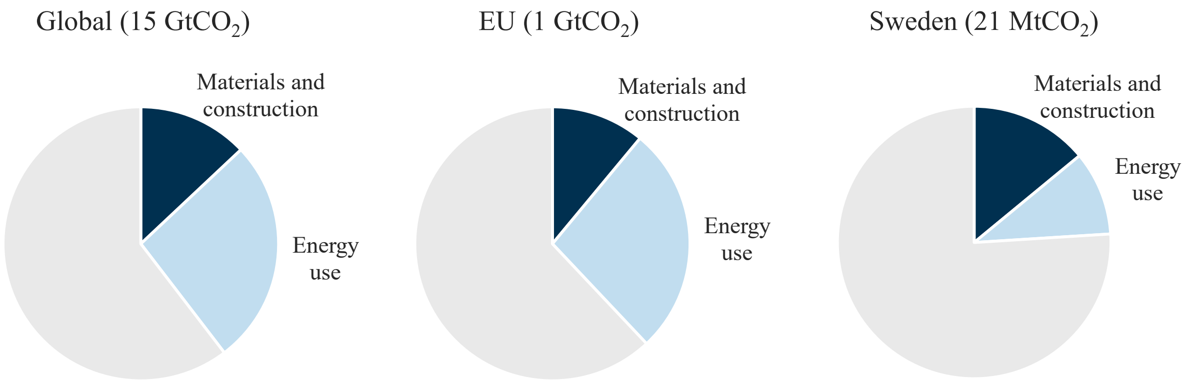


Figure 1. Comparison of global, EU, and Swedish CO_2 emissions from buildings and transportation infrastructure. Global data for 2022 [2, 9], and data from the EU [10–12], and Sweden [13, 14] for 2021. Swedish data represents consumption-based emissions, with a similar share for territorial emissions (12 Mt CO_2). Estimates are used for EU transport infrastructure emissions due to data unavailability.

Across various countries, there is a notable increase in minimum performance standards and building energy codes. Moreover, there is a growing adoption of more energy-efficient building technologies and renewable energy sources for electricity and heating [4]. Between 1990 and 2018, efficiency enhancements and the wider utilization of renewables have led to a 29% reduction in CO_2 emissions from residential buildings in the EU during their use phase [15]. Concurrently, the proportion of operational emissions over the life cycle of new constructions is declining [16–22].

This trend is exemplified at the national level by Sweden, where operational emissions have been cut by two-thirds since the 1990s (see Figure 2). The decrease is attributed to stringent energy efficiency mandates and the shift from individual oil heaters to heat pumps and bio- and waste-based district heating systems [13].

The transport sector is witnessing the initial stages of parallel advancements, with a significant focus on reducing operational carbon emissions. This is evident in the expansion of public transportation, implementation of vehicle efficiency standards, imposition of fuel taxes, investment in alternative fuels, transition to electric vehicles, and the integration of smart transportation systems [23–26]. While this has not yet altered the curve of transport carbon emissions, there are indications that it could do so by 2030 [27].

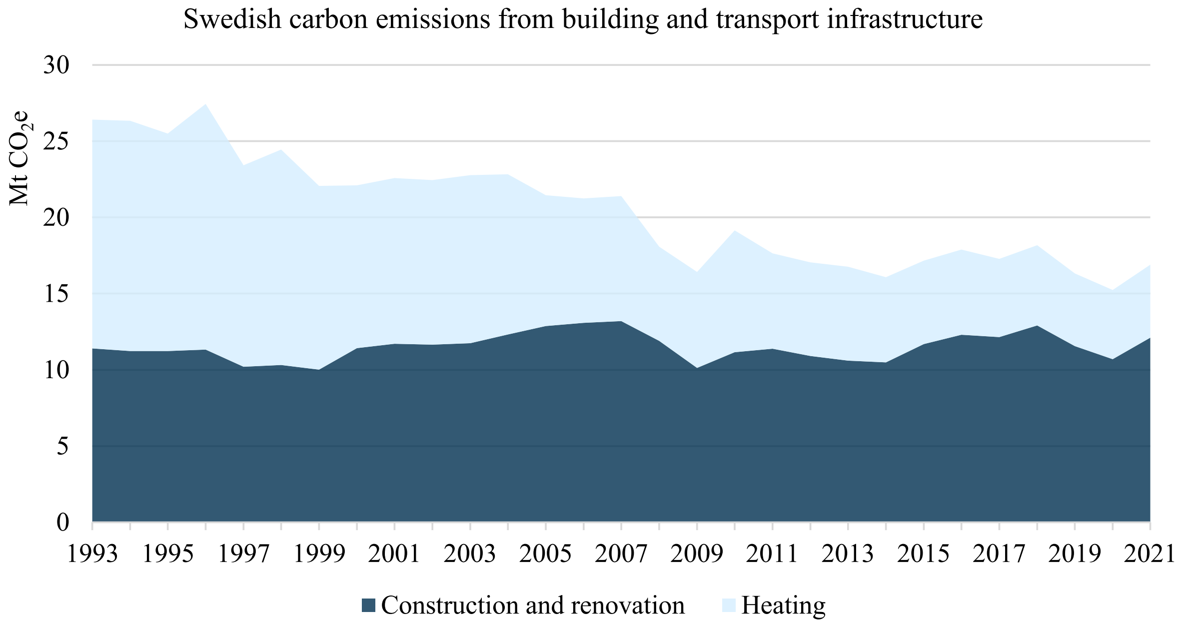


Figure 2. Comparison of development of the greenhouse gas emissions associated with construction and refurbishment of buildings and infrastructure and heating of buildings. Adapted from the 2024 environmental indicator reporting by The Swedish National Board of Housing, Building and Planning [13]. Note that the graph does not include emissions associated with other operational activities and maintenance, for which there is no separate historic data available from 1993-2008.

However, solutions aimed at mitigating the "embodied" CO_2 emissions of buildings and infrastructure — those emitted during manufacturing, transportation, construction, and end-of-life phases of built assets — have fallen behind [8]. Several studies suggest that if the current trend persists, the share of emissions related to embodied emissions from transportation and buildings could double compared to operational emissions in the coming decades [8, 28].

The global development appears to be trending towards a scenario akin to the current situation in Sweden, where embodied emissions have become the dominant factor in the impacts stemming from the built environment, as seen in Figure 2.

Simultaneously, there is a rapid expansion of global floor area, particularly notable in developing countries [4]. In the EU, the increase in floor area per capita has offset half of the emissions reductions achievable through the enhanced energy efficiency and renewable energy adoption [15]. Projections also indicate that to 2050, half of the global buildings and urban infrastructure are yet to be built [28–30].

Additionally, to align with a net-zero scenario, it is essential to retrofit 2.5% of the existing building stock annually [31], compared to the current rate of 1% [31]. Moreover, substantial investments in upgraded infrastructure are crucial to establish an efficient and low-carbon transport system [32, 33].

Besides, considering budgetary limitations related to greenhouse gas (GHG) emissions, embodied emissions are particularly relevant as they predominantly occur upfront, and remain "locked in" over the lifetime of the built asset [6].

1.3 Research context and aims

From the above it is clear that there is an urgent need to reevaluate our approach to building and utilizing the built environment. The most effective means of reducing embodied carbon is through prevention. This entails exploring alternative strategies to achieve desired functions, such as, where possible, maximizing the use of existing assets [28, 34]. By averting new construction, potential embodied GHG emissions are eliminated. Therefore, the initial step should involve proactive efforts in all planning processes and collaboration among stakeholders to avoid new construction whenever feasible. If new construction is unavoidable, prioritizing the reuse of available existing assets should be pursued.

While further work is required regarding planning measures [15, 35], this research focuses on scenarios where new construction or refurbishments is deemed necessary. To meet climate targets, it is crucial to outline how emission reduction measures can be allocated leading up to mid-century. This involves identifying measures applicable in the present and those requiring longer lead times for implementation [36]. The emphasis of this thesis is accordingly on the opportunities and challenges of achieving net-zero carbon emissions from construction and its supply chains within the next two to three decades.

The research novelty lies in: i) assessing supply chains with active involvement from value chain stakeholders; ii) considering the time perspective, technical maturity, and scalability of emissions reduction measures; iii) integrating outcomes and empirical data from practical implementations; and iv) laying the foundation for actionable roadmaps towards decarbonizing the embodied emissions of buildings and transport infrastructure.

The research included in this thesis introduces an original approach to explore avenues for advancing the climate transition in the building and infrastructure sector. It focuses on identifying opportunities and barriers for reducing carbon emissions across industry supply chains, spanning from raw material inputs to final products and services demanded by end-users [37, 38]. This approach is particularly relevant given the construction sector's intricate and multi-tiered supply base. Companies within this sector operate within fragmented supply networks, posing significant challenges in adopting a comprehensive lifecycle approach to construction and realizing shared goals [39].

Integrating upstream segments of the construction supply chain, including subcontractors, suppliers, and manufacturers, has been identified as crucial for delivering sustainable built structures [40].

Furthermore, employing a supply chain perspective enables a broader examination of both opportunities and barriers, as these often manifest within the interconnections between economic sectors and individual stakeholders [41].

The research has incorporated extensive stakeholder participation from across the value chain [42], as illustrated in Figure 3. This inclusive approach aims to co-develop solutions by leveraging the diverse, in-depth, and practical expertise of stakeholders.

It facilitates the collaborative and iterative production of knowledge, roadmaps, and action plans. Importantly, these outputs are created with, by, and for those individuals and entities best positioned to utilize them effectively [43, 44].

Figure 3. Main value chain actors involved in the participatory process of the thesis research.

The primary focus of the research has been collaborative mapping of emissions reduction measures and their potential across the construction supply chain. This has involved identifying barriers and enablers for implementation, supported by evidence from practical case studies. Additionally, the research has assessed how mitigation measures can be allocated, their potential for scaling up, and feasible timelines for enhanced implementation over time.

When the research commenced, existing literature had identified specific hot spots for CO_2 emissions in construction, particularly at the project level [16–18, 45–51]. However, national-level estimates remained highly uncertain. Therefore, research included in this thesis prioritized efforts to enhance and validate current estimates of the climate impact from building and infrastructure construction processes in Sweden. This endeavor involved combining material and energy flow analysis with a comprehensive literature review.

Studies focusing on current and future CO_2 emissions reduction options are increasingly prevalent in literature, with a growing body of research dedicated to individual sectors. For instance, there are studies examining emissions reduction strategies for steel [52–56], cement/concrete [57–59] and heavy transport and construction equipment [60–64]. Cross-sectoral analyses, particularly in the gray literature, offer syntheses of perspectives from various industries [65–69]. However, studies providing a comprehensive view of abatement options along the entire construction supply chain are limited [70, 71]. Recent developments include emerging evidence of cross-sectoral perspectives that consider measures across the entire supply chain for building construction [8, 72–74] and along with comprehensive reviews [75, 76]).

Nonetheless, there remains a lack of research that conducts detailed reviews across the various relevant material and activity categories linked with building and infrastructure construction, while also considering the time perspective of when and to what extent different emissions reduction measures are expected to be available for large-scale implementation. This is one of the unique features of the research included in this thesis, which has evolved to be more inclusive, integrative, experience-based, and holistic over the course of the research.

The initial assessments conducted in this research provide an in-depth analysis of supply-side measures related to material production and heavy vehicle technologies [77–79]. These assessments are updated continuously and enhanced to align with technical progress in various sectors, such as the electrification of heavy vehicles and the use of bio-binders in asphalt.

Throughout the thesis work, there has been a progression towards integrating more detailed analysis of demand-side measures linked to structures and their design. This includes exploring various types of circularity and material efficiency measures, such as structural optimization, element reuse, and improved site logistics.

It is acknowledged that technological advancements alone will not suffice to achieve the goals of the Paris Agreement [80, 81]. Therefore, interdisciplinary collaboration is essential for the rapid and large-scale implementation of holistic emissions reduction pathways [80, 82]. As a result, the research has evolved to involve collaborative identification, utilization, and synthesis of practical experiences.

The research is grounded in comprehensive knowledge and empirical data acquired through multiple channels. This includes insights from stakeholders across the value chain, gathered via a collaborative platform established within the interdisciplinary Mistra Carbon Exit (MCE) research program. Additionally, literature reviews encompassing academic and gray literature have been conducted. Practical experiences have been directly obtained from stakeholders or through involvement in industry research and innovation projects and platforms. By synthesizing information from these diverse sources, the research endeavors to compile a holistic and contemporary understanding CO_2 emissions reduction measures relevant to the construction and renewal of building and transport infrastructure.

Furthermore, despite the demonstrated potential to halve CO_2 emissions in both buildings and transport infrastructure construction [83–89], current best-available technologies are often underutilized [90–93]. Barriers at the project level, such as technical maturity and financial constraints, impede successful implementation [94–96]. Collaborative efforts are essential to overcome these obstacles.

As a result, the current focus of the research is moving even closer to implementation. This involves collaborating with stakeholders to integrate the knowledge developed throughout the thesis research into existing strategies, processes, tools, and templates. The aim is to expedite the implementation of identified reduction measures and accelerate progress towards emission reduction goals.

The primary focus of this work is on the Swedish context, which is considered apt given the country's evolving emphasis from operational to embodied emissions reductions. Moreover, Sweden has set ambitious climate targets, aiming for net-zero emissions by 2045 [97], alongside large-scale renewal initiatives in building and transport infrastructure [98, 99], and a collaborative approach to the climate transition [100]. As such, results from investigating Swedish conditions may provide valuable insights for other countries on how to tackle embodied emissions.

The analyses of abatement options, timelines and pathways in this thesis are expected to hold general relevance and applicability, particularly at the European level [28, 72]. Similarly, many challenges outlined in this research, essential for achieving a transition to zero-CO_2 production, and the practices applied in building and infrastructure supply chains, are universal [6, 29, 30].

1.4 Outline of the thesis

This thesis comprises five papers (referred to as Papers I–V) and an introductory essay. The introductory essay primarily highlights developments that have transpired throughout the research, in addition to those described in the appended papers. These developments encompass both research findings and contextual changes. Section 1 provides background information on the work and situates the appended papers within a broader setting. Section 2 offers an overview of the overall concepts and research methodology applied in the thesis work. To provide a comprehensive perspective, Section 3 detail technical and other developments linked to decarbonization across the construction value chain. This digest sets the stage for summarizing research results and progress in Section 4. Following this, Section 5 details developments related to the research moving towards efforts to accelerate implementation. Finally, the thesis will discuss a few central aspects moving forward in Section 6, before concluding with ideas for future research in Section 7.

2 Material and methods

The work presented in this thesis has co-developed knowledge with stakeholders via participatory integrated assessments. This approach involves systematically involving key stakeholders in developing theoretically coherent and practicable decarbonization strategies [101, 102]. Quantitative analysis methods, including scenarios and stylized models, are integrated with participation via continuous dialogue, meetings and workshops that involve relevant stakeholders in the assessment process. The quantitative analysis uses spreadsheet-based models to track material flows and CO_2 emission in an individual project or in the sector/supply chain. The participatory process aids in identifying main abatement options and adjusting decisions and assumptions regarding abatement portfolios and timelines to make them as realistic and feasible as possible.

Stakeholders, including industry representatives, experts along the supply chain, material suppliers, contractors, consultants, clients, and governmental agencies, provide input and feedback throughout the research. The overall method and workflow of the thesis work are depicted in Figure 4.

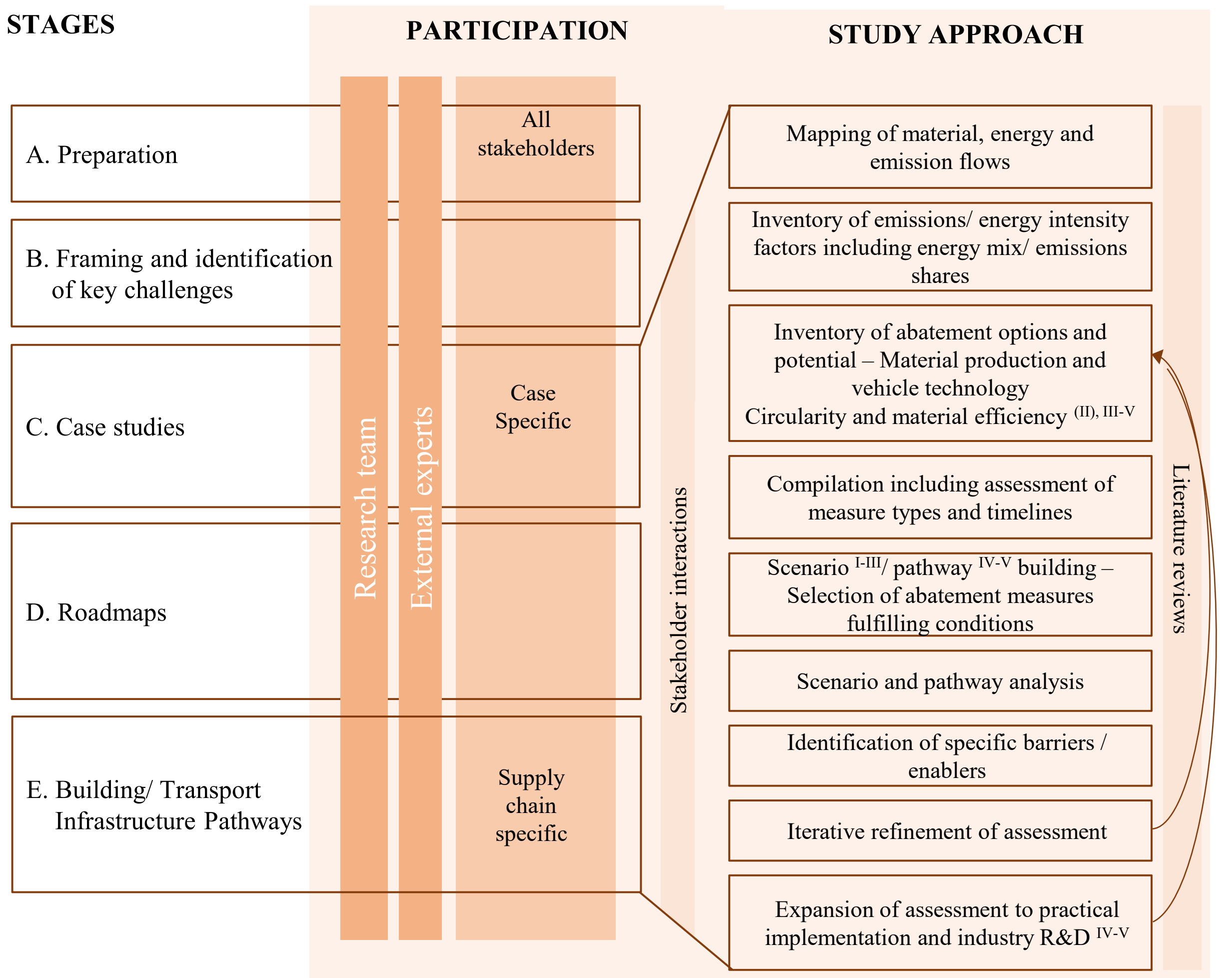


Figure 4. Outline of the overall methodological approach and research workflow. In the study approach, the superscript letters indicate attributes or activities only performed in some of the research studies, where the specific studies are indicated by its number (refer to the List of publications or Figure 5).

In the preparation stage (Stage A), the research team defined the initial scope of the assessment and engaged stakeholders. Framing with stakeholders (Stage B) implied a high-level classification of the challenges and potential solutions associated with the low-carbon transition in the construction sector, together with identification of suitable benchmark cases. The outcomes from the two first stages are detailed in a conference paper presented by Rootzén and Johnsson in 2018 [103]. The studies in stages C-E, has so far resulted in the five appended papers (see Figure 5).

This thesis refers to both supply chains and value chains. In this research context, the supply chain is the network of entities that source raw materials and transform them into finished assets. The value chain refers to creating or adding value to the end product at every step, from conception through to delivery. As such, it also includes for example planning entities, financial providers, third-party institutions, and governmental authorities.

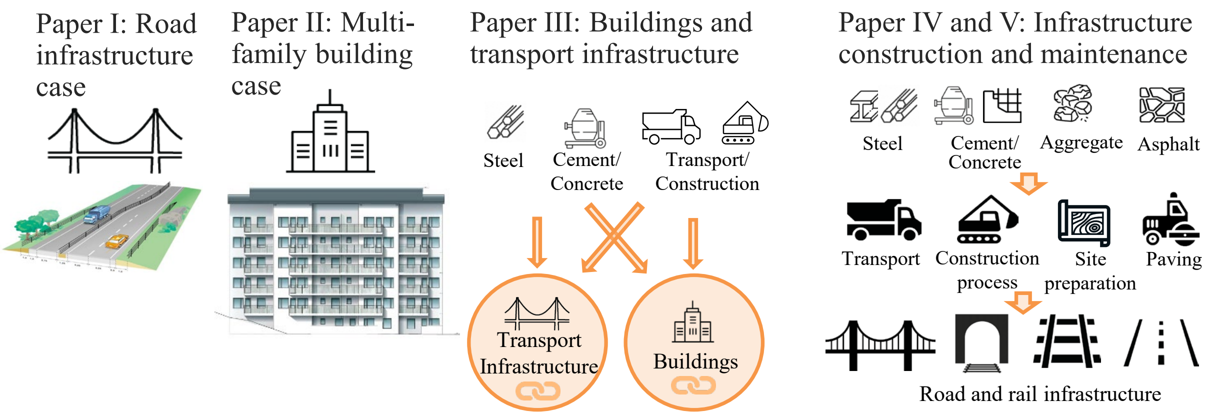


Figure 5. Illustration of the study objects for the five studies included in the thesis.

The five papers all apply the same basic methodological approach, which integrates analyses of material and emissions flows with the identification and analysis of potential CO_2 abatement options relevant to the respective construction supply chains. The latter are informed by inputs from supply chain stakeholders and comprehensive literature reviews, encompassing estimates of abatement potential and expected implementation timelines.

The literature reviews draw from a wide range of academic and gray literature, including industry decarbonization roadmaps, company plans, and findings from case studies and industry research and development projects (see Figure 6). This includes evidence from practical experiences obtained directly from stakeholders or via industry research and innovation projects and platforms.

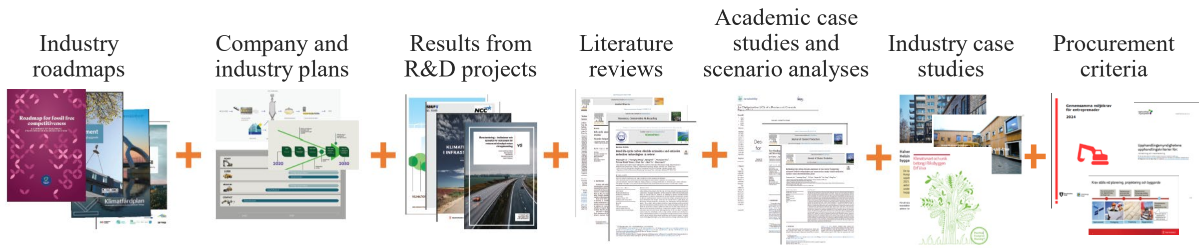


Figure 6. Examples of the types of academic and gray literature included in the literature reviews conducted as part of the research.

The primary research question addressed in these papers concerns the potential reduction in CO_2 emissions across different timeframes through the combination of identified abatement technologies along the supply chain. This question is answered by evaluating potential implementation timelines associated with the technical maturity of the abatement technologies and the expected extent of their implementation.

The case studies conducted in stage C, as illustrated in Figure 4, analyze road construction and multi-family buildings, as reported in **Papers I** and **III**, respectively. The benchmark material and emissions accounts utilized in these analyses have a comprehensive scope. For example, the building case study encompasses all materials and components down to the "bolts and nuts" level, while all on-site energy usage is included and based on actual data from construction companies, except for groundwork or soil stabilization.

The outcomes from the case studies serve as inputs to the development of decarbonization roadmaps (Stage D), which are produced for the Swedish cement and steel industries, in addition to the roadmap for the supply chains of buildings and infrastructure, as reported in **Paper II**.

These papers also provide scenario analyses exploring parameters that influence strategic considerations, including structural optimization via supply chain collaboration (Paper III), access to biofuels (Paper I) and enactment of transformative measures, such as electrification and carbon capture (Paper I and II). Key barriers and enables towards the implementation of the identified abetment measures are defined and detailed in all three papers. Additionally, associated technical reports [77–79] to the national roadmap in Paper II contain more detailed assessments of pathway choices, along with barriers, risks, and enablers. In the context of this thesis research, a scenario involves exploring abatement portfolios by testing certain parameters, while a pathway refers to an abatement portfolio comprised of emission reduction measures assessed as the most feasible for implementation in specific industry sectors.

The first two papers provide detailed analysis predominantly on supply-side abatement options that involve changes in energy supply, production technologies and deployment of carbon dioxide-removal technologies while maintaining end-user demand unchanged. The studies in **Paper III-V** build further on these analyses, complementing this approach with analyses of demand-side solutions linked to the design and structure of the built assets.

Demand-side solutions are generally categorized into three groups: Avoid, Shift, and Improve [104]. The distinction between these categories varies depending on whether the perspective is on products and the material industry or on built assets. The perspective of built assets is primarily relevant for the construction supply chain, as exemplified in Figure 7.

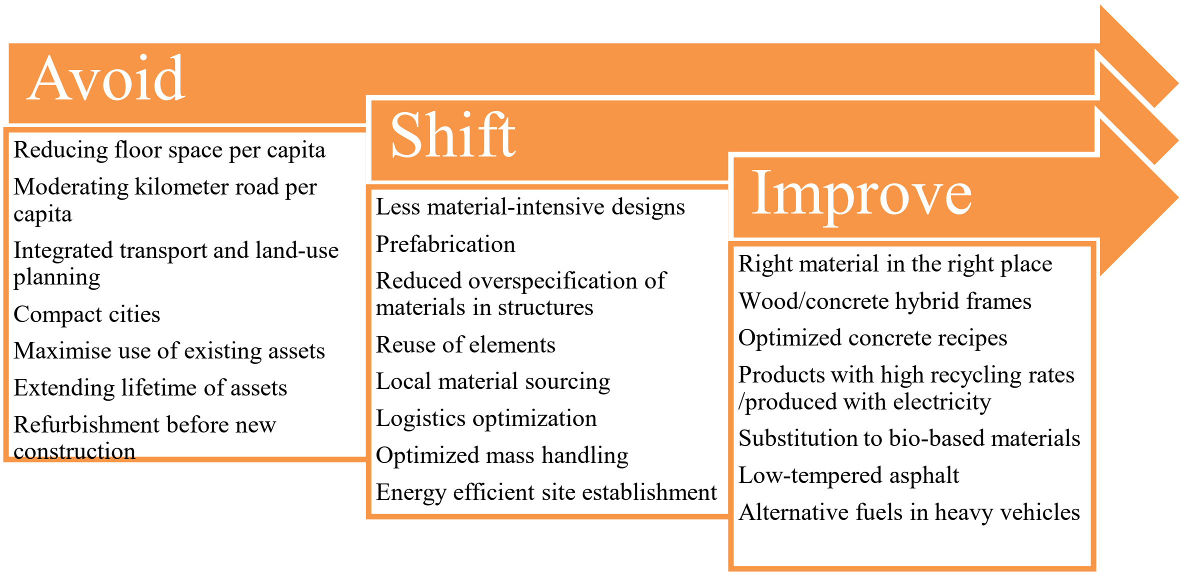


Figure 7. Simple analytical framework for demand-side carbon mitigation options with examples for built assets based on Creutzig *et al* [104] and results from literature reviews performed within this thesis research.

'Avoid' denote mitigation options that reduce unnecessary consumption. In the context of built assets, 'avoid' measures implies sufficiency and planning measures. The planning measures of the 'avoid' categories are explored briefly in Paper V, while the primary focus of the research included in this thesis has been in the 'Shift' and 'Improve' categories. The 'Shift' category involves transitioning to available competitive low-carbon technologies and service-provisioning systems, incorporating optimization and material efficiency measures [15, 35]. On the other hand, 'Improve' refers to enhancing efficiency in existing technologies, where adoption by end users is crucial. The research in Papers III-V delves into the 'Shift' and 'Improve' measures in detail.

Simplified schematics of the calculations performed in the material and emissions flow analysis, and the buildup of mitigation measure portfolios applied in the research, are illustrated in illustrated in Figure 8 and Figure 9, respectively. Developments in the background systems can impact emission factors, particularly when electricity or district heating is utilized, whether in material production, transportation, or the construction process. When feasible, the emissions intensity factors are divided into components, to enable assessments of different mitigation measures.

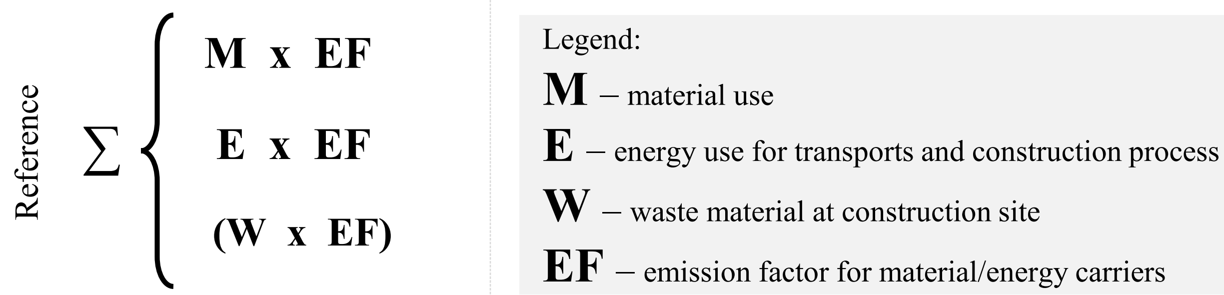


Figure 8. Simplified schematic of the calculations of embodied CO_2 emissions. The parameters include material use in unit of material for all the materials included in each specific study (M), energy use for transport and the construction process per energy carrier (E), material waste at the construction site (W), and the emission factor per unit for each material and energy carrier included in the analysis (EF).

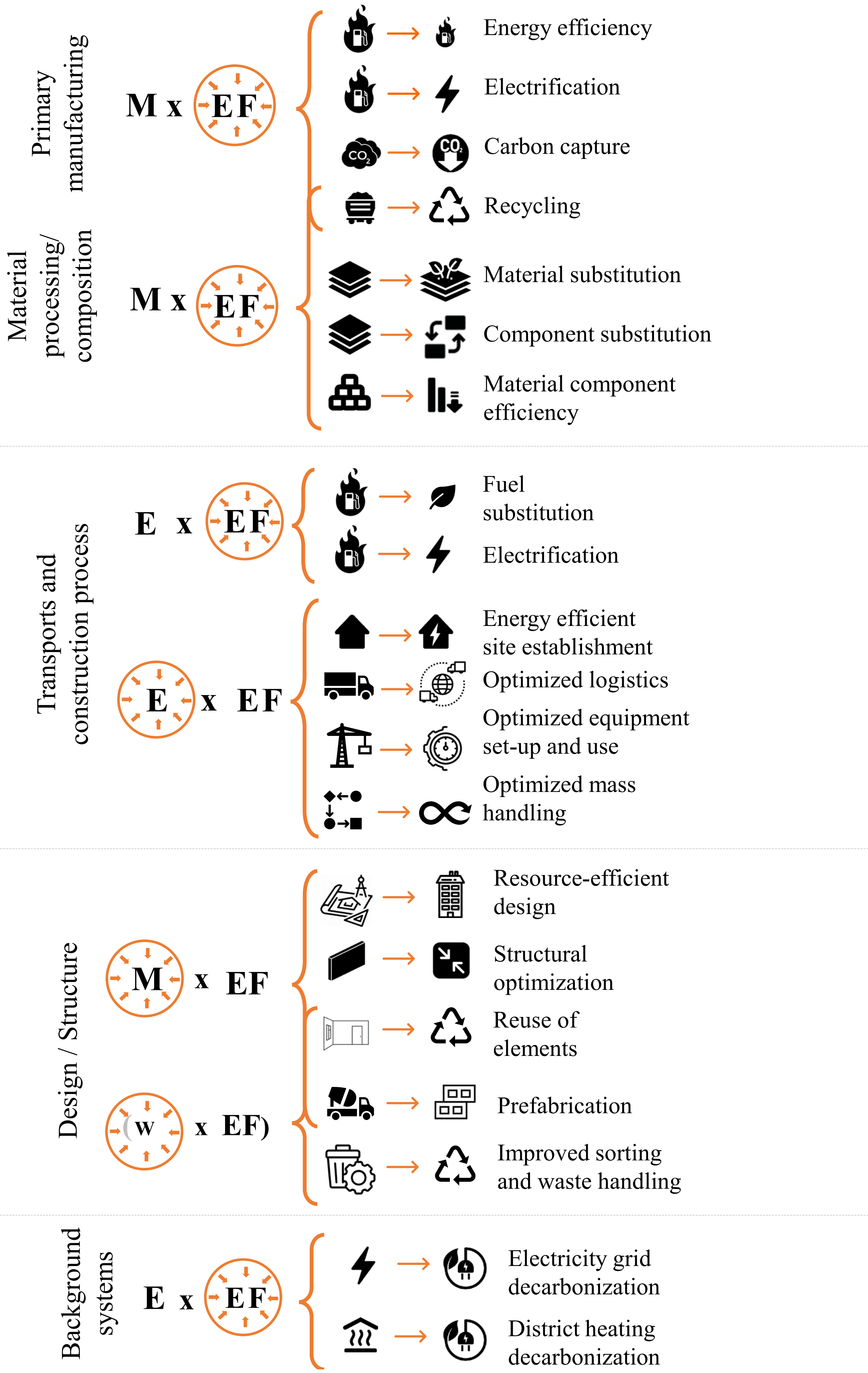


Figure 9. Simplified schematic of impacts on the calculation parameters in Figure 8 from the compositions of different mitigation measure portfolios along the supply chain. The orange circles denote parameters impacted by the specific mitigation measures.

The demand-side measures explored in Papers II-IV are material efficiency and optimization measures that restrict the material and energy use along the construction supply chains.

A combination of scenarios developed in the national roadmap has been chosen for further pathway development, deemed the most feasible future technical orientations for the individual sectors assessed. This involves a focus on electrification for most material production and heavy vehicles, complemented by an emphasis on biofuel substitution with carbon capture for cement clinker production.

The resulting pathways for the construction and renewal of buildings and transport infrastructure, respectively, have been continually refined based on new insights into technical advancements, roadmaps, strategies, plans, successful applications, and achieved emissions reductions.

The refinement and update process has revealed that certain categories, such as asphalt production and heavy transports, have experienced faster development and/or implementation of emissions reduction measures than anticipated in 2020, while forecasts for other categories remain unchanged. Additionally, the pathways have been augmented with more detailed analysis for additional material and activity categories, as well as with the inclusion of new abatement measures.

The pathway for buildings is a work in progress, with some of the results presented in this thesis. For transport infrastructure, knowledge gained from practical experiences by actors within and beyond the MCE program has been synthesized with a comprehensive literature review in Papers IV and V. These papers focus on actionable project-specific carbon reduction measures, i.e., measures and requirements within a project's domain of influence. The emphasis on practical implementation and applied knowledge aims to bridge the gap between achievable emissions reductions and current implementation. The study employed an integrative review method [105, 106] to identify carbon emissions reduction measures applicable within the project's influence, with potential to be upscaled and strengthened over time towards zero or close-to-zero CO_2 emissions.

2.1 Scope and limitations of the research

The primary focus of this work is on GHG emissions from materials production, transport, and the construction process up to the completion of a new construction or major refurbishment [7], encompassing lifecycle stages A1–A5 and B5 in the European lifecycle assessment standard, EN 15978:2011 [28], as illustrated in Figure 9. [107]

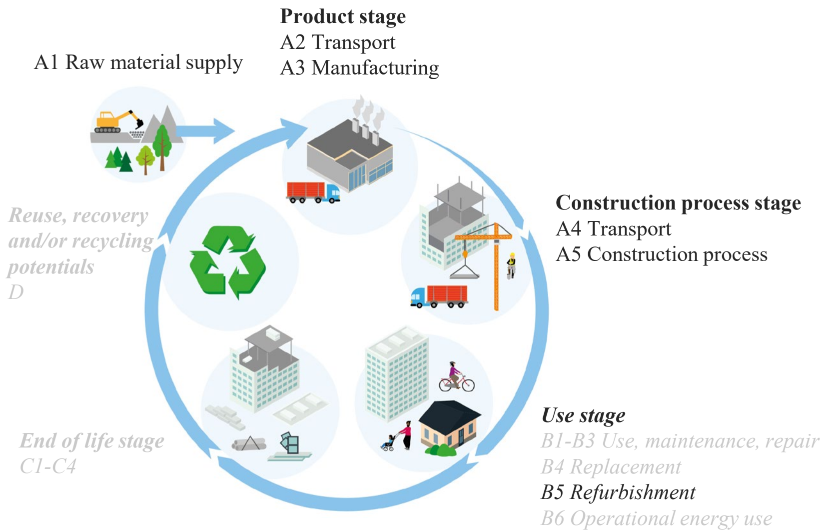


Figure 10. Depiction of the lifecycle stages of built assets according to the European lifecycle standard. The lifecycle stages in black are within the scope of the research, i.e. A1-A5 plus B5, where the latter is included only in the national assessments. Adapted from Boverket Climate Declaration Handbook [107].

Although embodied emissions occur during other life cycle stages, a recent European review study found that approximately two-thirds of the embodied emissions of buildings are emitted upfront during lifecycle stages A1-A5 [108]. This emphasizes the need to prioritize reduction efforts on upfront carbon emissions rather than future end-of-life scenarios.

The national assessments in Papers II, IV, and V include refurbishment components, while the case studies on building and road infrastructure (Papers I and III) primarily address new construction. In literature, terms such as renewal, renovation, or maintenance are sometimes used interchangeably with refurbishment. For the purposes of this research, refurbishment or renewal refers to significant technical or functional alterations to a built asset beyond routine maintenance or predictable repairs. These modifications may also fall within modules A1 to A5 if they are not initially considered in a life-cycle assessment (LCA).

Biogenic carbon is evaluated as carbon neutral in this research, aligning with common practice in LCAs. However, this approach tends to underestimate the benefits of storing carbon in long-lived products while overestimating the benefits of short-lived products, such as biofuels incinerated shortly after harvest [109–112]. To qualify as a temporary carbon sink, a stable carbon pool in the forests from which the products are harvested is necessary, which has not been the case in Swedish forests over the last 10 years [113]. The assumption of carbon sequestration in the forest occurring before or after material manufacturing also impacts the results [114]. Therefore, temporary carbon sequestration has not been included in this thesis work.

The assessment of mitigation measures has been broadened throughout the research to cover a wider range of materials and activities. The most updated national pathways developed within this thesis work, includes assessment for the components depicted in Figure 15.

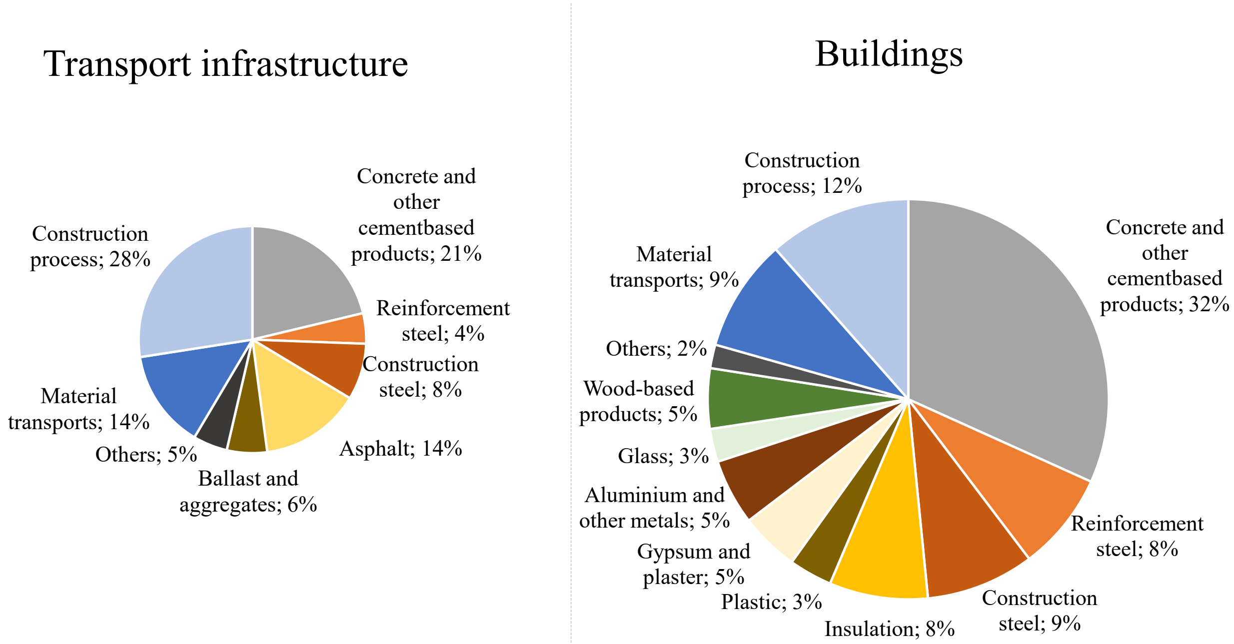


Figure 11. Components of the annual embodied greenhouse gas emissions associated with the construction and renewal of buildings and transport infrastructure in Sweden. The size of the respective pie charts reflects the relative magnitude of emissions. Adapted and updated from Paper II.

For buildings, the primary focus lies on the foundation, building structure, and building envelope, encompassing materials like concrete, metals, insulation, gypsum, and glass. Analysis of installations and piping is limited to main incorporated materials such as steel and plastic, while interior fittings and furnishings are excluded from the mitigation analysis.

In the case of transport infrastructure, attention is directed towards site preparation, substructures, bridges, tunnel structures, and superstructures like asphalt paving and railway tracks. This category also encompasses urban development, associated site preparation, and local transport infrastructure construction and renewal. Groundwork for buildings falls within a gray area between buildings and civil engineering, with some of its impacts potentially allocated to the construction process of transport infrastructure.

The national assessment outlined in Paper II utilizes 2015 as its reference year, covering material and energy usage along with emission factors applied to materials and energy carriers. It assumes a consistent level of construction and renovation activity through 2045. However, this assumption carries uncertainty, as various sources present divergent forecasts regarding the development of demand for building and transport infrastructure construction and renewal [115–119]. Economic progress stands as a pivotal factor influencing demand. Consequently, the national assessment detailed in Paper II is supplemented with a sensitivity analysis, exploring the potential impact of reductions or increases in construction demand.

There are evidently numerous carbon emissions mitigation measures available or under development linked to the construction supply chain. This thesis research does not intend, or see the feasibility, to be all-encompassing regarding both current and possible future mitigation measures.

Based on comprehensive literature reviews and stakeholder input, the aim is to further explore emissions reduction measures identified as having significant potential for upscaling and widespread use, with the potential to be strengthened over time, thus contributing towards zero or close-to-zero GHG emissions. The assessment encompasses various material substitutions, and where such substitutions are made for structural materials, it also implies additional use of plasterboards for fireproofing. In the context of renovation, the research assesses material production and substitutions, but does not encompass measures such as alternative renovation strategies.

As mentioned previously, the assessment does not encompass sufficiency measures and only briefly touches upon planning measures, such as those that limit the need for construction by exploring alternatives or maximizing the use of existing assets. These aspects are proposed to be explored in future research.

The assessment uses a transition of the energy system as a background system. The research thus considers decreasing emission factors for electricity and district heating over time. Future emission factors are based on data and analysis from Morfeldt *et al* [81], the Swedish Energy Agency [120] and estimates made by the European Energy Agency [121] (before the revised EU-ETS target of net-zero by 2040 [122]), suggesting that GHG emissions related to electricity generation in the EU will reach zero by 2050.

3 Developments across the construction value chain

Since the inception of this thesis research in 2018, the construction sector has made concerted efforts to address embodied carbon emissions within the supply chain. The ongoing participatory process throughout the research has gathered extensive insights into developments taking place across the construction value chain since the beginning of the MCE research program. These developments span both the buildings and transport infrastructure value chains, with some developments specific to each respective chain. Figure 11 aims to encapsulate the insights garnered throughout the thesis research concerning the construction value chains in general. Additionally, Figure 12 gives a snapshot of anticipated developments. Alongside the insights acquired for the individual building and transport construction value chains, as delineated in Figure 13 and Figure 14, respectively, these summaries provide a contextual backdrop for the subsequent section on research progress.

General value chain

2018

- Identified hotspots: Concrete, steel, and diesel use.
- Overspecification of materials and limited alternative binder usage.
- Electrification of heavy vehicles perceived as unfeasible
- Full scale fossil-free steel expected by 2035-2040.
- Pilot projects testing innovative solutions.
- Goal setting and analysis of barriers.
- Climate mitigation efforts a priority mainly for environmental manages/specialists.
- Collaboration in the construction supply chain to create a national roadmap.
- Establishment of local and regional carbon reduction networks.
- Early experience sharing and knowledge building.

2024

- Knowledge of key abatement measures and the need for early integration
- Sector roadmap with commitments for supply chain actors.
- Local and regional initiatives driving developments.
- Fast development for electrification of heavy vehicles.
- Large-scale tests of electrified construction equipment.
- Commercial fossil-free steel production planned for 2026.
- First cement clinker manufacturing plant with carbon capture online in Norway.
- Mainstream adoption of concrete with at least 10-20% alternative binders.
- Products with high recycling rates and initiatives promoting reuse.
- Projects demonstrating 50% reduction → first mover client requirements.
- Involvement of additional and new roles.
- Overall sector emissions remain unchanged, but decreasing emissions intensity compared to production value.
- Lack of detailed data for monitoring sector development.
- General skills shortage on climate impact reduction.
- Lack of upscaling across project portfolios.
- Climate goals not linked to wider business arrangements.

Figure 12. Sector and context developments linked to the Swedish construction value chain.

Initially, the construction industry pinpointed hotspots like concrete, steel, and diesel use for carbon emissions. Challenges include overspecification of materials and limited alternative binders in concrete. Efforts focused on pilot projects and supply chain collaboration. By 2024, significant progress is made, with key abatement measures identified and an upgraded roadmap launched. Local initiatives drive progress, emphasizing early integration of climate considerations. Electrification of heavy vehicles advances rapidly, especially for trucks. Concrete with alternative binders gains mainstream adoption, alongside large-scale reuse projects and high-recycling-rate products. Challenges remain with climate goals not integrated into wider business arrangements, limited scaling of solutions, and a need for capacity building on carbon reduction across the value chain.

General value chain

Next 3-5 years

- Sufficiency and planning measures emerging.
- Standardized implementation of digital information chains.
- Strenghtened EU regulations with supply chain impacts.
- Municipalities/ companies with 2030 net-zero targets leading the way.
- Collaboration linking competitiveness with emissions reductions.
- Continued investments in knowledge and capacity building.
- Systematic learning structures for experience sharing.
- Long-term procurement roadmaps with strengthened requirements.
- Enhanced focus on resource efficiency.
- Business models and support infrastructure for large-scale reuse.
- Evolving requirements on zero-emissions vehicles.
- Projects and initiatives for integrating knowledge, tools, templates, and processes.
- Development of data collection and reporting for monitoring sector progress.
- Upscaling efforts across the board.

Figure 13. Anticipated developments linked to the construction supply chain and its context over the next few years.

Looking ahead, the focus shifts to upscaling, resource efficiency, sufficiency, and planning measures. Standardized digital information chains are central, fostering a combination of collaboration, competitiveness, and emissions reduction. Long-term procurement roadmaps, zero-emission vehicle requirement, alongside business models and infrastructure for large-scale reuse are on the rise. Tightening EU regulations and municipalities and firms with net-zero by 2030 targets drive developments.

As indicated in Figure 13, a lack of open data and harmonized calculation methods hindered progress early on related to building construction. Wood frames emerged as a primary mitigation measure. At present, mandatory climate declarations have been implemented for new constructions, though quality challenges exist. Optimization leads to cost-neutral projects with up to 50% reduction, with increased focus on renovations and emergence of wood-concrete hybrid frames. National limit values for new construction could be introduced by 2025, albeit initially at a low level, alongside efforts for voluntary higher standards. Accelerated renovation activities are prompting calls for associated carbon reduction.

Buildings

2018

- Limited knowledge of detailed embodied emission aspects, e.g. renovation and installations.
- Absence of harmonized calculation methods and open databases.
- Inadequate incentives to reduce embodied carbon.
- Wood frames primary mitigation measure.

2024

- National climate database, EPDs and harmonized calculation method, with local variations.
- Mandatory climate declarations for new construction - but challenges with low-quality.
- Array of guidelines and support for calculations and carbon requirements.
- Cost-neutral projects with up to 50% reduction through optimization.
- More data on renovations.
- Mainstream adoption of brick reuse and Large-scale tests of concrete and steel element reuse.
- Emergence of wood-concrete hybrid frames.

Next 3-5 years

- Potential introduction of national limit values in 2025, albeit at a low requirement level.
- Progress towards voluntary, higher amibition limit values.
- Growing emphasis on embodied emissions in groundwork.
- Accelerated rate of renovation activities and emerging requirements for reducing embodied carbon
- Sustainable forestry requirements.
- Increased focus on planning processes to enable climate-optimized construction.

Figure 14. Sector and context developments linked to the building construction value chain.

Regarding transport infrastructure, as described in Figure 14, climate reduction requirements were integrated early on into large state-owned projects, along with efforts to transition asphalt production to biofuels. Since 2018, the emphasis on circularity around excavation masses has grown, but regulatory obstacles persist. Carbon emission requirements for asphalt and vehicle fuels are set with a downward trajectory toward 2030. Going forward, sharper measures will be needed to meet increasing carbon reduction requirements.

Transport infrastructure

2018

- Harmonized calculation method with open database and tool
- Conversion of asphalt production to biofuels
- Evaluation of hindering regulations for mass handling
- Requirements for climate reductions in large transport administration projects
- Implementation of cost reduction or fuel shift measures – low-hanging fruits

2024

- Increased emphasis on circularity and mass handling - but obstacles to circular mass management persist.
- Shift from climate calculations and goals to measures and goal conflicts.
- Rising reduction requirements in transport administration projects necessitate sharper measures.
- Specific asphalt and vehicle fuel requirements.

Next 3-5 years

- Targeted material requirements for various product categories
- Carbon reduction requirements in municipal infrastructure and civil engineering projects
- Data and emphasis on net-vegetation removal with attention to creating carbon sinks
- System pilots for large scale implementation of electric construction machinery

Figure 15. Sector and context developments linked to the transport infrastructure construction value chain.

4 Developments over the course of the research

4.1 Identification and potential of assessed emissions reduction measures

A brief overview of the types of CO_2 emissions abatement measures related to building and infrastructure construction explored throughout the thesis research is offered in Figure 8 in Section 2. When considering new construction or renovation, pivotal mitigation options tied to the product stage encompass material efficiency, circularity measures, and material substitution towards alternatives with reduced embodied carbon levels (for reviews, see e.g. [7, 8, 17, 73, 123–126]). Moreover, strategies like shifting fuels and enhancing energy efficiency within material production facilities represent significant avenues for action [127–131].

These approaches are further complemented by direct or indirect electrification initiatives (including hydrogen/power-to-X) and/or the integration of carbon capture technologies within material production facilities [128, 130–133]. Likewise, electrification or the adoption of fuel cells in heavy-duty trucks and construction equipment offer viable methods for substantially reducing emissions [132, 134–137].

Efforts in material efficiency may alleviate transport requirements, consequently lowering emissions linked with transportation systems. Additional contemporary measures for material transportation abatement comprise optimizing logistics and transport distances, substituting fuels, or altering transportation modes [134, 138, 139].

In construction processes, alongside electrification, primary mitigation measures involve heightened levels of prefabrication coupled with improving construction efficiency through optimizing mass and material handling requirements, site layout, vehicle utilization, and selection of construction equipment tailored the intended use [17, 123, 137, 140, 141]. Fuel substitution and hybridization emerge as crucial technical abatement measures for the heavier construction machinery types [64, 142, 143].

To ensure the validity of the measures and timelines employed in the thesis research, they are cross-referenced with pertinent climate neutrality or net-zero roadmaps and pathways outlined by authoritative sources such as the European Commission [144], the International Energy Agency [145], other research institutes [8, 72, 73, 128, 130, 131, 133, 134, 146], the Swedish Energy Agency [116], and industry roadmaps developed as part of the Fossil Free Sweden initiative on fossil-free competitiveness [147]. There are detailed descriptions of the mitigation measures in the earlier Licentiate thesis [148], combined with a deep dive for project-level measures for transport infrastructure in Paper IV.

4.2 Towards a more holistic approach

The research conducted in the two case studies, focusing on the construction of a road segment with associated bridge structures and the construction of a multi-family building (featuring various building system options [149]), revealed comparable reduction potentials in their respective scenarios when the most comprehensive mitigation portfolios were implemented, as illustrated in Figure 15 (a and b).

Significant differences in the mitigation measures contributing to reduction potentials exist between the two case studies, as illustrated in Figure 15 (c and d). Although this contrast stems partly from the distinct nature of the projects, it is also influenced by the specific assessments' emphasis on certain types of measures. In the road construction case, the focus is on supply-side measures, whereas the building case also includes demand-side measures ('shift' and 'improve' as per Figure 7).

In the road construction scenario, over half of the current emissions reduction potential comes from replacing diesel with transport biofuel. Conversely, in the building case, approximately 60% of the reduction stems from material efficiency measures to streamline construction, optimized concrete recipes, and cement clinker substitution in concrete.

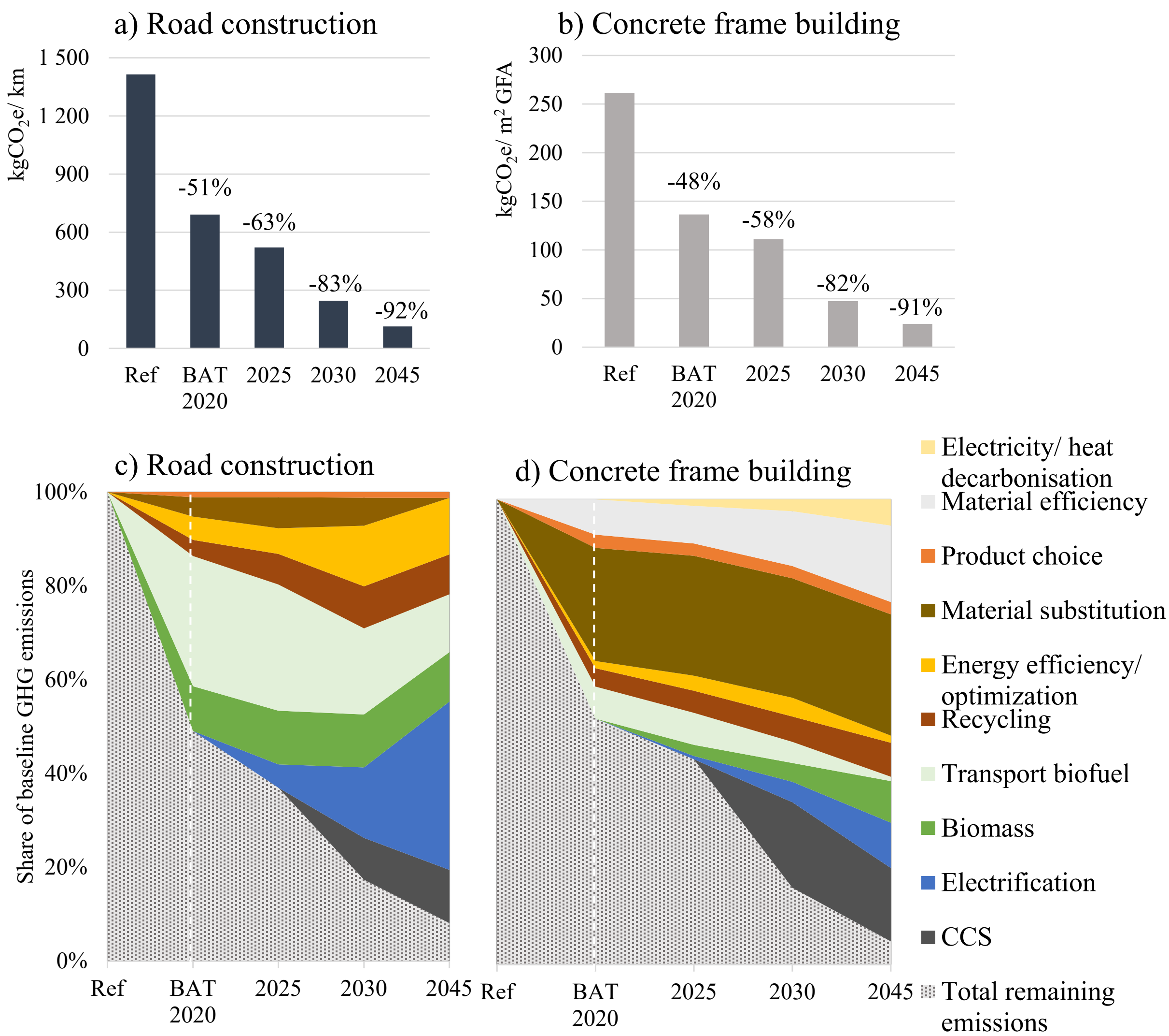


Figure 16. Overall embodied greenhouse gas emissions reduction potentials for a road construction case (a) and a concrete-frame multi-family building system (b), respectively, with best-available technologies and practices (BAT 2020) and over time until 2045 with the types of mitigation measures contributing to the GHG emissions reductions over time (c and d). The concrete frame building is based on a common building system with in-situ cast concrete and lightweight wood/steel outer walls. The building emissions are reported per square meter gross floor area (GFA).

Achieving the reduction in the road infrastructure case hinges on the availability of sustainably produced second-generation drop-in biofuels, such as hydrogenated vegetable oil (HVO). While biofuels are crucial for transitioning away from fossil fuels, especially in the short term, there are constraints on the supply of truly sustainable biomass [132, 150].

Therefore, while transport biofuels play a significant role in short-term climate mitigation, greater efforts are required to expedite the adoption of alternative measures. These include optimizing materials, design, mass handling, and transport systems, increasing recycling of steel, asphalt, and aggregates, and advancing the use of alternative binders in concrete.

The evolving nature of the research toward a more holistic approach, coupled with technical advancements over the last five years, is evident when applying the mitigation measures, reduction potentials, and timelines developed in Paper IV and V to the initial road construction case. The assessment format is not completely comparable with the transport infrastructure synthesis and roadmap studies of Paper IV and V being national assessments applying estimated national average reduction potentials. Still, Figure 16 showcases the potential for resource efficiency and circularity type measures to complement measures in material production and vehicle technologies.

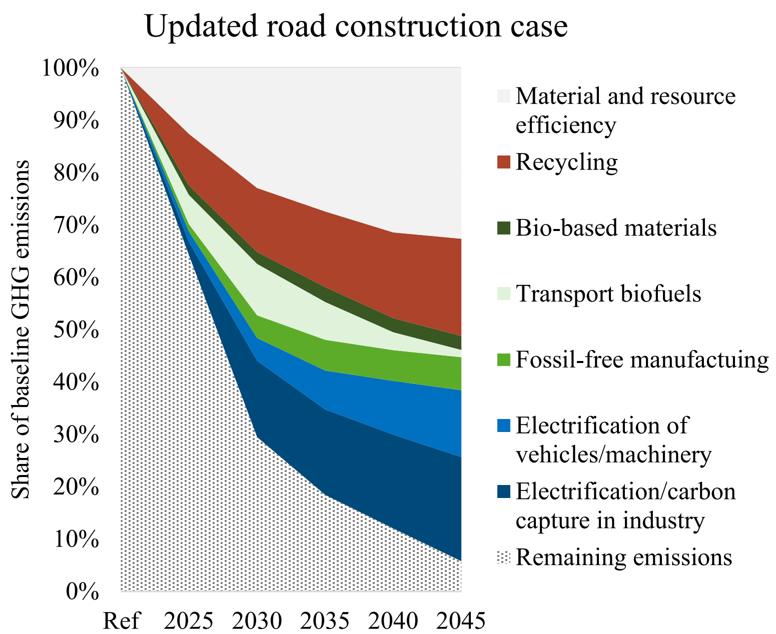


Figure 17. Updated CO2 emissions reduction potentials and measure types for the road construction case compared to the original assessment depicted in Figure 15. This updated assessment applies the mitigation portfolio developed in the transport infrastructure synthesis and roadmap studies of Paper IV and V. Note the different time steps on the x axis compared to Figure 15 c.

In the updated assessment shown in Figure 16, the emission reductions from biofuels for 2030 have decreased to approximately 15%, compared to 30% in the original assessment. Conversely, emissions reductions from material and resource efficiency measures, (corresponding to material efficiency and energy efficiency/ optimization in Figure 15 c), have risen from 13% to 23%.

To fully harness the potential of resource efficiency measures, extensive collaboration across the entire construction value chain is essential. Taking concrete as an example, achieving the potential benefits of cement clinker substitution, optimized concrete recipes, and structural element slimming requires close collaboration among all relevant stakeholders. This includes cement producers, concrete producers, structural engineers, procurers, clients, and architects, beginning from the design and early procurement phases and maintaining continuous communication throughout planning and construction [151].

This collaborative approach also necessitates coordination between demand-side actors, such as investors, developers, and designers, and those on the supply side, including contractors and materials manufacturers.

While material efficiency measures can lead to reduced material costs, they also entail intangible costs associated with the adapted working methods and project and production planning required for its implementation [152, 153]. To facilitate the necessitated collaborations, incentives must be revamped, including adjustments to procurement requirements and contract forms that enable balanced risk sharing and involve contractors early in the planning and design stages [154, 155]. This transformation should be accompanied by robust policy and regulatory support initiatives, improved access to finance, and measures that promote risk distribution along the value chains [28, 128, 156].

The findings from the building case study also contribute valuable insights into the ongoing debate between wood and concrete. Transitioning to bio-based construction materials can significantly reduce embodied CO_2 emissions, as evidenced by various case studies in the literature (see, for example [17, 124, 157, 158]).

However, many municipalities adopt a narrow approach by mandating the use of wood frames to lower embodied carbon in building construction, instead of assessing environmental performance based on calculated embodied carbon [159]. This restrictive approach may hinder the substantial scaling up of a diverse portfolio of mitigation options necessary to achieve climate targets [160].

Looking at Figure 17, two lines are drawn across the graph to illustrate the comparison between a wood- and concrete-building system for the same building. The first line (1) indicates that the wood frame building system has approximately 25% lower embodied carbon emissions in the reference setup. However, with mitigation measures applied for both building systems (denoted BAT 2020), the second line (2) shows that the embodied emissions become comparable.

Moreover, the concrete frame with mitigation measures applied exhibits 30% lower embodied carbon emissions than the reference wood-framed building system. This suggests that there are optimization opportunities available to reduce embodied impacts regardless of the building system or frame type, emphasizing that these factors should not be the sole determinants in decarbonization efforts.

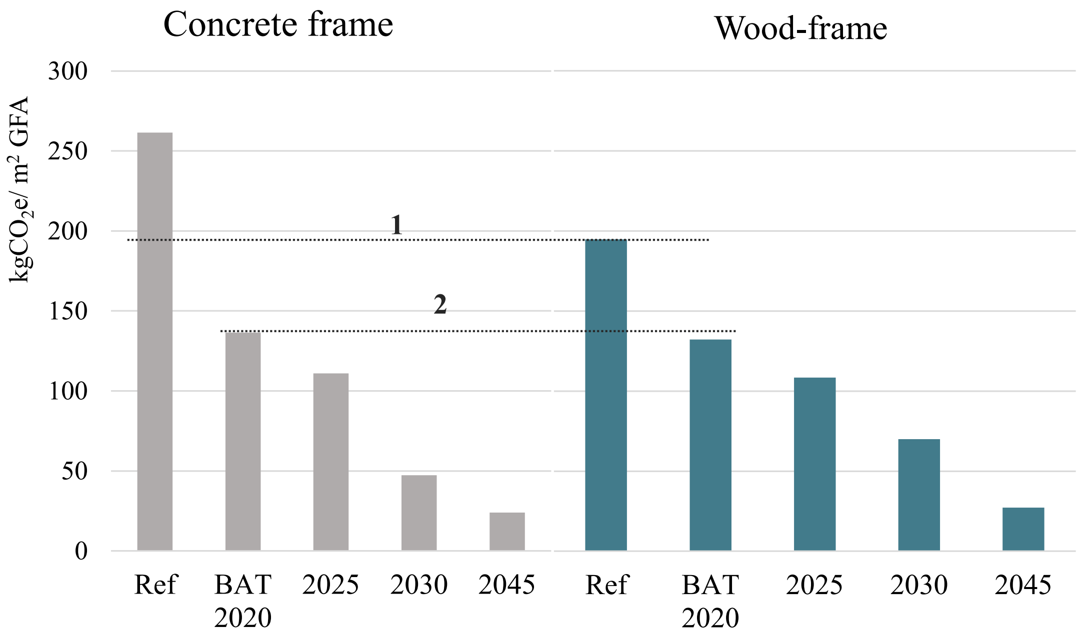


Figure 18. Overall embodied GHG emissions reduction potentials for the same multi-family building with a concrete-frame compared to a wood frame, with best-available technologies and practices (BAT 2020) and over time until 2045. The emissions are reported per square meter gross floor area (GFA).

A more pertinent focus lies in selecting the right material for the right purpose. This entails optimizing resource efficiency by matching specific material properties with the desired or necessary function of a building product, system, or entire building.

Traditionally, building systems and designs have been developed independently within each material industry, often relying on single materials [161]. However, recent trends indicate a shift in focus from the material itself to its function. There is potential in solutions that combine materials, such as timber, concrete, and steel for structural frames. Combining timber with concrete, for instance, can achieve structural performance, high fire resistance, acoustic behavior, thermal inertia, and durability, while steel adds ductility to the structure [162]. Moreover, hybrid and composite elements can be designed to fulfill multiple functions within the same product.

By incorporating conscious design principles that prioritize circularity and the ability to disassemble and reuse, combinations of materials and their properties can lead to reduced material volumes. This approach has the potential to simultaneously decrease emissions and costs.

4.3 Advancing emissions reduction potentials

As mentioned earlier, a consolidated pathway stemming from the national assessment in Paper II has undergone further refinement and regular updates, integrating new technical insights, strategies, successful applications, and achieved emissions reductions. This merged pathway prioritizes electrification alongside biofuel adoption and carbon capture in cement clinker production.

The update process has revealed accelerated emissions reduction measures, particularly notable in biofuel conversion for asphalt production and electrification of heavy vehicles, both exceeding expectations for 2020.

Furthermore, the pathways for buildings and transport infrastructure have been enriched through detailed analysis and the introduction of new abatement measures. These include a blend of material efficiency and optimization measures, material replacements, and strategies for recycling and reusing materials. For transport infrastructure, the refined pathway is detailed and reported in Papers IV and V, while for buildings, it is work in progress developed as decision support for progressive municipalities and building companies. The outcome of these updates and enhancements is illustrated in Figure 18.

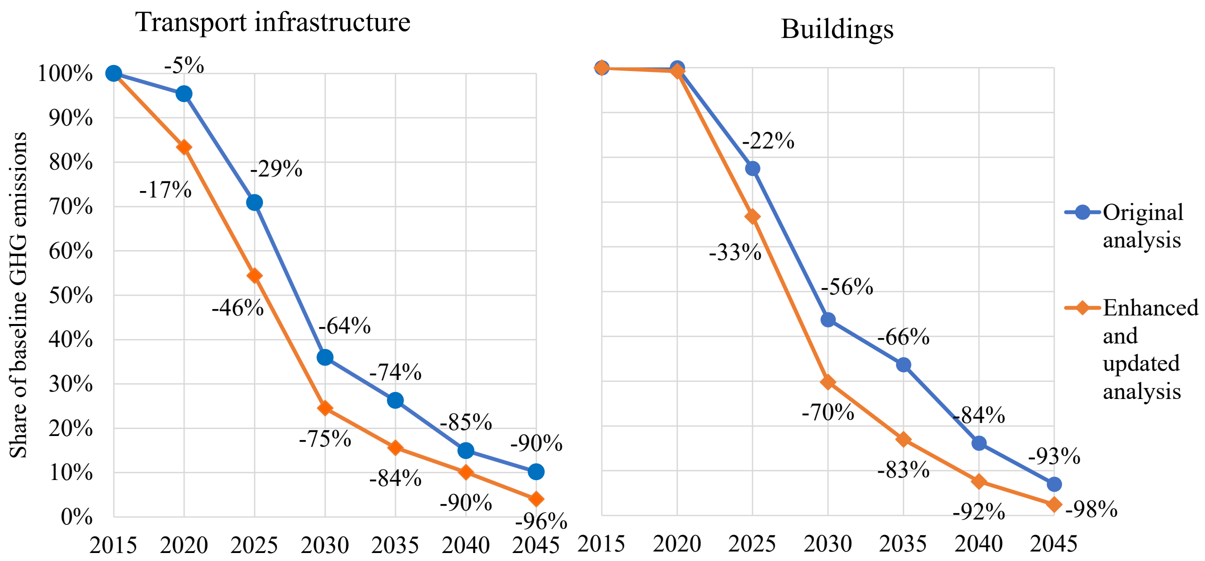


Figure 19. Comparison of greenhouse gas emissions reduction potentials related to Swedish national transport infrastructure and building construction and renovation between the original publication assessment of 2020 (Paper II) and the updated and enhanced assessment of 2024 (Paper IV- V, and reported in this introductory essay, respectively).

The reduction potentials have evolved, particularly over the short to medium term up to 2035. Predominant shifts stem from the electrification of heavy vehicles, accelerated advancements in material manufacturing plants, and increased focus on and potential for reuse and improved recycling. Figure 19 illustrates the contribution of the main measure types to these reduction potentials. This highlights the potential impact of resource efficiency and circularity measures, which could contribute to a 25%-30% reduction in emissions by 2030 and a 40%-45% reduction by 2045.

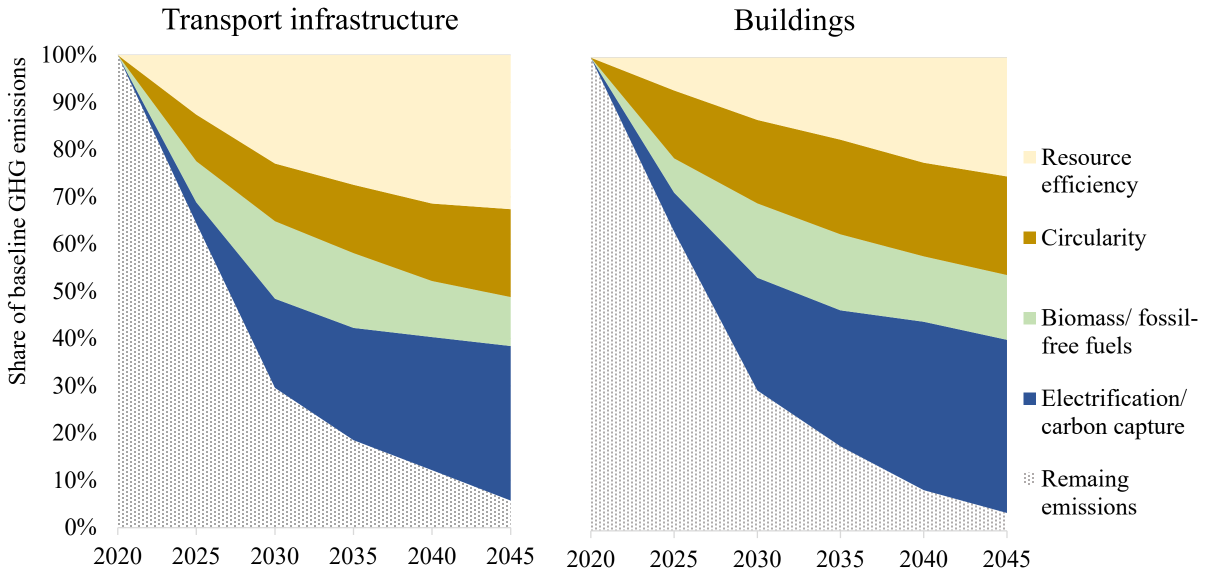


Figure 20. Comparison of the main types of greenhouse gas emissions reduction measures contributing to the mitigation of Swedish national transport infrastructure and building construction and renovation, respectively, in the updated and enhanced assessment of 2024.

In comparison, a recent European assessment of "circular economy actions" in the building sector, which included not only resource efficiency and circularity measures but also optimizing space use and prioritizing renovation over new construction, demonstrated a potential reduction of around 60% between 2015 and 2050 [72]. Moreover, when considering material substitution from concrete to timber in structures (included as a bio-based measure in Figure 19), the potential increased to 65%.

Details on the enhanced transport infrastructure assessment are provided in Paper IV and V. The updated building assessment is ongoing and will be substantiated by empirical data from practical implementation as part of future research. Still, Table 1 presents the current details of the included emissions reduction measures in the assessment up to 2030, in comparison to the baseline and the original analysis. Additionally, Figure 20 illustrates the components of the baseline building emissions and how these components evolve over time.

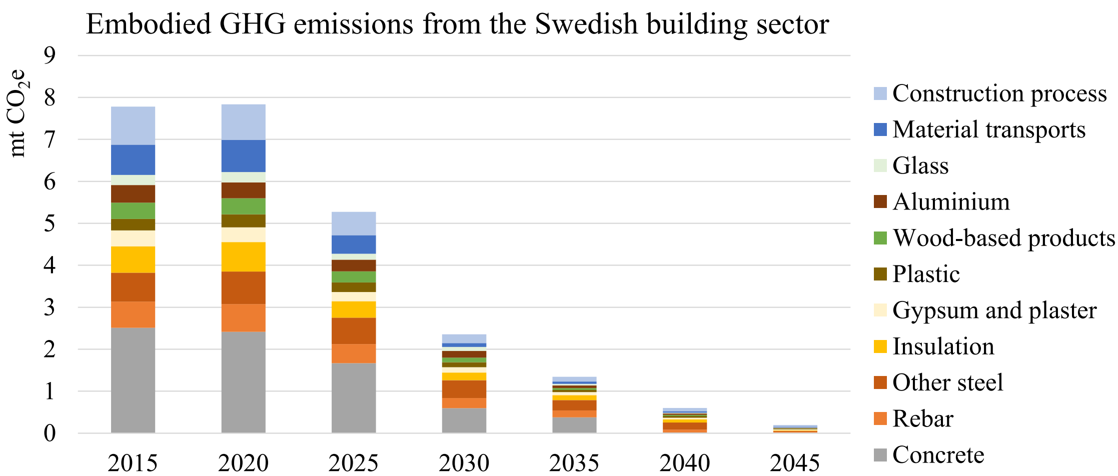


Figure 21. Components of the embodied greenhouse gas emissions from the Swedish building sector over time to 2045 in the updated pathway assessment of 2024 (developed for this introductory essay).

Table 1. Updates to the CO_2 emissions reduction potential from 2015 to 2030 for national building construction and renovation between the 2020 and 2024 assessments

	Reference (2015)	**Reduction potential and measures to 2030**	
		Updated assessment 2024	Original assessment 2020 (Paper II)
Overall		**70%**	**46%**
Reinforcement steel		**66%**	**66%**
	85% recycled steel	Only recycled steel 10% reduced material volume from optimization 5% reuse *50% fossil free fuels replacing gas in preheating* *10% energy efficiency; electricity emission factor improvement*	Only recycled steel 10% reduced material volume *Plasma heating ovens replacing gas in preheating* *10% energy efficiency*
Other steel		**40%**	**34%**
	20% recycled steel Primary steel produced in blast furnaces	40% recycled steel 15% material efficiency 25% substitution of steel joists with wood/wood tubes (around 30% of steel use) *Biomass replacing 20% of coal as fuel in blast furnaces*	20% recycled steel 15% material efficiency Biomass replacing 20% of coal as fuel in blast furnaces
Concrete		**76%** (58% without cement clinker CCS)	**37%**
	10% cement clinker substitution 420 kg cement/m³ concrete in binder intensity *17% biofuels*	20% material efficiency (structural optimization and/ or prefabrication) 8% reuse 12% material substitution - Structural timber and light wall substitution for both multi-family buildings and offices 35% cement clinker substitution 15% reduced binder intensity *35% biofuels in cement clinker production* *Energy efficiency measures in concrete production and casting*	15% material efficiency from optimization/prefabrication 3% material substitution - only structural timber for multi-family buildings 25% cement clinker substitution 10% reduced binder intensity *30% biofuels*
Insulation		74%	40%
	Assuming 60% polystyrene (EPS/ XPS) and 40% mineral wool (50/50 glass/rockwool) *100%/ 75% fossil energy in polystyrene/ mineral wool manufacturing*	8% material efficiency 7% reuse Overall composition: 30% polystyrene, 70% mineral wool, 5% natural fibers Polystyrene-based: 12% recycled EPS; 18% graphite EPS Mineral wool: 40% recycled mineral wool Natural fiber insulation: Combination of cellulose, wood fiber, hemp Overall around 50% recycling *Electrification /fossil-free fuels in all mineral wool production*	50% substitution to mineral wool - giving 30% EPS, 70% mineral wool *Electrification of all glass wool production*
Plastics		**68%**	**44%**
	Average of polyethylene (PE) and polyvinylchloride (PVC) 0% recycling *100% fossil energy*	5% material efficiency 5% reuse; 20% recycling *30% Electrified cracking (or CCS) plus 20% biomass feedstock* *Full potential for energy efficiency and fuel change*	5% material efficiency 5% recycling *Full potential for energy efficiency and fuel change*

Gypsum/ plaster		**70%**	**52%**
	Only gypsum-based plasterboards *100% fossil energy in manufacturing*	5% material efficiency 30% less wastage 7% reuse 30% substitution towards plaster-cellulose boards. 50% post-consumer recycled gypsum *50% fossil-free manufacturing (electrification or biogas)* *25% low-carbon electricity*	50% substitution towards plaster/cellulose boards. Remaining 50% produced with 50% recycled gypsum.
Others (bricks, tiles, composites etc.)		**64%**	**42%**
		Proxy assessment based on assessment of reduction potentials for other materials	Proxy assessment based on assessment of reduction potentials for other materials. Also used for Al, glass and wood-based products.
Aluminium and other metals		**62%**	
	100% primary aluminium 88% electricity, 12% fosslie energy in manufacturing	50% recycled Al 20% primary Al produced with low-carbon electricity (Swedish average) Overall EU electricity emissions factor improvement 10% of coal and gas substituted for fossil-free fuels	Only proxy assessment
Glass		**60%**	
	Average of flat glass and glass used in windows and doors 20% recycling	40% recycling/reuse 30% electrification or fossil-free fuels	Only proxy assessment
Wood-based products		**72%**	
	Average of cross-laminated timber, glulam, sawn timber, plywood and fiberboards	10% reuse 30% recycling/down-grading HVO for transports 25% electrified forestry operations 50% HVO in forestry operations	Only proxy assessment
Material transports		**90%**	**87%**
	17% biofuels (blending in Diesel MK1)	8% energy efficiency from hybridization/fleet upgrades 17% reduced transportation demand from logistics optimization and material efficiency/reuse 70% biofuels 30% electrified transports/modal shifts	10% efficiency from hybridization 13% logistics optimization and material efficiency/reuse 63% biofuels 20% electrified transports/modal shifts
Construction process		**79%**	**77%**
	Energy used in construction processes assumed to consists of 65% diesel (and LPG), 23% electricity and 11% district heat. 17% biofuels (blending in Diesel MK1)	6% energy efficiency from machine upgrades 13% energy efficiency from optimized machine setup and use 80% biofuels 20% electrified construction equipment 50% energy efficient sheds 100% site office energy management	14% energy efficiency from machine upgrades and optimized use 75% biofuels 9% electrified construction equipment 50% energy efficient sheds 100% site office energy management

5 Current work to accelerate implementation

Throughout my thesis work, I have actively participated in research utilization efforts. These endeavors have involved providing decision support to various stakeholders. Table 2 provides an overview of continuous research utilization efforts effected during this thesis work.

Table 2. Overview of the research utilization efforts conducted during the thesis research, along with selected outcomes.

Research utilization efforts	Results
Assisting the Swedish Transport Administration (STA) in defining achievable climate reduction requirements toward carbon neutrality over time.	Augmented carbon emissions reduction goals incorporated in the STA procurement requirement framework [163].
Collaborating with a government commission to expedite the implementation of limit values for the climate impact of buildings.	Analysis included in the regulation proposed for introduction in 20205, out on referral as per May 2024 [164].
Supporting Gothenburg City and Älvstranden Development in determining feasible reduction requirements for building project to 2030.	Not yet finalized and published.
Contributing to the enhancement of roadmaps for the concrete and aggregate industries, and the building and construction sector as part of the Swedish government's Fossil-free Sweden initiative	Upgraded roadmaps launched for the concrete industries [165], and the building and construction sector [166]. The latter with clear commitment for each link in the construction supply chain. Upgrading process ongoing for the aggregates industry as per May 2024.
Engaging with numerous companies across the construction value chain, including material producers, contractors, consultants, property developers, property owners, and financial institutions.	In addition to dedicated dialogue, workshops etc., engagements such as an external representative in a climate strategic council, a knowledge group for climate leadership [167] and in various national and international outreach forums [168, 169], including a podcast [170].
Participating in various industry research and development projects.	Reference group representative in, and analysis provided to, various projects, e.g. [171, 172].

Building on the research conducted in Paper IV-V, I am currently collaborating with leading technical consultants to leverage the detailed pathways developed in this thesis research to support the construction industry's climate transition.

Feedback from stakeholders in the value chain highlights the pathway's value in providing insights derived from roadmaps, industrial plans, pilot projects, and industry research and development results. The knowledge gained may serve as a foundational resource for projects of all scales, fosters dialogue in collaborative efforts, and acts as a checklist throughout project phases. Additionally, it can act as a benchmark for companies, prompting consideration of costs and cost-effectiveness.

To actualize these insights, the ongoing collaboration aims to integrate pathway information into existing tools used in daily construction project work, such as technical handbooks and reference materials. A schematic of the process for the ongoing collaboration is provided in Figure 21. Case studies in three municipalities will test the hypothesis that integrating climate change scenarios into existing tools and processes accelerates the transition to a climate-neutral construction industry. Additionally, the project involves exploring industry-wide tools to understand their purpose, content, update mechanisms, and how the knowledge developed can be integrated into these tools.

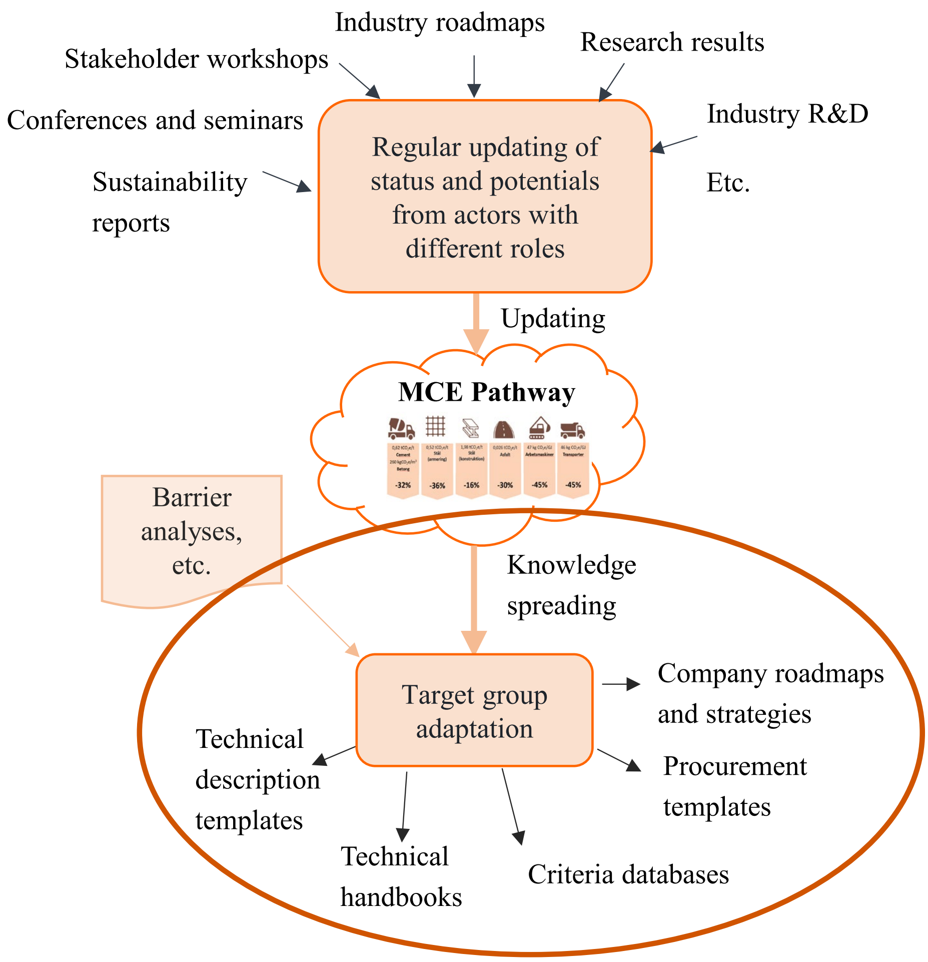


Figure 22. Schematic representation of the current collaboration project aiming to accelerate implementation based on the pathway towards decarbonization developed as part of this thesis research, here denoted MCE Pathway.

The initial project workshops and mapping have led to the identification of three key preconditions The optimal conditions for accelerated implementation seem to be where organization, knowledge and tools are available and supportive, as per Figure 22. Upon completion, the project aims to be able to address the following key questions:

- Identifying the most critical tools and processes for different municipalities.
- Understanding how municipal organization influences the usage of tools and governance in construction projects.
- Exploring opportunities to integrate climate change scenario information into relevant tools and processes.

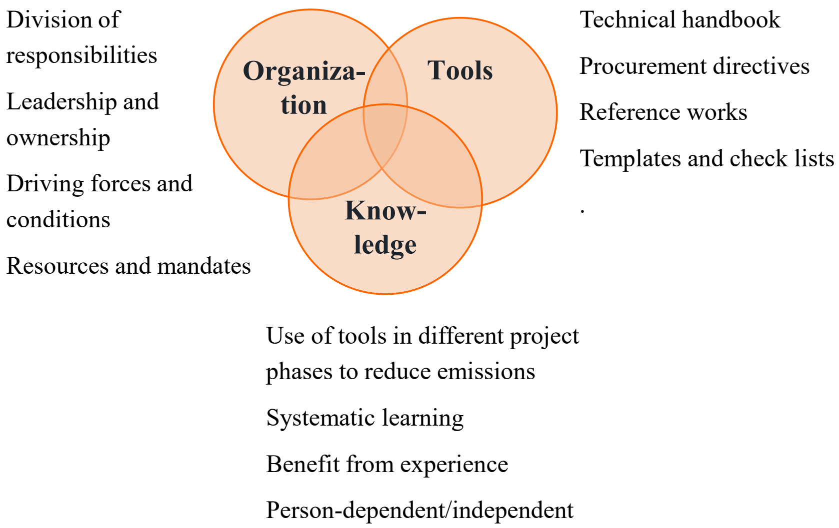


Figure 23. Illustration of the identified sweet spot between organization, tools and knowledge showcasing the enablers and relevant factors identified to date.

Overall, the project aims to drive tangible progress towards a climate-neutral construction industry by integrating climate change scenarios into industry practices and tools. Finally, an example illustrating how pathway information has been adapted into a more easily digestible format is displayed in Figure 23.

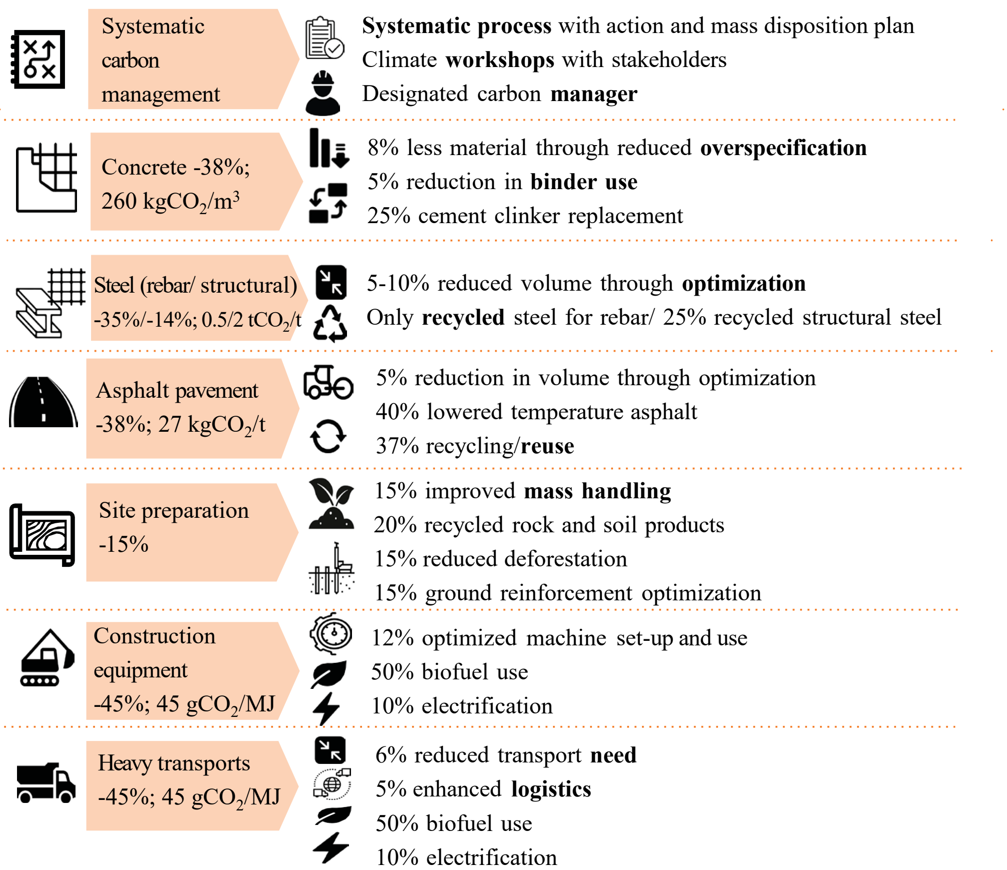


Figure 24. Example of target group adapted presentation of pathway details on reduction measures with estimated implementation and reduction potential in 2025 compared to the embodied emissions of an average infrastructure project in 2015.

6 Discussion

The research presented in this thesis focuses on reducing CO_2 emissions in Sweden's construction sector, aiming to align with the country's commitment to achieving net-zero greenhouse gas emissions by 2045. By combining top-down and bottom-up assessments and adopting a participatory approach, the research presents a holistic and comprehensive assessment of emission reduction potential in construction supply chains. The studies assess various strategies for reducing emissions across the construction supply chain, including material efficiency, circularity measures, and the adoption of electrified vehicles and industrial processes.

The results indicate that significant reductions are feasible with current technologies, reaching around 70% reduction by 2030 and close to zero emissions by 2045 if all stakeholders collaborate effectively. Overall, the research provides valuable insights for stakeholders to accelerate the climate transition in infrastructure construction, emphasizing collective action and holistic approaches to carbon reduction.

Over the course of the research, the construction industry and its surrounding conditions have evolved. While this work reveals favorable conditions for transition, it also underscores obstacles and enablers. Some obstacles have been addressed, while others persist, or new ones emerge. The same applies to enablers. In this concluding discussion, I will briefly outline a few key challenges and opportunities anticipated in the coming years for buildings and transport infrastructure construction supply chains.

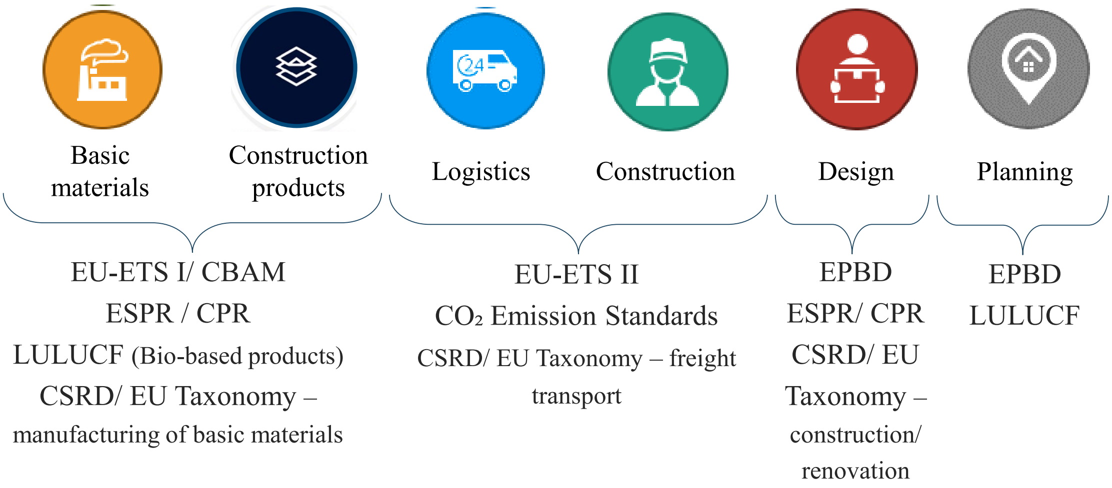
The impact of EU Climate Regulations on construction supply chains

In recent years, the EU has significantly strengthened its climate regulations in response to the growing urgency of addressing climate change [173]. Related to the construction industry, the EU has revised or introduced regulations and initiatives that will address emissions throughout the supply chain [174], as illustrated in Figure 24.

The phase-out of free allowances for manufacturing industries under the original emission trading system (EU-ETS) from 2026 to 2035 is expected to enhance cost efficiency in investing in emissions reduction measures. Additionally, stringent new emissions standards for heavy vehicles will drive progress in freight transport, while the new EU ETS2 will extend coverage to construction equipment.

In terms of project design, the Ecodesign for Sustainable Products Regulation (ESPR) establishes a framework for setting ecodesign requirements, alongside requirements for digital product passports providing information about products' environmental performance. Specifically for buildings, the recast Energy Performance for Buildings Directive mandates Member States to introduce limit values on whole-life cycle carbon from 2030, with a progressive downward trend. National targets will also be required for the circular use of materials.

As a result, the implementation of more stringent and comprehensive climate regulations by the EU is anticipated to catalyze significant changes within the construction value chain.



Abbreviations:

- CBAM - Carbon Border Adjustment Mechanism
- CPR - Construction Products Regulation
- CSRD - Corporate Sustainability Reporting Directive
- EPBD - Energy Performance of Buildings Directive
- ESPR - Ecodesign for Sustainable Products Regulation
- EU-ETS - Original EU Emissions Trading System – power sector and manufacturing industries
- EU-ETS2 - EU Emissions Trading System for buildings, road transport and additional sectors
- EU Taxonomy – Classification system to support financing of environmentally sustainable activities
- LULUCF - EU rules on land use, land use change and forestry

Figure 25. Interpretation of the central EU regulations impacting the emissions linked to the construction and renovation of buildings and transports infrastructure along with the parts of the supply chain most impacted by the respective regulation.

Carbon budgets

While the research included in this thesis begins with the CO_2 emissions reduction potential across the construction supply, identified through measures, technologies, commercialization, and scale-up, several studies take a different approach. These studies focus primarily on the emission space available to the construction sector from a carbon budget perspective. Predominantly concentrating on new housing construction and utilizing various methodologies, these studies find that reductions of 56% to 80% from 2020 to 2030 are required [175–177]. Reduction requirements increase when considering renovation alongside new construction [178].

While combining perspectives holds potential, there is a risk in solely relying on carbon budget limits without a comprehensive action plan defining scalable measures necessary for national or international implementation. Large emissions reductions can be achieved on a project level by replacing traditional materials with alternatives such as reused concrete or steel elements, wood-based products, foam glass, natural insulation, or recycled packaging building boards [8, 179]. However, implementing these solutions without considering resource efficiency, limits to upscaling, or other impacts such as land use change or biodiversity, could outweigh their benefits.

Existing or proposed regulations on construction and renovation limit values underscore a gap between adopted approaches and climate science imperatives [180].

The proposed Swedish regulation, for instance, is partly based on the tolerance of cost-sensitive actors in the construction industry [164]. Proposed limits imply no improvement in upfront embodied emissions by 2025 and only a 25% reduction by 2030, falling short of carbon budget limitations.

A carbon budget analysis for transport infrastructure performed in Paper V of this thesis research show that only pathways with full supply chain measures have potential to remain within budgetary limits. Accordingly, integrating budgetary limitations with comprehensive bottom-up mitigation analysis is crucial to aligning the building and transport infrastructure sectors with climate science requirements.

Emissions reduction measure prioritization

To facilitate the necessary reduction of carbon emissions associated with the built environment, planning measures that restrict the levels of new construction could offer support. CO_2 emissions reductions can be achieved through the consideration of resource efficiency and circularity opportunities across all stages of the value chain. However, the earlier in a project's lifecycle, the greater the opportunity to reduce climate impact.

Along with various other research [28, 125, 165, 181], I propose employing a cascade principle, akin to the "waste hierarchy", as a straightforward approach to maximize the potential for carbon emissions reduction. Drawing on the concept of demand-side measures proposed by Creutzig *et al* [35] (illustrated in Figure 7 in Section 1.3), and combining elements of both demand-side and supply-side mitigation measures, an adapted version of this cascading principle developed for this introductory essay is illustrated in Figure 25.

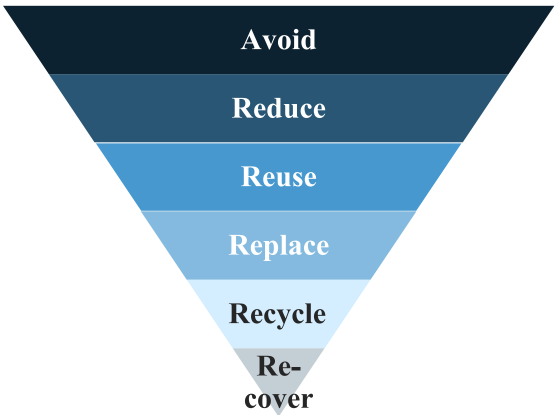


Figure 26. Illustration of a resource hierarchy for the building and transport infrastructure value chains combining demand-side and supply-side carbon emissions reduction measures. Inspired by various sources, e.g. [28, 125, 165].

The first step in the resource hierarchy involves rethinking and addressing needs without significant changes. This is where sufficiency comes into play, challenging the root cause of the need to build. Alternative approaches aim to achieve desired outcomes by maximizing existing assets.

Applying sufficiency principles to housing includes capping per-capita floor area, prioritizing multi-family buildings, constructing smaller dwellings with shared spaces, and implementing co-housing strategies [182–185].

Optimizing existing structures through maintenance, repairs, and adaptations further extends their lifespan and reduces material demand. Research suggests that untapped sufficiency potential could lead to a 30% reduction in emissions in wealthy countries [15]. This could thus ease the required downward curve regarding limits values for new constructions and renovation while still observing carbon budgets. Material efficiency measures also cut down on transportation needs, lowering the carbon footprint of heavy transport. Improving logistics and increasing vehicle utilization support this effort.

Next, maximizing component reuse is crucial, necessitating business models that integrate existing suppliers and utilize digital support systems to establish databases for, and track, material availability [186, 187].

Replacement involves selecting appropriate materials, in the structural frame but also including alternative binders in concrete, wood tubes instead of steel joists, natural fiber-based insulation or building boards or advanced bio-based products, such as resins, plastics, and bitumen. Electrification of production processes and heavy vehicles are also included in the concept of 'Replace'.

Recycling measures follow, essential for most materials including metals, asphalt, insulation, glass, and building boards.

In the last step of the resource hierarchy, the use of bio-based fuels in production processes and heavy vehicles is considered. Due to sustainability concerns and competition for food production and land use, the overall potential of bioenergy is constrained [188, 189]. Therefore, biofuels are primarily viewed as relevant for reducing fossil fuel use during a transition period until electrification reaches its full potential [134].

Circularity as a means to counteract restricted supply

Net carbon storage in growing trees in Sweden has halved over the past decade [113], prompting a reevaluation of forest resource utilization. Currently, only 20-25% of harvested trees in Sweden are transformed into long-lasting products [190]. To meet increasing demands while ensuring sustainability [191], wood usage must align with the cascading principle [192].

Wood should primarily be used for durable long-lived materials and products, replacing carbon-intensive and fossil-based counterparts like those in buildings and furniture. [160]. The cascading use of wood maximizes utility and carbon storage via reuse and recycling before energy generation. [160, 162]. Research and innovation focusing on utilizing low-grade wood and enhancing cascading use, are crucial for advancing circularity.[192].

Cost efficiency via resource efficiency

Finally, there are large opportunities related to resource-efficient design. A recent review study highlighted a significant variation in material intensities among buildings, measured in tons of materials per square meter of gross floor area (GFA) [193].

In a Swedish national reference value study, it was discovered that around 1.5 tons of concrete are needed per square meter of gross floor area (GFA) for multi-family buildings. Conversely, the most common building system studied in Paper III utilized 1 ton of concrete per square meter of GFA. A resource efficient design could thus potentially save 500 kg/m^2 of concrete, resulting in carbon emissions reduction of approximately 75 kg CO_2e/m^2 GFA [194]. equivalent to about a 20% reduction based on baseline values [108, 195].

Another case object studied as an ongoing extension of this thesis research, showcases the potential of cost efficiency via resource-efficient design based on a multi-family building constructed with a prefabricated concrete frame. By implementing slimmed concrete elements, optimized concrete recipes, and substituting to lighter walls where possible, this project achieved upfront embodied emissions of 207 kg CO_2e/m^2 GFA. This represents a 36% reduction compared to comparable reference projects, as shown in Figure 26.

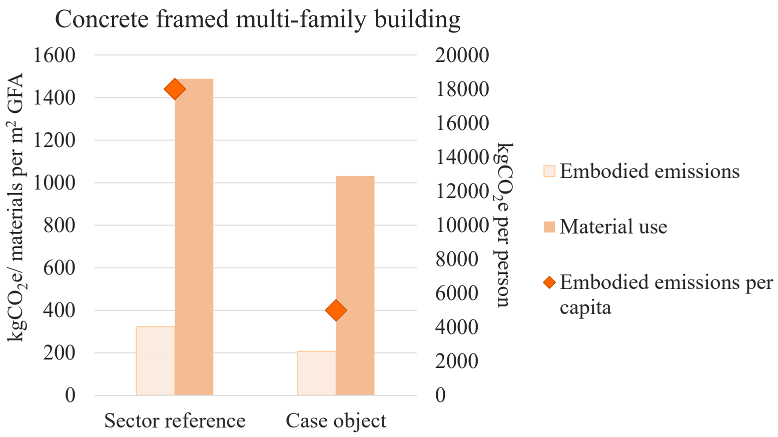


Figure 27. Comparison of the material intensity and embodied CO_2 emissions per square meter and per capita for comparable concrete-framed multi-family buildings and a case object studied in the development of this introductory essay. Sector reference data based on Malmqvist *et al* [195].

Partly due to a collaborative approach initiated early in the project, these reductions were achieved while lowering the cost of the structural frame by around 5%. Further, compared to reference projects, the case object halved embodied CO_2 emissions per person for whom the building is designed.

To ensure both cost and carbon efficiency, it is crucial to consider the impact of material intensity in building typology and design [108]. Moving forward, metrics on emissions per square meter (or per kilometer for infrastructure) should be complemented by emissions per capita that the asset was designed for. This additional metric provides relevant information on the asset's contribution to decarbonization and carbon efficiency.

7 Future research

As indicated in this introductory essay, my ongoing research extends beyond the five appended papers. There is a range of prospective challenges and potential enablers to delve further into, particularly those discussed in the preceding discussion section.

I am enthusiastic about continuing collaborative efforts aimed at expediting the implementation of carbon emissions reduction measures by tailoring knowledge to supply chain actors and integrating it into tools and resources utilized by the target audience in their daily work. This may include guiding reference materials, procurement documents, and design instructions. While the current focus is on the transport infrastructure sector, I would like to undertake similar research initiatives related to buildings.

By leveraging the research included in this thesis alongside practical experiences and data from pilot projects and other initiatives, this synthesized knowledge can be adapted into an accessible format. Such resources can play a pivotal role in addressing many of the challenges identified by the sector and supporting efforts toward carbon emissions reduction.

There will likely be a notable focus on renovation and optimizing the use of existing assets moving forward. It would thus be appealing to gather contemporary knowledge and practical evidence specifically focusing on carbon reduction measures related to renovation projects, with a particular emphasis on energy efficiency renovations.

Exploring sufficiency and planning measures, such as those that limit the need for new construction through alternatives or maximize the use of existing assets, would also be relevant to further complement and enhance the national pathway progressed throughout this thesis research.

Finally, no scenario in the various studies included in this thesis achieves zero carbon emissions. Therefore, it is important to further investigate the potential for and limitations of negative emissions (such as carbon capture of biogenic emissions) and carbon sinks (such as the use of long-lived wood products in construction). This exploration will enable an approach towards achieving net-zero emissions by 2045.

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