Achieving net-zero carbon emissions in construction supply chains - A multidimensional analysis of residential building systems

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Achieving net-zero carbon emissions in construction supply chains – A multidimensional analysis of residential building systems

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ABSTRACT

The construction sector accounts for approximately 25% of global CO_2 emissions. In this paper, we provide a multidimensional assessment of the potential for greenhouse gas emissions abatement in relation to the construction of multi-family residential buildings. Different building designs are compared, whereby the study analyzes the potential reductions in greenhouse gas emissions when combining abatement measures with a perspective of the technologies and practices available now, and those that are likely to become available on a timescale up to Year 2045. Further, the assessment analyzes the potential for emissions reductions when applying abatement measures at different points in the supply chain, from primary material production via material composition to the final building structure. The results indicate that the greenhouse gas emissions can be reduced by up to 40% with currently available technologies and practices, with even greater potential reductions of 80% to Year 2030 and 93% to Year 2045.

1. Introduction

Greenhouse gas (GHG) emissions caused by human activities have become an existential threat to modern civilization (IPCC, 2018a,b). The landmark special 1.5 °C report from the UN Intergovernmental Panel on Climate Change released in 2018 (IPCC, 2018a,b), presented a stark picture of the world we will inhabit if global average temperatures rise by 2 °C. Limiting global warming to well below 2 °C will require drastic reductions in global GHG emissions up to Year 2050 with subsequent negative emissions (UNFCCC, 2015). In response to this, many countries around the world have set goal to reach net-zero emissions around mid-century. Sweden are among these countries, having set a long-term goal of having no net GHG emissions by Year 2045, with the requirement that domestic emissions are decreased by at least 85% compared to the levels in 1990[1] (Regeringskansliet, 2017).

Consequently, the climate emergency calls for immediate action to start the transformation towards deep GHG emissions cuts over the coming decades (World Green Building Council, 2019). In order to succeed with this transformation, there is a need to map how mitigation measures can be allocated up to mid-century, to identify those measures that can be applied already today and those that will require longer lead times for planning and implementation (Bataille et al., 2016). This mapping aims to ensure that the incremental or low-hanging-fruit measures are implemented, while at the same time initiating the planning and preparations needed for the more transformative measures required to reach zero or near-zero emissions by mid-century (Karlsson et al., 2020). The emphasis in this work is on the challenges associated with achieving net-zero carbon emissions from the construction industry and its supply chains within the next two to three decades - using the construction of common building systems for residential multi-family housing as a case study.

The construction of buildings currently accounts for 11% of global carbon emissions and thus has a vital role to play in responding to the climate emergency (World Green Building Council, 2019). While GHGs

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[1] The remaining up to 15% can be reduced by so called complementary measures including land use change, bio-CCS and measures abroad (if in addition such that would have been done by the foreign country).

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released during the operational life of buildings have historically been in focus, the implementation of more-energy-efficient building technologies, together with improvements in the carbon intensities of the electricity and heating supply, are increasing the relative impacts of embodied GHG emissions, i.e., emissions that occur during the manufacturing, transportation, construction and end-of-life phases of built assets (Cabeza et al., 2014; Akbarnezhad and Xiao, 2017; Pomponi and Moncaster, 2016; Islam et al., 2015; Ibn-Mohammed et al., 2013; Malmqvistet al., 2018; Cabeza et al., 2013). The levels of these embodied emissions will continue to increase in a business-as-usual scenario (World Green Building Council, 2019). Moreover, many of the activities essential for the construction sector, such as heavy transport and the production of carbon-intensive structural materials (mainly steel and cement), entail emissions that require transformative process alterations for their elimination (Daviset al., 2018; Energy Transition Commission, 2018). Indeed, materials production for buildings is the main contributor of GHG emissions in building construction (Monahan and Powell, 2011; Material Economics, 2019) with concrete structures, including reinforcement steel, making up the major component (World Green Building Council, 2019; Akbarnezhad and Xiao, 2017; Andersson et al., 2018; Habertet al., 2020). Therefore, it is crucial to act now to reduce the environmental impact of construction within the coming decades (Habertet al., 2020).

With the increase in the relative contribution of embodied carbon to lifecycle carbon emissions, we see a shift in the focus of research in the last decade towards investigating strategies to reduce the embodied carbon of buildings (for reviews, see (Akbarnezhad and Xiao, 2017; Pomponi and Moncaster, 2016; Malmqvistet al., 2018; Kumari et al., 2013)). However, whereas the existing literature, which is often based on lifecycle assessments (LCAs) (Öman et al., 2012; Reijnders, 2017; Bahramian and Yetilmezsoy, 1995; Birgisdottiret al., 2017; Chastas et al., 2018; Buyle et al., 2013; Fenner et al., 2018; Moncaster et al., 2018; Nwodo and Anumba, 2019; Schwartz et al., 2018), may benefit the decision making for projects that are taking place in the near term, those studies are an insufficient basis for longer-term policymaking, which will require comprehensive assessments of not just the current but also prospective abatement options and potentials. To lay the foundations for the low-carbon transition in building construction supply chains, there is a need to complement traditional lifecycle assessment approaches with dimensions and dynamics that reflect the variations in the surrounding industrial and environmental systems (Weidema et al., 2018; Fouquetet al., 2015; Collinge et al., 2013; Shimako, 2017).

Dynamic lifecycle approaches have been developed for operational carbon, which for example takes account of developments over time in the energy systems that provide heat and electricity to buildings (Collinge et al., 2013; Negishi et al., 2018; Su et al., 2017). However, we have found little in the literature on dynamic approaches regarding embedded carbon, with few published studies identified for new construction (Hawkins et al., 2021; Resch et al., 2021). Additional dynamic studies focus on materials for repair and refurbishment (Fouquetet al., 2015; Negishi et al., 2019; Potrč Obrecht et al., 2021; Kang et al., 2019). In the present study, the ambition is to move beyond static analyses of embedded carbon by considering the development, over time, of emission abatement measures in different parts of the construction supply chain. An already established LCA of common building systems for multi-family housing in Sweden, as reported by Erlandsson and Malmqvist and colleagues (Erlandsson et al., 2018; Malmqvist et al., 2018) is used as the basis for an assessment of the near-term and long-term abatement options and potentials in the building construction sector.

Future carbon abatement options have been considered for individual sectors in an array of studies (see e.g. (Wörtleret al., 2013) for steel, (IEA and CSI, 2018; Favier et al., 2050) for cement/concrete, and (IEA, 2017a; Skinner et al., 2010) for heavy vehicles). In addition to sector-specific abatement studies, cross-sectoral studies, particularly in the gray literature, have provided a synthesis of perspectives from different industries (Energy Transition Commission, 2018; Material Economics, 2019; Batailleet al., 2018; Wyns and Axelson, 2016; Schneideret al., 2020).

With respect to the building and construction sector, we find some examples of national and international assessments of future abatement options and potentials and pathways towards close-to-zero emissions (World Green Building Council, 2019; Byggallianse and Eiendom, 2016; Allwood and Cullen, 2012; Green Construction Board, 2013; Le Denet al., 2020). However, there have been few project-level assessments.

In Sweden, within the government-initiated Fossil Free Sweden[2] initiative, individual industries and business associations have drawn up roadmaps towards Year 2045. These provide key information on abatement options within individual industry sectors, with the construction sector roadmap capturing a cross-sectorial perspective (Sverige, 2018a; Sverige, 2018b).

This study aimed to identify the extent to which abatement technologies across the supply chain of building construction projects can reduce GHG emissions if combined to their full potential. We also exemplify what this potential would imply for construction of a typical multi-family building and develop scenarios highlighting the potential of measures implement along the supply chain.

This paper is organized as follows: Section 2 outlines the material and methods used, while Section 3 describes the main results of the analysis. Section 4 continues with a discussion of the results, including barriers, opportunities and strategic choices now and towards 2045, with Section 5 ending with concluding remarks.

2. Material and methods

This work has been structured as a participatory integrated assessment (Stalpers et al., 2008; Salter et al., 2010). This is an approach that engages relevant stakeholders in the assessment process, as described in Fig. 1. Stakeholders include industry representatives and experts along the supply chain, as well as materials suppliers, contractors, consultants, clients and governmental agencies.

Following the study methodology depicted in Fig. 1, scoping and initial stakeholder engagement (Stage I) was followed by high-level classification of the challenges and potential enablers for the low-carbon transition in the construction sector (Stage II). Together with stakeholders, suitable benchmark cases (i.e., the case study object) were subsequently identified.

With the support of the LCA of the benchmark building systems, estimates were made of the magnitudes of the current and future potentials for GHG emissions reductions across the building construction supply chain (Stage III). This was achieved by: (i) mapping the materials and GHG emissions flows through the supply chain of common building systems for multi-family residential buildings; (ii) identifying possible GHG abatement options; (iii) using (i) and (ii) to assess the impact of combining abatement measures for the construction of a functionally equivalent building, albeit with lower GHG emissions; and (iv) crafting scenarios to highlight the challenges and possibilities up to Year 2045 associated with measures implemented along the supply chain.

The inventory of GHG abatement options includes current best-available technologies, practices and products on the market (denoted as 'BAT Now'), as well as technologies that are deemed as likely to become available up to Year 2045.

A timeline is applied to test the potential implications for climate impact when constructing the same building in 2025, 2030 and 2045, while applying a combination of GHG abatement measures along the supply chain that have been appraised to have reached commercial maturity at these points in time. The abatement measures are combined in scenarios according to specific conditions (Amer et al., 2013), with

[2] http://fossilfritt-sverige.se/in-english/.

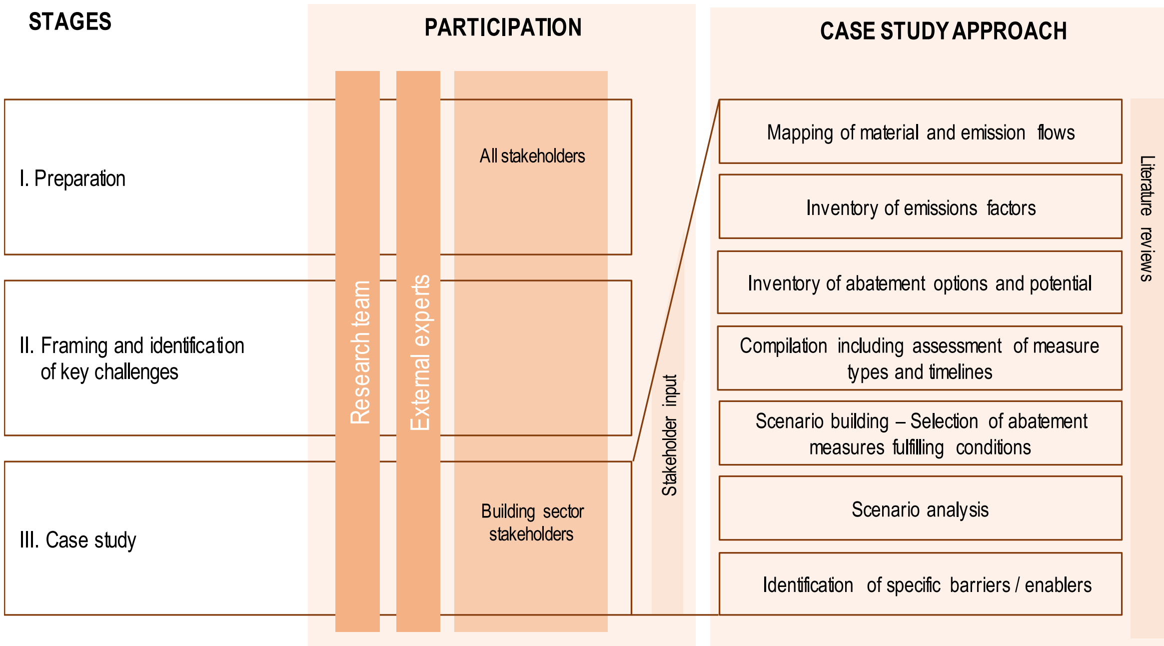


Fig. 1. Outline of the methodological approach (adapted from Karlsson et al. (2020); Karlsson et al. (2020)) used in the present study.

the focus on measures implemented along the supply chain, from primary material production, via material processing and composition, to the building design and structure, and including impacts on material transports and the construction process.

The inventory of GHG abatement options (described in detail in Section 2.3.2) is established by means of a comprehensive literature review[3] that includes industry and governmental agency reports (gray literature), together with inputs from supply chain stakeholders.

2.1. Building systems

The study takes its departure point from an LCA performed by Erlandsson et al. (2018) in which five different construction designs were studied for the same reference building, developed in collaboration with different construction companies and materials suppliers. The building systems were all designed based on the same drawing for a house in the *Blå Jungfrun* neighborhood of Stockholm (see Fig. 2), which was constructed in 2011 (Liljenström, 2015), i.e., this building was used as a reference building.

All building systems have the same expanded polystyrene (EPS) insulated concrete slab and the same interior surface layers, furnishings and installations, as well as a cardboard-covered roof and a plastered façade, which is currently the façade material of choice for apartment buildings in Sweden.

The building systems were chosen to represent the way in which most apartment buildings in Sweden are built today. It is worth noting that in an international comparison, the thermal performance requirements of the Swedish building code, which necessitate large amounts of insulation, are for external building envelope elements (Boverket and Boverkets byggregler, 2011; Tettey et al., 2019). Table 1 provides a general description of each building system.

The building systems have the same heated floor area (HFA) of 2198 m^2. However, the various widths and heights of the structural elements in the different platform alternatives imply that the gross area and building heights differ, as per Table 2. The functional requirements that apply mean that all the building platforms meet or exceed the building regulation requirements, with an energy requirement defined as 41 kWh of district heating and 12 kWh of property electricity per m^2 HFA and year.

2.2. Material and GHG emission flows

Lifecycle based GHG emissions intensity factors for materials, activities and fuels were combined with the emissions data given in the reference study, to estimate the material demand. The emissions intensity factors were sourced from a literature review, as detailed in Table A. 1 and Table A. 2 in the Appendix.

2.2.1. Scope and boundary

The GHG emissions associated with the building systems are reported as kg CO_2e per square meter of gross area, in line with the Swedish climate declaration regulation, which is intended to be enforced by Year 2022 (European Commission, 2020; Boverket, 2020),.[4] This study is concerned with the GHG emissions associated with the initial construction of the building and, thus, includes the emissions from materials production and the construction phase (i.e., corresponding to lifecycle stages A1–A5, as per the European standard (European Standards, 2011)). Further details as to the scope and boundary of the assessment and aspects are given in Table 3.

2.2.2. Benchmark GHG emissions

The benchmark GHG emissions for the five building systems included in the present study are displayed in Fig. 3. They demonstrate

[3] Literature searches were conducted using a combination of academic bibliometric databases (Scopus and Web of Science) and web browser searches were used to enable the sourcing of the relevant gray literature, which is not as evident in academic bibliometric databases. Search string algorithms targeted a combination of the material/activity in question (focusing on the key emissions sources as per Fig. 6) together with “carbon emissions” OR CO_2 OR GHG OR “greenhouse gas emissions” AND abatement OR “emission* reduction” OR mitigation OR decarbonization.

[4] To use gross area as the functional area seems also to be favored by the stakeholders involved in the assessment process. However, we note that several building standards, including the system Level(s) use heated area as functional unit.

Fig. 2. Drawing for the reference house for which each respective construction solution was designed (Photos: Reflex Arkitekter AB).
Source:Erlandsson et al. (2018).

Table 1
General descriptions of the analyzed building systems (Erlandsson et al., 2018).

Building system	Name	Description
A	In situ cast concrete with load-bearing outer wall	Inner and outer walls cast in place in adjoining moulds of cement-bonded boards with precast reinforced joists (slab supports) completed with cast concrete on site. This is the original construction of the reference house as built.
B	In situ cast concrete with lightweight walls	Outer walls composed of sheet metal and wood studs with load-bearing steel columns integrated in the facade. Floors of precast reinforced joists (slab supports) completed with cast concrete onsite. Load-bearing apartment-separating inner walls cast within reusable moulds, combined with other inner walls composed of plasterboard-covered steel beams.
C	Prefabricated concrete with load-bearing outer walls	Partly load-bearing, half-sandwich, prefabricated outer walls, precast load-bearing inner walls and hollow floor slabs overlaid with a floating floor of sheet metal joists and particleboard.
D	Prefabricated wooden volume element	Prefabricated volume elements with a wooden-beam joist frame. Double-layered floor and load-bearing, half-sandwich outer wall. Double-layered, load-bearing apartment-separating inner walls with other single-layered inner walls.
E	Cross-laminated wood frame and outer wall	Cross-laminated timber (CLT) floors overlaid with sheet metal joists and particleboard. Load-bearing CLT outer and inner walls combined with other non-load-bearing inner walls of plasterboard-covered steel beams.

that the main contributors to the embodied climate impact of the building systems on a general level are cement/concrete, steel, insulation, plasterboard, material transports and the construction process.

The embodied GHG emissions for the five building systems average 242 $kgCO_2e/m^2$ gross area, where the systems based on prefabricated concrete and in situ-cast concrete with lightweights walls (B and C) have around 15% lower embodied GHG emissions than the system with in situ-cast concrete with load-bearing outer walls (A). The two timber-frame systems (D and E) have around 35% lower embodied GHG emissions than the heavy in situ-cast concrete system (i.e., System A).

The main differences between the systems lie in the emissions embodied in the materials used (lifecycle stages A1–A3), which range from 150 to 160 $kgCO_2e/m^2$ gross area for the two timber-frame systems (D and E) and 208–218 $kgCO_2e/m^2$ gross area for Systems B and C, to 258 $kgCO_2e/m^2$ gross area for System A. On average, the materials make up 82% of the embodied emissions. The material transports and construction process stages (A4–A5) account for 38–48 $kgCO_2e/m^2$ gross area for the five systems, with material transports making up a larger share of the emissions for the prefabricated system (C–E). We note here again that this includes all components (also installations and elevator), the material transports and the construction process.

In the benchmark data, all components above the slab's draining layer are included and all resources used for the construction phase are included (Erlandsson et al., 2018; Malmqvist et al., 2018). For the analysis of mitigation potential, all building elements, with the exceptions of installations and elevators, are included (with the latter corresponding to 14 $kgCO_2e/m^2$ gross area for each building system). This is in line with the first stage of the Swedish climate declaration regulation, where the intention is to include the building's entire climate envelope and all supporting structural elements and interior walls of the building, while excluding installations and elevators (Boverket, 2020).

2.3. GHG abatement options and analysis

2.3.1. Climate impact calculations

For each scenario and during each time period, the total climate impact of each building system was estimated based on specific emissions intensity factors (Equation (1)).

$$Etot = i = 0, t = 0nMi*Efi,t \quad (1)$$

where E_{tot} is the total GHG emissions associated with the project; $Ef_{i,t}$ is the specific emissions intensity factor for each material/activity type i in year t; M_i is the amount/use of each material/activity; and $i = 1,2, \ldots,n$, is the material/activity types considered, i.e. concrete, steel, heavy transport etc.

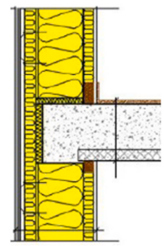
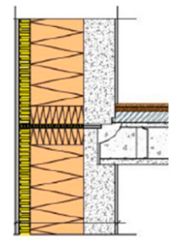
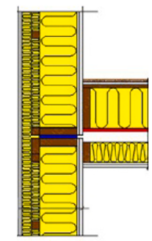
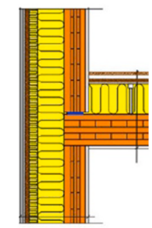
To enable assessments of different mitigation measures, the emissions intensity factors were divided into components where deemed feasible (Equation (2)).

$$Efi,t = j = 0, t = 0nEshj*Efj,t \quad (2)$$

where $Ef_{j,t}$ is the emissions factor for component j in year t; Esh_j is the share of the emissions factor from emissions component j; and $j = 1,2, \ldots, n$, are sources of emissions e.g. raw materials, production, and transport.

The emissions intensity factors were adjusted in the abatement analysis, on the basis of the abatement options selected and applied in

Table 2
Overall dimensions and illustrations of the analyzed building systems.

Building system	A	B	C	D	E
Illustration of building system					
Exterior wall dimensions (mm)	460	354	370	374	436
Floor structure dimensions (mm)	265	265	287	519	478
Interior wall dimensions (mm)	248	200	150	270/90	160
Gross floor area (m^2)	2524	2455	2454	2468	2508
Building height (m)	19.2	19.2	19.3	20.5	20.3

the assessment for each supply chain activity (Equation *3a* and *b,* where *a* is applied when the abatement measures reinforce each other and *b* is applied when abatement measures are applied independently).

$$Efi,j,t^* = Ab1^* \, Ab2^* .. ^* \, Abn^* \, Efi,j,t \tag{3a}$$

$$Efi,j,t^* = 1\text{-}Ab1^* Ab2^* \, Efi,j,t \tag{3b}$$

where $Ef_{i,j,t}$ is the emissions factor for material/activity type *i* and/or for component *j* where relevant in year *t*; $Ef^*_{i,j,t}$ is the amended emissions factor; *Ab* is the share of emissions remaining after the specific abatement measure has been implemented; and *1,2..n* are the types of abatement measures investigated, e.g. product choice, energy efficiency, fuel substitution etc. The adjusted emission factors were subsequently inserted into the initial material flow to give an updated picture of greenhouse gas emissions associated with the case object.

2.3.2. *Inventory of abatement options*

A summary of all the abatement options and their identified emissions reduction potentials are described in Fig. 4. The graph illustrates the range of the potential GHG emissions reductions recognized in the literature for each of the abatement options explored, where the range may depend on the level of the abatement measure that is adopted. The abatement options in this section are categorized according to their technical maturity.

For cement/concrete, the main emission abatement options currently available include: reducing the amount of cement clinker through the use of supplementary cementitious material (SCMs); optimizing concrete recipes to use less cement; and the slimming of the structures of constructed buildings (Habertet al., 2020). In the cement plant, there is also potential to substitute the conventional fossil-based fuels towards bio- or waste-based fuels. In the longer term, deep abatement measures include carbon capture in the cement clinker production with or without electrification (Wilhelmsson et al., 2018; Kajaste and Hurme, 2016; Lechtenböhmer et al., 2016).

Regarding steel, construction steel is predominantly produced from primary steel, while reinforcement steel is mainly produced from scrap steel (Ferdosian et al., 2017). Overall, enhanced material efficiency and circularity measures, such as increased scrap rate for construction steel, are key current abatement options to reduce the embodied emissions associated with steel (Energy Transition Commission, 2018; Material Economics, 2019; Allwoodet al., 2019; Material Economics, 2018). In the mid-term, bio-based fuels and reducing agents (charcoal or biocoke) are additional feasible options to mitigate GHG emissions (Suopajärviet al., 2018) in modern integrated steel plants. Achieving further CO_2 emissions reductions is difficult without drastic changes to the technology. Technologies with the potential for deep emission cuts include top-gas recycling blast furnaces with carbon capture, different smelting technologies, electrowinning, and hydrogen direct reduction (Wyns and Axelson, 2016). For scrap-based steel, electricity is the main energy carrier, which is why the emissions intensity of the electricity used is an important factor (Lindgrenet al., 2017; Celsa Steel Service, 2012). In addition, there is potential for biomass to substitute for fossil process energy, both as a reducing agent and as the fuel in reheating furnaces (Bianco et al., 2013; Norgate et al., 2012; Gunarathne et al., 2016).

For other materials, material efficiency measures and material substitution together with recycling are the main current abatement measures (for reviews, see e.g. (Akbarnezhad and Xiao, 2017; Kumari et al., 2013; Zabalza Bribián et al., 2011)). For insulation, i.e. mineral wool and polystyrene, other abatement measures include fuel changes (including electrification) and energy efficiency measures in the production processes (Material Economics, 2019; Schiavoni et al., 2016). In plastics production (which is also a raw material in polystyrene insulation), deep abatement options include electrification or carbon capture in cracking and polymerization (Material Economics, 2019; Lechtenböhmer et al., 2016). In the longer term, it may also be possible to foster the circular use of plastics in the form of thermochemical recycling plants for plastics (“recycling-plastic refineries”) (Thunmanet al., 2019).

For the production of plasterboards, the most prominent abatement measure is the use of recycled gypsum (Lushnikova and Dvorkin, 2016; Pedreño-Rojas et al., 2020). For aluminum production, in addition to circularity measures, i.e., the production of secondary rather than primary aluminum, abatement measures include biofuel substitution, electrification of alumina refining and secondary production, and inert anodes to reduce process emissions (Material Economics, 2018; Energy Transition Commission, 2017; Sandberg et al., 2019; Schüwer and Schneider, 2018; Energimyndigheten, 2018; Åhman et al., 2012; Wesseling et al., 2017). As the production of primary aluminum is electricity-intensive, the GHG emissions intensity of the production process is closely linked to the emissions intensity of the electricity production (Material Economics, 2018; McLellan et al., 2012).

Wood products are generally considered to have a low climate impact, with the main prerequisite being sustainable forestry, which from a CO_2 perspective, implies that the managed forest must capture more CO_2 per year and area than is captured by an equivalent standing forest (Hafner and Schäfer, 2018; Berndeset al., 2018). Lifecycle approaches and standards commonly presume that this prerequisite is safeguarded and, thus, consider wood products to be carbon-neutral over the lifecycle of a building (Tellnes et al., 2017; Skullestad et al., 1876). The climate impacts of wood products are also influenced by emissions from other elements of the supply chain, such as forestry, glues, and processing (Moore, 2020; Ramageet al., 2017), where mitigation measures relate to harvester machines and timber transports,

Table 3
Details of scope and boundary of the case study assessment.

	Aspect	Scope/boundary	Details
Mapping of material and emission flows	Lifecycle stages of the building (as per the European standard (European Standards, 2011))	GHG emissions embodied in materials and associated transports and construction process (A1-A5)	The assessment is concerned with emissions materializing up to the point of construction. GHG emissions associated with operation, maintenance, renewal and end of life of the respective building systems can be found in Erlandsson et al. (2018).
	Material production stage (A1–A3)	GHG emissions embodied in materials	The benchmark GHG emissions contain embodied emissions for all materials and components down to the “bolts and nut” level, calculated in the reference LCA study by combining the resource compilations with generic LCA data from the database provided by the IVL Swedish Environmental Research Institute via its free Building Sector’s environmental calculation tool.
	Material transports (A4)	GHG emissions associated with transports of materials to the construction site	Transports to the construction site (lifecycle stage A4) were calculated in the reference LCA study using generic transport distances for each material/component, except for prefabricated elements (Systems C, D and E) for which the actual distances from the production plants were employed (Erlandsson et al., 2018; Erlandsson, 2018).
	Construction process (A5)	GHG emissions associated with waste, energy and fuel use on the construction site. Does not include groundwork.	The production and management of waste materials on site were calculated based on employed waste percentages in the generic LCA data for each material. Energy and fuel use on the construction site were calculated in the reference LCA study based on detailed data provided by the construction companies. The study does not include emissions associated with the groundwork or soil stabilization needed to prepare the construction site, which is the most common boundary used in building LCA studies.
	Emissions from electricity/district heating	GHG emissions associated with the use of electricity and district heating in both the production plants and on the construction site	Assumes Swedish/Nordic electricity and district heating emissions factors for the construction site and that products are predominantly produced in the Nordic countries, e.g., wood products, cement and plasterboard, and assumes European electricity emissions factors for products that are predominantly produced internationally, e.g., steel and aluminum. The analysis assumes that the emissions factors for electricity and district heating decrease in accordance with the scenario analysis from the Swedish Energy Agency and estimates made by the European Energy Agency, implying that GHG emissions related to electricity generation are approaching zero in 2050 (Energimyndigheten, 2016; EEA, 2018) (see Table A. 2 in the Appendix).
	Emissions associated with vehicle fuels	Cradle-to-tank	Includes upstream emissions from extraction and refining according to lifecycle assessments performed by the Swedish Energy Agency (Energimyndigheten, 2020).
	Emissions from construction equipment and trucks	Operational emissions	Life-cycle emissions from production and end-of-life of construction equipment and trucks are not included due to the complexity of calculating and attributing these parameters to a specific project.
	Emissions attributed to biogenic carbon	Considered CO_2-neutral	The emissions that are attributed to biogenic carbon remain a subject of debate in the literature (for example, see (Plevin, 2017; Tellnes et al., 2017)) and are dependent upon the raw material source and management thereof. In this study, the wood products used in the different building systems designs are considered carbon-neutral based on the assumption of a carbon-neutral forestry system at the landscape level, in which the carbon uptake is greater than or equal to carbon withdrawal (Kumar et al., 2020). However, the reference LCA study has calculated the temporary carbon sink, i.e. the conversion of built-in biogenic carbon in the form of CO_2 in the wood products used in the different building systems designs based on the assumption of a carbon-neutral forestry system, in which carbon uptake is greater than or equal to carbon withdrawal. Erlandsson et al. (Erlandsson et al., 2018) have consequently reported that this accounts for: 28–41 $kgCO_2e/m^2$ gross area for the concrete-based systems; 142 $kgCO_2e/m^2$ gross area for the system with volume elements in wood; and 311 $kgCO_2e/m^2$ gross area for the solid frame in cross-laminated timber. However, for the purpose of this study the use of wood products is considered CO_2-neutral, i.e. we have not factored the effects of sequestration of biogenic carbon in timber.
	Concrete carbonation	Not included	While concrete structures reabsorb some of the embodied CO_2 if exposed to air, this happens mainly in the end-of-life phase (Peñaloza et al., 2018). This is not considered in the present study, as the focus is on emissions at the point of construction. Concrete carbonation is, however, included in the reference LCA study (Erlandsson et al., 2018).
Inventory of abatement options	Materials	All except installations, elevators and minor components Included	Mitigation options and potentials are assessed for all the major materials used in the structure and façade of the building. As such, this analysis does not include installations and elevators.

(*continued on next page*)

Table 3 (*continued*)

Aspect	Scope/boundary	Details
Abatement technologies in material production		The assessment includes fuel substitutions, energy efficiency measures, electrification and carbon capture and storage.
Optimization/alternative design	Partly included	Material, work or transport efficiency measures are included in the calculations for the case study assessment; modal shifts and measures that would require a structural redesign are not included.
Material substitutions	Partly included	Material and material component substitutions are included, whereas material substitutions that would require a structural redesign, such as a change of insulation materials, have not been included.
Recycling/reuse	Partly included	Potentials regarding increasing levels of recycling in material production are included, while measures concerned with the reuse of elements are only briefly considered.

while electricity (combined with forest residues) is used as the energy in processing. This means that the carbon intensity of the electricity supply is of importance (Skullestad et al., 1876; IVA, 2017; Skogsindustrierna and Sverige, 2018). Regarding adhesives, the most promising abatement option is the use of natural resins (Lettneret al., 2018; Sandberg, 2016; Ferdosian et al., 2017; Hemmilä et al., 2017; Nakos et al., 2016).

The entire construction supply chain benefits from a focus on material efficiency measures (Energy Transition Commission, 2018; Material Economics, 2019; Allwood and Cullen, 2012; Allwoodet al., 2019; WRAP, 2013; Wyns et al., 2019), which also reduce transport needs and, thereby, the emissions associated with transports. Other current abatement measures for material transports include optimization of logistics, utilization rates, and transport distances (Skinner et al., 2010; Green Construction Board, 2013; Ko, 2010). In the short-to-medium term, abatement measures for heavy vehicles and machinery also include fuel substitution and hybridization (Delgado et al., 2017; Gaoet al., 2015). Over the longer term, deeper reductions in emissions would accrue from direct or indirect electrification of construction equipment and heavy trucks (e.g. battery-electric or fuel-cells) (Energy Transition Commission, 2018; IEA, 2017a; Nykvist and Olson, 2019; Bondemark and Jonsson, 2017).

For construction processes, abatement measures also include enhancement of the efficiency of the construction by optimizing the material handling requirements, site layout, utilization of vehicles, and choice of construction equipment for the intended use (Akbarnezhad and Xiao, 2017; Kumari et al., 2013; Green Construction Board, 2013; Swedish Transport Administration, 2012).

2.4. Scenario building and analysis

Starting out from the supply chain focus of the assessment, three scenarios that include GHG abatement measures in different parts of the supply chain are devised in the present study. The first scenario focuses on abatement measures in primary material production. The second scenario takes a step down the supply chain and focuses on the processing of primary materials in combination with the composition of materials or material components in the building systems. The third scenario also adds measures related to the design and structure of the building systems, thereby concentrating on material efficiency measures. Everything from the previous scenarios applies unless explicitly stated otherwise. Thus, the scenarios are additive, such that the abatement measures detailed in the second and third scenarios build on the abatement measures included in previous scenarios. A schematic of the main abatement measures included in the different scenarios is provided in Fig. 5. Further details of the abatement measures included for each component in each scenario and timestep is included in the Supplementary Material.

The scenarios are predominantly based on reaching the medium-high range of the emissions reduction potentials for each selected abatement measure (as per Fig. 4), with measures and timelines that are largely compatible with the roadmaps and pathways developed within the European Commission long-term climate strategy (combination of electrification and hydrogen scenarios), along with the industry roadmaps developed within the Fossil Free Sweden project on fossil-free competitiveness (Energy Transition Commission, 2018; Sverige, 2018a; European commission, 2018).

3. Results

The potential reductions in GHG emissions from now to Year 2045 for the studied building systems in the three different supply chain scenarios are shown in Fig. 6. The figure exhibits the GHG emissions for the building system construction that includes embodied emissions in materials and emissions from material transports and the construction process (including all materials, with the exceptions of installations and elevators). The GHG emissions reductions depicted result from the combination of abatement measures applied in the scenario (as per the matrix in Fig. 5), as compared with the benchmark. Fig. 6 depicts the combined abatement across the supply chain if constructing an equivalent building while applying the current best-available technology and practices ("BAT Now"), along with the resulting abatement if applying the abatement measures that are deemed likely to be feasible when constructing the same building in 2025, 2030 and 2045, respectively. It should be noted that the percentage values for the reductions given in the boxes relate to the reference value for each individual curve. The reference values correspond to the reference building built using the different building systems, with benchmark emissions as described in Section 2.2.2.

The results indicate potential reductions in GHG emissions of 25%–40% and medium-term GHG abatement potentials of 59%–80% to Year 2030. In addition, they demonstrate that it should be possible to reach close-to-zero emissions in Year 2045 (85%–93% reduction) for the construction of all five building systems and in all three supply chain scenarios. There are, however, notable differences between the scenarios, predominantly in the short-to-medium term, and particularly for the concrete-intensive building systems, i.e., building Systems A–C.

Starting with the potential for GHG emissions reductions in the short term, Fig. 6 demonstrates that applying abatement measures only to primary material production yields emissions reductions of 25%–30% when using currently best-available technologies, practices and products (BAT Now). These emissions reductions would stem predominantly from the use of cement clinker substitutes in concrete and biofuel substitutions in material and timber transports and some construction equipment, combined with choosing the best-available products on the market regarding plasterboard, reinforcement steel and insulation.

When also taking into consideration abatement options in material processing and composition, as per Scenario 2, the potential reduction in GHG emissions using currently available technologies (BAT Now) increases to 28%–36%, with a higher potential for the concrete-intensive building systems, primarily due to optimization of concrete recipes to

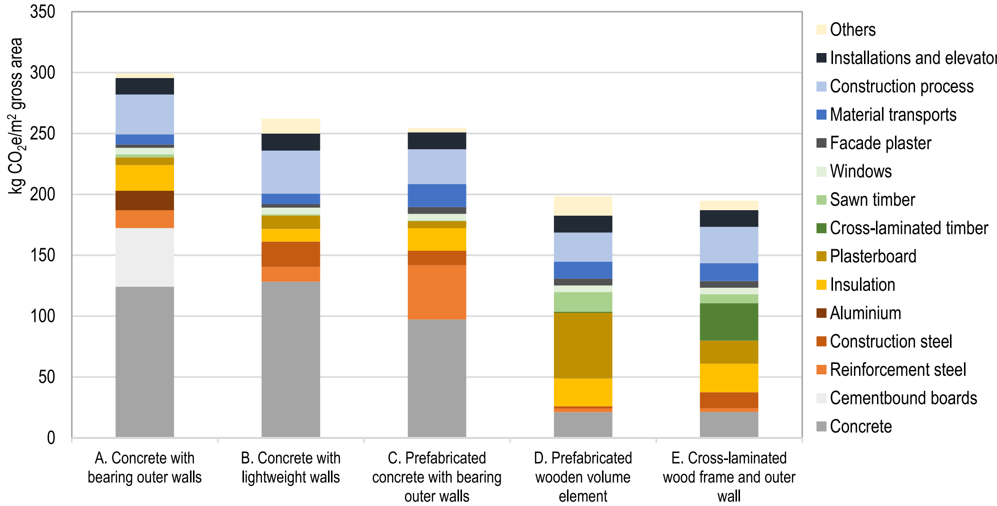


Fig. 3. Building construction GHG emissions, by category, associated with construction of the respective building systems in the benchmark case, i.e. before consideration of any measures to reduce emissions (including lifecycle stages A1-A5).

reduce the binder intensity of the concrete, which would reduce the share of cement clinker and associated emissions.

The final scenario, Scenario 3, which focuses on abatement options implemented for the structure at the design stage, i.e., material efficiency measures, demonstrates a slightly higher potential for emissions reductions (31%–40%) through the application of currently available technologies (BAT Now), with the additional reduction mainly linked to slimmed structural elements and a reduced need for material transports. In the structure scenario, the concrete-intensive building systems have the potential to reach the same levels of embodied emissions as the original timber-framed building systems (i.e., 193–195 $kgCO_2e/m^2$ gross area), although this does not include the temporary carbon sinks that could be associated with the increased level of wood products in the timber-framed systems (Hafner and Schäfer, 2018).

Up to Year 2025, the GHG emissions reduction potential appraised in the analysis ranges from 31% to 54% Continuing efforts regarding biofuel substitution in construction equipment, cement clinker substitution, and increased levels of recycling linked mainly to plasterboard and insulation are the main contributors to the additional reductions in the primary material reduction scenario. Optimization of concrete recipes with strict adherence to concrete standards and increased levels of scrap-based steel in structural steel contribute additional reductions in the material processing and composition scenario, while material efficiency measures across the materials used are the main contributors to the additional reduction in the structure scenario.

Looking towards Year 2030, we envisage a significant increase in the potential for GHG emissions reductions linked to the construction of equivalent building systems, with a >60% abatement potential across the board. For the concrete-intensive building systems, the potential for a reduction in emissions is predominantly the result of the implementation of carbon capture in cement clinker production, although there are also other contributors particularly in the material processing and structure scenarios.

Some of the emissions abatement stems from electrification of construction equipment, in combination with biofuel substitution and electrification in material production processes, with the former, for example, in steel and mineral wool production and the latter in the production of plasterboard and plastics (with carbon capture as an alternative in chemicals/plastic production). The differences between the scenarios are slightly smaller in 2030 compared to 2025. However, optimization and material efficiency measures make up a greater share of the abatement in Year 2030 than in Year 2025.

In Year 2045, we foresee potential GHG emissions reductions of 84%–93%, noting large differences in how this abatement potential is realized between the different scenarios. In the concrete-intensive building systems, a large share of the total GHG emissions abatement in the primary material production scenario derives from carbon capture in the cement clinker production, combined with cement clinker substitution. This reduction is supported by further implementation of carbon capture or electrification in the production chain of plastics, which also impact the embodied emissions of polystyrene insulation. Further reductions result from indirect electrification via hydrogen reduction in primary steel production and biofuel substitution in scrap-based steel and downstream steel metallurgy and processing. For the wood-framed building systems, the main additional GHG abatement in the primary material production scenario from 2030 to 2045 results from biofuel substitution and increased recycled feedstock in plasterboard and mineral wool production. This is supported by the electrification of forestry operations and timber transports, together with the use of natural resins in adhesives for cross-laminated timbers and other glued wood products.

We see only slight differences in the overall GHG emissions reduction potential between the primary material production and the material component scenario. A larger share of the reduction in the concrete-intensive building systems results from the optimization of concrete recipes with the support of admixtures, fillers and granular optimization with finer aggregates, to allow for significantly lower binder intensities. The structure scenario has the potential to achieve GHG emissions reductions of >90%, with a significant share of the abatement linked to material efficiency measures, particularly in the building systems based on in situ-cast concrete.

To highlight further the types of abatement measures that yield the potential GHG emissions reductions over time, we focus on System A, where the structural frame is based on reinforced concrete cast in situ in a mould of cement-bound boards with polystyrene-based insulation. Fig. 7 provides a comparison of the GHG emissions reductions from applying the abatement measures in the three different supply chain scenarios for System A. When applying the best-available technologies and practices, we see that more than half of the GHG emissions reductions result from material substitution measures, i.e., cement clinker substitutes in concrete and cement-bound boards. In the material composition scenario, the share of the reduction which result from material substitution measures increases to two thirds of total emissions reduction. This additional abatement derives from the optimization of

Fig. 4. Range of GHG emissions reduction potentials for the abatement options identified in the literature review for the main emissions sources (color-coded). The analysis is based on reaching the medium-high range of the emissions reduction potentials for each selected abatement measure when fully implemented. The Supplementary Material provides full details of the measures for all activities, including timelines, potentials and references. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

concrete recipes to reduce the binder intensity, where the binder is substituted by aggregate or filler, combined with substituting a share of the plastic in polystyrene-based insulation with graphite. In the structure scenario, applying material efficiency measures to slim the construction contributes about one-fifth of the GHG emissions reduction.

Similar trends are followed regarding the GHG emissions reduction measures adopted in Year 2025, while we see the picture changing to a greater extent up to Year 2030, and even more so up to Year 2045.

In Year 2030, half of the GHG emissions reduction potential in the primary material production scenario results from what we here refer to

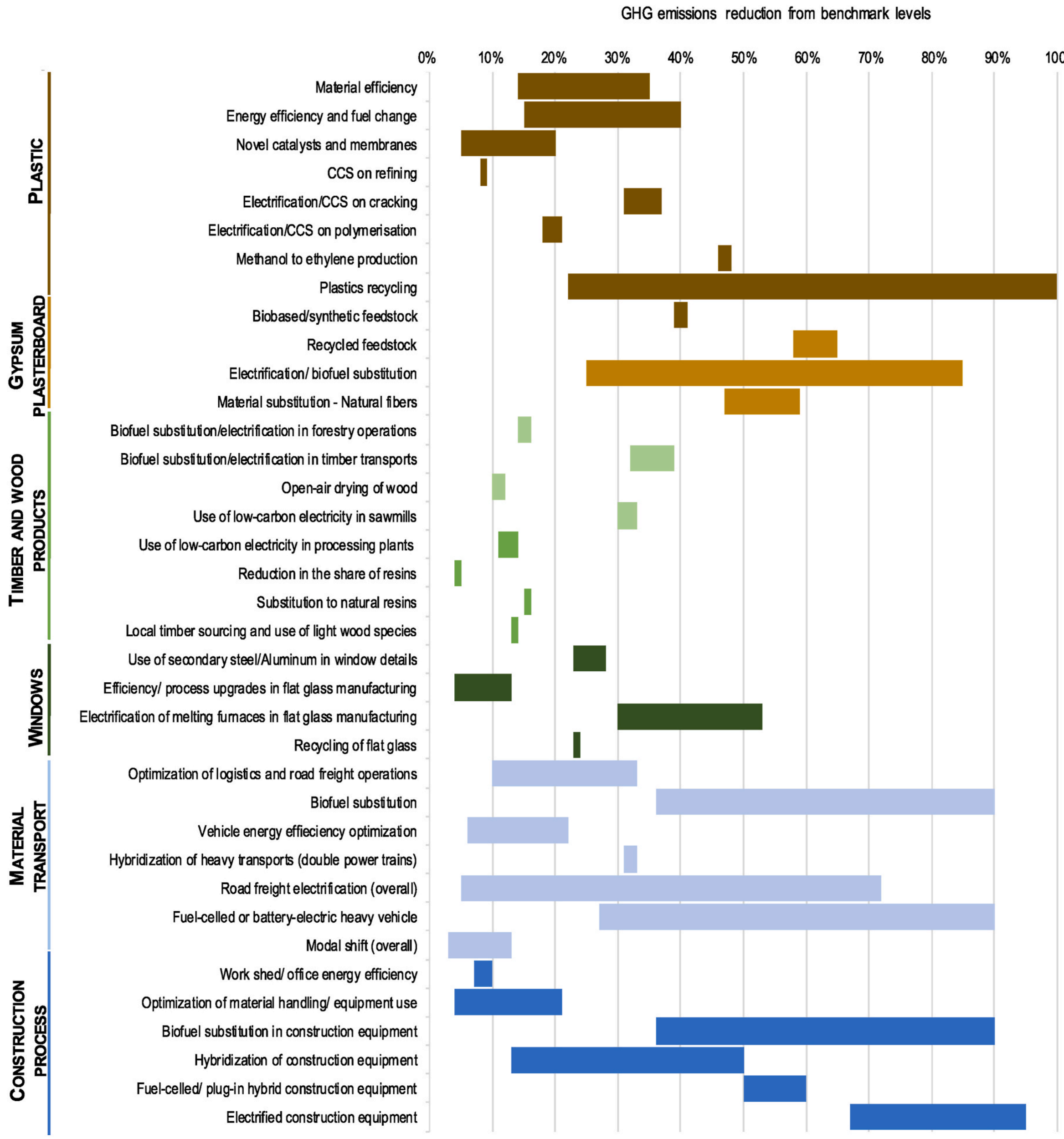


Fig. 4. (*continued*).

as 'transformative measures', i.e., breakthrough technologies such as electrification and carbon capture, applied in cement clinker production, the production of plastic for polystyrene insulation, and in the use of electrified construction equipment. As a consequence of these measures, the share of abatement resulting from cement clinker substitution and the use of transport biofuel is reduced accordingly. The absolute GHG emissions reductions from recycling and optimization of logistics and equipment use increase further up to Year 2030.

Optimization of concrete recipes to reduce binder intensities in both concrete and cement-bound boards contributes significantly to the GHG emissions reduction in the material component scenario to Year 2030, which reduces the share of abatement from electrification and CCS from half of the abatement in Scenario 1 to one-third in Scenario 2. In the structure scenario, the reliance on electrification and CCS decreases to 25% of the total GHG emissions reduction, while material efficiency measures contribute with similar levels.

Up to Year 2045, however, the share of total GHG abatement from electrification and CCS increases slightly in all three scenarios, mainly as a result of the electrification of transports and construction equipment, together with the implementation of electrification or carbon capture in plastics production.

Fig. 8 provides further details into the types of abatement measures contributing to GHG emissions reductions related to concrete for building system A. This underlines the potential that results from material efficiency measures, i.e., measures to slim construction elements and optimize concrete recipes to reduce binder intensity and be more strictly in line with concrete standards. In the short term, it provides for the GHG emissions abatement to be double compared to applying measures only in cement production. In the longer term, even though the total abatement is equivalent, more than half of this GHG emissions reduction is derived from carbon capture in cement clinker production in the primary material production scenario, while this is halved to 30% in the structure scenario.

While they provide a comprehensive picture, there are also abatement measures that are not reflected in the developments of System A due to its original material composition, including abatement measures

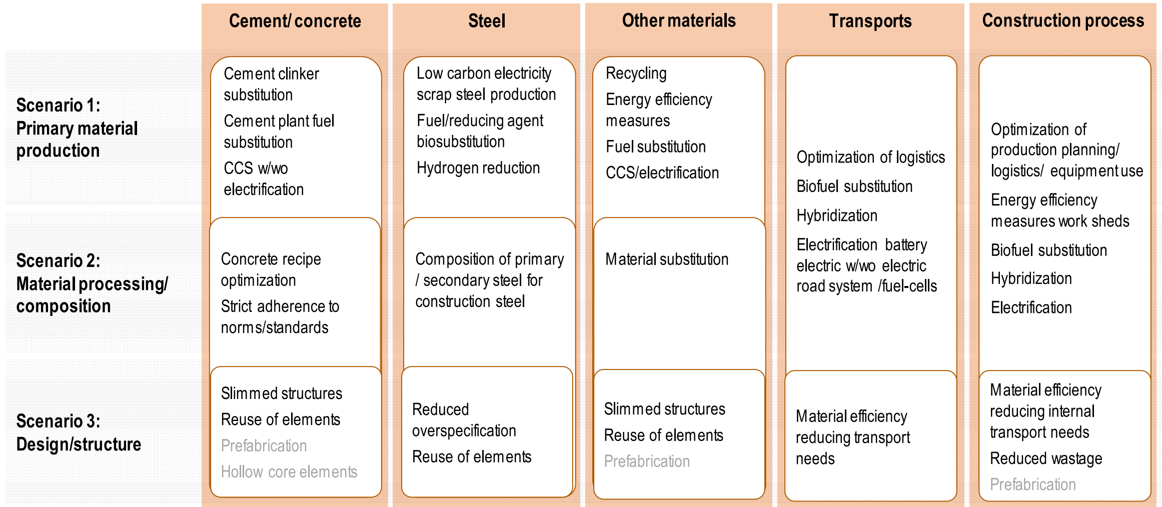


Fig. 5. Outline of the main GHG abatement measures included within the different scenarios tested in the case study scenario analysis. Measures indicated in gray are abatement measures that are included in the various building systems. The Supplementary Material provides further details on the abatement measures included in each time step for each component.

linked to construction steel, mineral wool and timber products, which are relevant for several of the other building systems. To demonstrate the differences compared to System A, an equivalent comparison of the types of abatement measures that are contributing to the GHG emissions reduction for System E, which is based on a structural frame of cross-laminated timber with stone wool insulation, is shown in Fig. 9.

We here see that a large part of the GHG emissions reduction obtained when applying best-available technologies, practices and products (BAT Now) results from biofuel substitution in the transport of timber, materials and structural elements. It is worth noting here that modal shifts to the use of train transports or intermodal solutions could be an alternative to this abatement measure, where such opportunities exist.

In addition to transport biofuel, around 20% of the GHG emissions reduction in all three supply chain scenarios in the short term results from product choices, including the choice of reinforcement steel produced from low-carbon electricity and stone wool insulation produced in electric arc furnaces rather than gas-driven furnaces. There are also contributions from measures concerning concrete, while these reductions are significantly lower than those in the concrete-framed building systems, as this building system contains only concrete in the foundation. In the structure scenario, material efficiency measures contribute to 14% of the total abatement at present.

Looking forward towards 2030, we see that the picture is shifting, with the share of total abatement from the benchmark resulting from transport biofuel decreasing significantly. In the first two scenarios, the main increase in GHG emissions reductions results from other biobased measures, including biofuel substitution in cement and steel production and substitution towards natural resins in the adhesives used to glue the cross-laminated timber. These measures are supported by recycled feedstocks in the production of structural steel, plasterboard and stone wool insulation, as well as by the optimization of equipment use and transport and construction site logistics. We note that the overall GHG emissions reductions to Year 2030 are in relative terms lower for the timber-framed systems than for the concrete-framed systems.

For the timber-based systems, the importance of electrification to achieving deep decarbonization is demonstrated in the time-step to Year 2045, where the electrification of heavy transports, forestry and construction equipment and the electrification of primary steel production based on hydrogen reduction together contribute with 25% of the total GHG emissions reduction from the benchmark in the primary material production scenario. This share goes down in the structure scenario, where material efficiency measures account for around 20% of the total abatement, with the overall GHG emissions reduction from the benchmark reaching 90%.

In summary, we note that for all systems, a considerable share of the total GHG emissions reductions to 2030 and 2045 comes about as a result of decarbonization of the energy system, particularly the electricity system. This has consequences both for electrified material production and electrified transports and activities on the construction site.

4. Discussion

With potential reductions in the range of 31%–40% for the individual building systems when applying currently best-available technologies, practices and products, this study demonstrates that by including the entire supply chain in the mitigation efforts, it is possible to increase the potential from the 15%–30% reduction potential reported previously by the Swedish National Board of Housing, Building and Planning (Boverket, 2020).

While culture, available competence, and regional building habits (rather than environmental impacts) have traditionally been the key reasons for developers and designers to decide on the type of construction system for a building (Andersson et al., 2018), several recent initiatives signal that this is about to change. These include the Roadmap to Fossil Free Competitiveness that the Swedish building and construction sector has developed, which sets targets of 50% reduction by Year 2030 and net-zero emissions by Year 2045 (Sverige, 2018b), along with regulations for climate declarations for new buildings that are to be enforced in Sweden by 2022 (Boverket, 2020) with linked thresholds introduced in 2027. We also see the development of certification schemes and local and regional initiatives, such as the Malmö City roadmap LFM30, which aims for a climate-neutral building and construction sector in Malmö with net-zero CO_2 emissions by Year 2030 (LFM30, 2019).

Focusing in on the types of measures that contribute to the abatement potentials demonstrated, there is a clear impact of material efficiency measures. Accordingly, if measures linked to materials are only applied in primary material production, the potential reduction decreases significantly, particularly in the short term, decreasing by over 10 percentage points in relation to the current level and that to Year 2025 (down to a maximum of 30% and 40%, respectively). We note that despite this potential, work conducted in recent years to reduce emissions has focused on primary industry on the one hand, and energy use

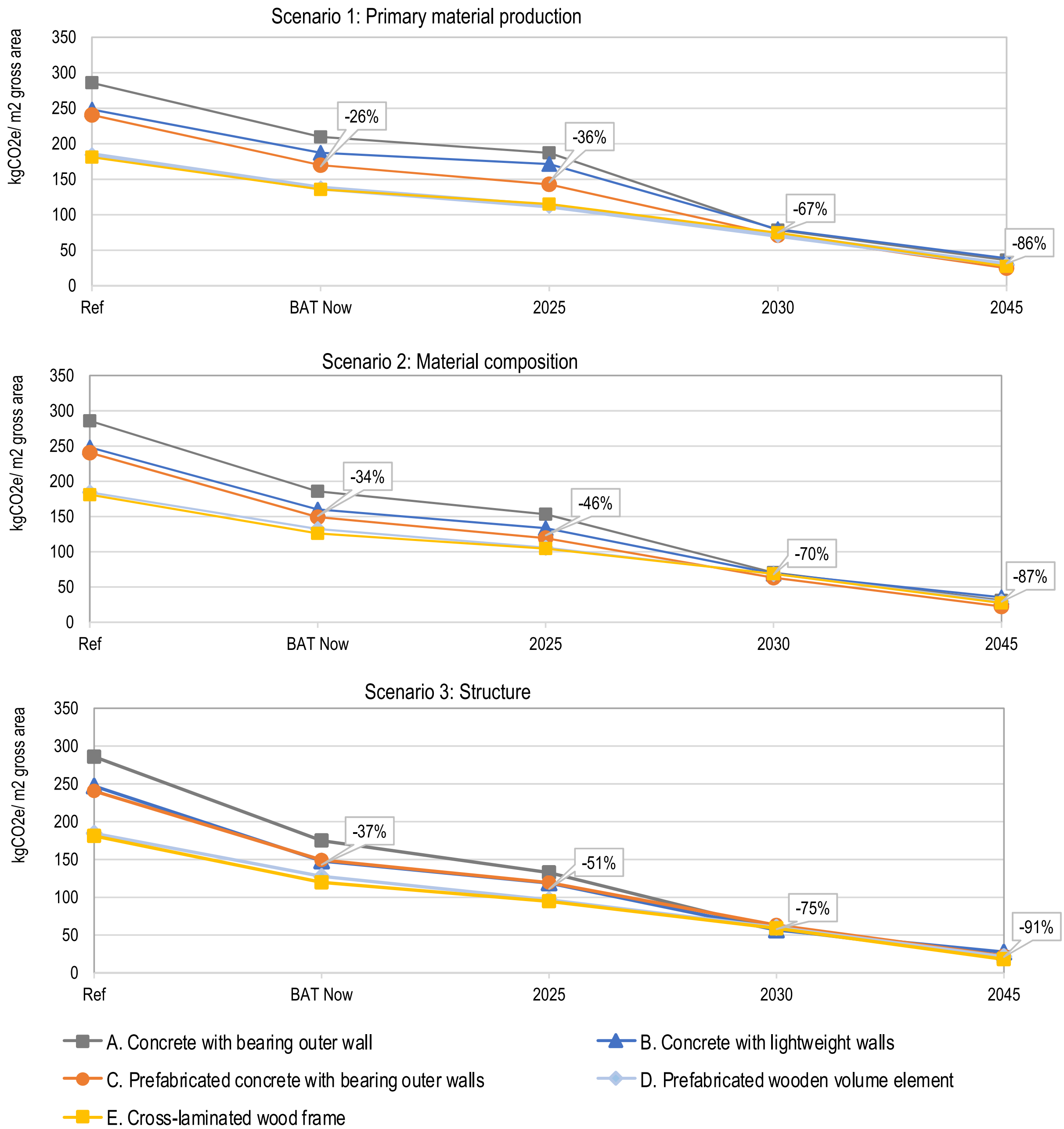


Fig. 6. Potential reductions in GHG emissions (when constructing an equivalent to the multi-family reference building shown in Fig. 2) from now until Year 2045 for the five studied building systems under the three different supply chain abatement scenarios investigated in this work. To exemplify the reduction potentials, the graph depicts the average percentage reductions in the three scenarios, starting from abatement resulting from applying best-available technologies, practices and products (BAT) at the present time and on a timescale if the same building would be constructed with materials and technologies that are deemed likely to be available in 2025, 2030 and 2045, respectively.

in the use phase of buildings on the other.

This focus has neither included the middle segments nor has it favored interactions between stakeholders along the entire value chain (Favier et al., 2050; Sveriges Byggindustrier and Iva, 2014). In order to realize the potential that can be provided by applying measures across the supply chain, we see a need for far greater collaboration along the whole value chain. Taking the example of concrete, to realize the emissions reduction potential demonstrated in this study, close collaboration between all the relevant actors in the supply chain, including cement producers, concrete producers, structural engineers, procurers, clients, and architects etc., would need to be initiated already during the design and early procurement phases, with close and continuous communication activities throughout the planning and construction phases (Moore, 2020). This also implies that demand-side actors within the value chain, including investors, developers and designers, work together with those on the supply side – the contractors and materials manufacturers. However, while material efficiency measures would reduce material costs, they are associated with higher transaction costs due to the complexity and implications linked to their implementation (Holmes, 2010; Mundaca T et al., 2013).

For these types of collaborations to take place (i.e., a prerequisite for material efficiency measures to become widespread), incentives must also be changed, including strong policy and regulatory support and access to finance along with measures towards risk distribution along

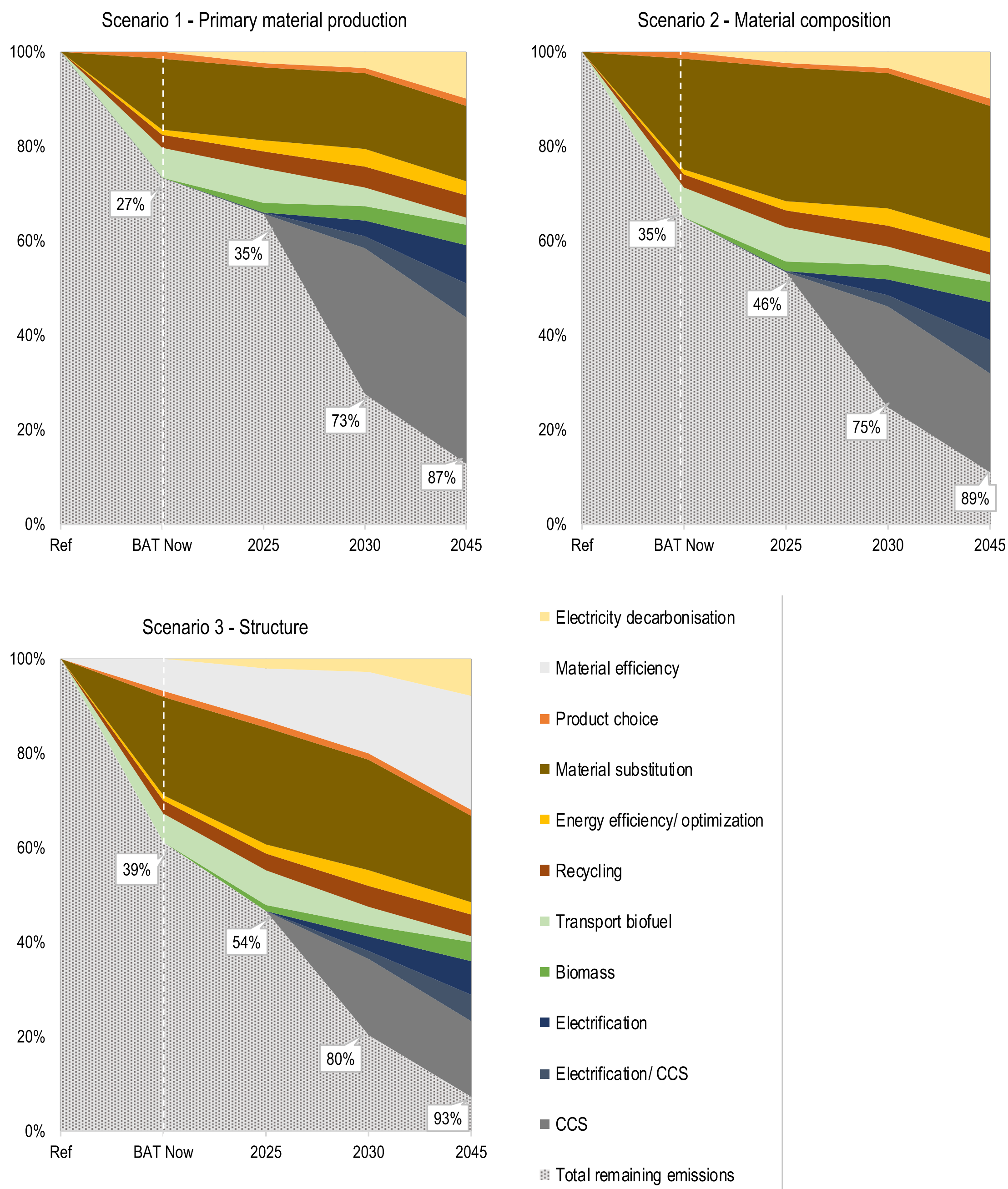


Fig. 7. Comparison of the GHG reductions achieved through application of different types of abatement measures in the three supply chain scenarios for now until Year 2045 for building System A: In situ-cast concrete with load-bearing outer walls. 100% refers to the Reference building with the benchmark emissions described in Section 2.2.2.

the value chains (World Green Building Council, 2019; Material Economics, 2019). In addition to the early involvement of designer and material suppliers in the planning process, the enabling actions include: clear legitimization and prioritization from project management and top management, together with the allocation of sufficient resources, competence and time; increased digitalization of material properties data, logistics and materials flows; and the use of pain-gain sharing arrangements to incentivize/de-risk innovation (Rootzén et al., 2020; Kadeforset al., 2020).

The realization of these high-potential measures would also be incentivized by better measurements and reporting of materials efficiency in the construction sector. In this context, several reports have proposed implementing policy instruments linked to key performance indicators, such as the level of cement clinker and binder in concrete, measured as kg clinker/binder per cubic meter and MPa (Habertet al., 2020; Favier et al., 2050). Indicators have also been proposed that relate to the level of embodied GHG emissions in the structure of the building, which would target the potential for slimmed construction. Indeed, studies have demonstrated that many construction projects use 30%–50% more cement and steel than would be necessary with an end-to-end optimization (Allwood and Cullen, 2012; Wyns et al., 2019), which arises from a standardized design process in combination with minimal economic gains of an optimized design (Andersson et al., 2018; Allwood et al., 1986). Thus, there is great potential in policy instruments that

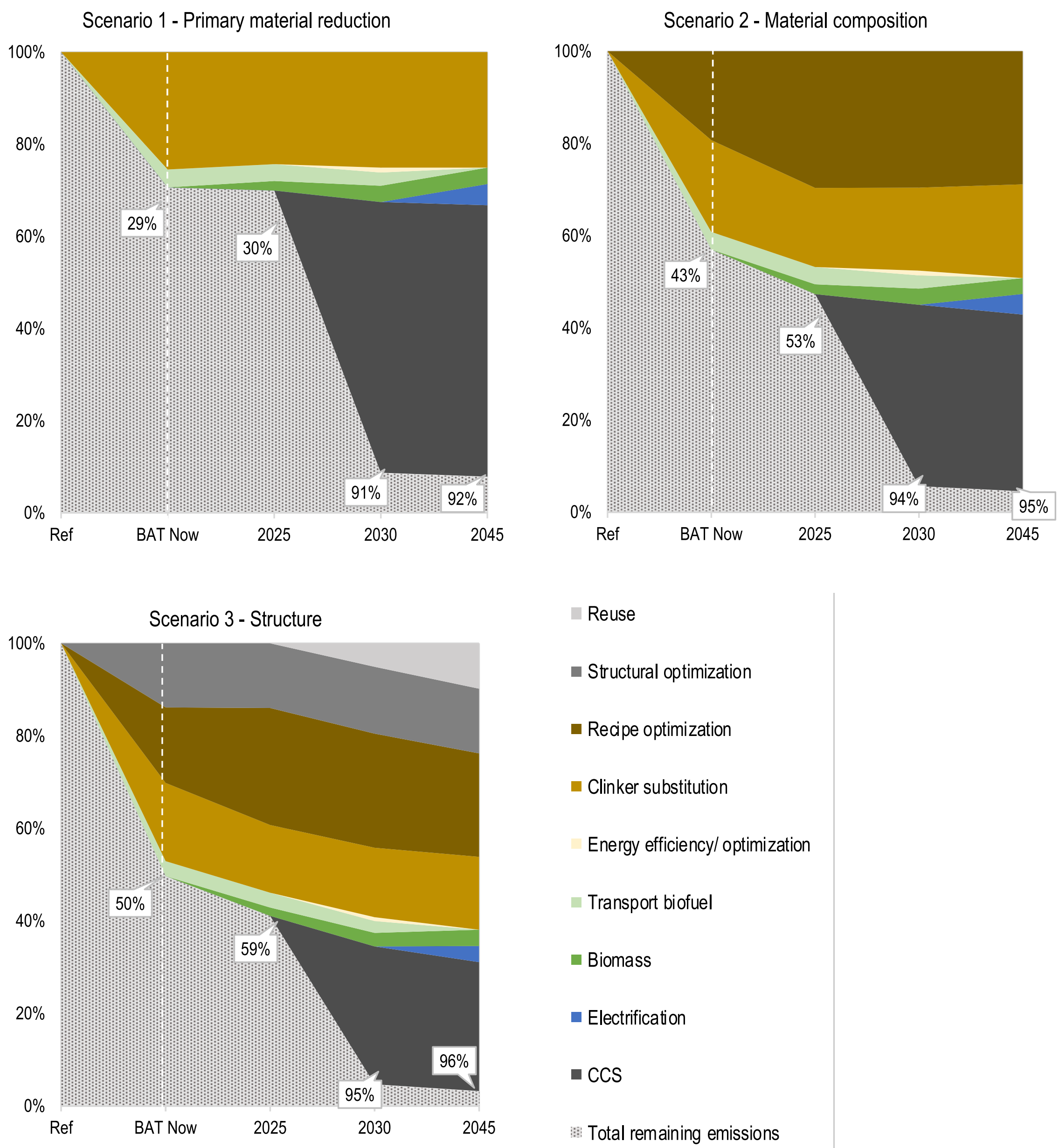


Fig. 8. Comparison of the GHG reductions achieved through application of the different types of abatement measures in the three supply chain scenarios from now until Year 2045 for the use of concrete in building System A: In situ-cast concrete with load-bearing outer walls. 100% refers to the concrete used in the Reference building with the benchmark emissions described in Section 2.2.2.

deal with the current asymmetry of costs, whereby downstream production (and design) are currently dominated by labor costs rather than material costs (Energy Transition Commission, 2018; Material Economics, 2019; Allwood and Cullen, 2012; Allwoodet al., 2019; WRAP, 2013; Wyns et al., 2019).

Looking forwards towards Year 2045, transformative technologies are required to reach the goal of net-zero emissions, including the application of carbon capture in cement clinker production and the electrification of primary steel production, heavy transports and construction equipment. These technologies are characterized by long lead times for their implementation, as well as high investment costs (Daviset al., 2018; Batailleet al., 2018; Klugmanet al., 2019). Thus, while necessary for realizing the net-zero emissions goal, these technologies will take time to be implemented. Furthermore, by focusing on material efficiency and optimization measures that can be implemented at significant levels in the short-to-medium term, there is a potential to reduce the investment costs required for the transformative technologies in the longer term (IEA and CSI, 2018). Indeed, the results of this study demonstrate that 14%–26% of total GHG abatement from the benchmark to Year 2045 could be achieved through material efficiency measures, which would thus make up a significant share of the required abatement that would otherwise need to be brought about by transformative measures.

5. Conclusion

This study involves a multidimensional assessment of the potential for GHG emissions abatement related to the construction of multi-family housing. The assessment is made along the value chain from material production via material transports and the construction process up to

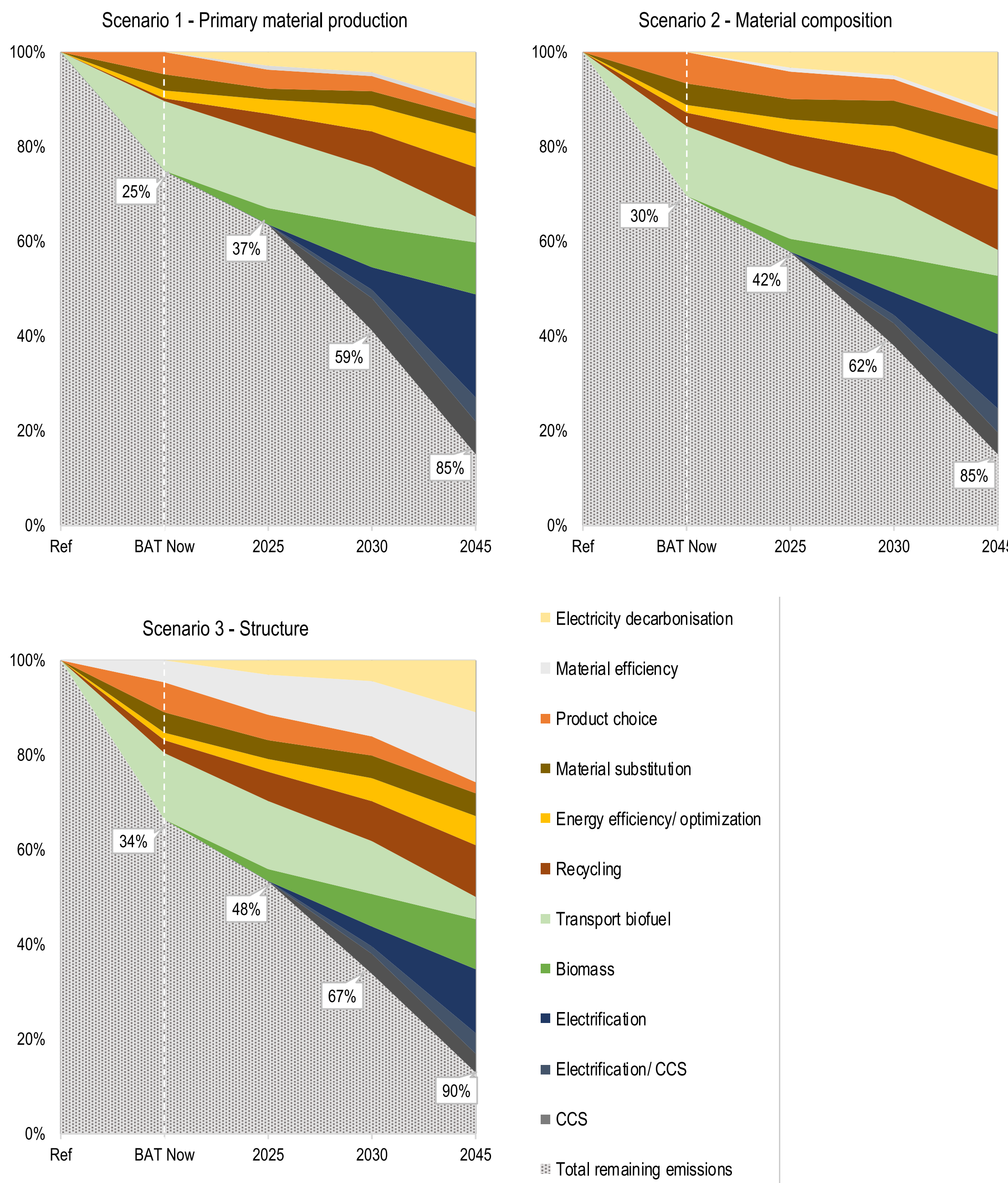


Fig. 9. Comparison of the GHG reductions achieved through application of the different types of abatement measures in the three supply chain scenarios for now until Year 2045 for building System E: Load-bearing cross-laminated timber frame. 100% refers to Reference building with the benchmark emissions described in Section 2.2.2.

the point of a finished building (equivalent to lifecycle stages A1–A5, as per the European standard (European Standards, 2011)). The first dimension relates to different building designs with the same functionality, whereby the study starts out from an existing comparison study developed by Erlandsson et al., in 2018 (Erlandsson et al., 2018), featuring standard structural frame designs. The building systems include in situ-cast and precast concrete frames along with prefabricated timber frames, constructed with whole timber beams and cross-laminated timber, respectively. The benchmark embodied GHG emissions for the five building systems are in the range of 195–299 $kgCO_2e/m^2$ gross area, with materials accounting for an average of 82%, which places them in the medium range of equivalent buildings in comparison with the results from recent relevant LCA reviews (Moncaster et al., 2019; Seleborg, 2019; Zimmermann et al., 2020).

The second dimension of the study relates to time, whereby the study builds up an inventory of abatement options in the supply chain of building construction and analyses the potential GHG emissions reductions when combining these measures with the perspective of technologies and practices that are available at the present time and that are deemed to become available on a timescale up until Year 2045, when Sweden has set a goal of net-zero GHG emissions.

The third dimension of the study analyses the potential for GHG emissions reductions when applying abatement measures at different points along the supply chain, from primary material production via material processing and composition to the design of the final building structures. In applying measures along the supply chain, this building system case study assessment establishes the potential for reducing by up to 40% the GHG emissions associated with the construction of common building systems for multi-family housing using existing best-available technologies. This reduction increases to 54% by 2025, with even greater potential reductions of 80% by 2030 and 93% by 2045.

In view of the stringent, long-term climate objective, the main value of this work is to add supply chain and time dimensions to the analysis of where and when different mitigation measures need to be in place if emission reduction targets are to be met. This is particularly relevant given the slow uptake of innovations in the project-based, risk-averse construction industry. By including these dimensions, we identify where in the supply chain large shifts are needed and highlighting strategic choices needed required to make the necessary provisions that will facilitate the net-zero emissions target being reached in Year 2045.

Funding

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.dibe.2021.100059.

Appendix

Table A 1
Emissions factors and emissions components in the production of the main materials used in the construction of the buildings case study building systems.

Reference materials (*i*)	Unit	Emissions intensity Efi (kgCO2e/unit)	Emissions share Eshj					Details	References
			Raw materials	Manufacturing					
				Process emissions	Fossil fuels	Electricity	Transports		
Concrete	m^3	305	97%		<1%	<1%	2%	18% cement share (corresponding to 420 kg of cement per m^3 of concrete) as the average for Swedish building concrete.	(Kurkinen et al., 2017; NaturvårdsverketBoverket, 2019; Betong, 2019; Erlandsson, 2019)
Cement	kg	0.69		65%	35%	<1%		Cement with 86% cement clinker as the average for Swedish-produced cement.	(Betong, 2019; Cementa, 2019; Kungliga IngenjörsVetenskaps Akademien, 2019; Ishak and Hashim, 2015)
Cement-bound boards	kg	0.80	63%		14%	18%	5%	Boards composed of around 60% cement, around 35% wood shavings, with the remainder the rest minor elements and paint.	(VST Nordic, 2019; Eternit, 2008; Cembrit Holdings, 2016; CIDEM Hranice, 2015)
Reinforcement steel	kg	0.53		15%	38%	39%	8%	100% scrap-based steel including metallurgy (casting and rolling). European average electricity emissions factor.	(Andersson et al., 2018; Wörtleret al., 2013; Bianco et al., 2013; Gunarathne et al., 2016; Zabalza Bribián et al., 2011; Kurkinen et al., 2017; Basbagill et al., 2018; Chau et al., 2015; S. (Trafikverket) Toller, 2018; IVL Swedish Environmental Research Institute, 2019; Otto et al., 2017; Xylia et al., 2018)
Construction steel	kg	2.12			94%	2%	4%	100% primary steel. Includes both steel beams and sheet metal.	(IVL Swedish Environmental Research Institute, 2019; Otto et al., 2017; Xylia et al., 2018; Mousa et al., 1247; European General Galvanizers Association, 2016; Industrial Galvanizers, 2013; Lasvaux et al., 2015)
Insulation polystyrene-based	m^2	3.40	70%		85%	15%		Average climate impact from references for expanded polystyrene (EPS) with an insulation performance equivalent to a thermal resistance value R of 1 m^2K/W; 70% of the climate impact from plastic.	(Zabalza Bribián et al., 2011; Basbagill et al., 2018; IVL Swedish Environmental Research Institute, 2019; Lasvaux et al., 2015; Hill et al., 2018; Pargana et al., 2014)
Insulation rock wool	m^2	2.25		4%	85%	15%	6%	Average climate impact from references for rock wool with an insulation performance equivalent to a thermal resistance value R of 1 m^2K/W. Rock wool produced in coke-	(Zabalza Bribián et al., 2011; Basbagill et al., 2018; IVL Swedish Environmental Research Institute, 2019; Hill et al., 2018; Pargana et al., 2014; Keys et al., 2019a; Ecofys, 2009; Paroc, 2014)

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Table A 1 (*continued*)

Reference materials (*i*)	Unit	Emissions intensity Efi (kgCO2e/ unit)	Emissions share Eshj: Raw materials	Manufacturing: Process emissions	Manufacturing: Fossil fuels	Manufacturing: Electricity	Transports	Details	References
								driven furnace is currently the dominant production technology.	
Insulation glass wool	m^2	0.83		11%	51%	33%	5%	Average climate impact from references for glass wool with an insulation performance equivalent to a thermal resistance value R of 1 m^2K/W. Glass wool is produced with the average current production technology being a 50/50 split of electric-/gas-driven furnaces with an average of 50% recycled glass.	(Basbagill et al., 2018; IVL Swedish Environmental Research Institute, 2019; Lasvaux et al., 2015; Hill et al., 2018; Ecofys, 2009; Keys et al., 2019b; Saint-Gobain Sweden AB ISOVER, 2018; ISOVER, 2019)
Insulation phenolic foam	m^2	1.54	85%		15%			Phenolic foam with an insulation performance equivalent to a thermal resistance value R of 1 m^2K/W; 85% of the climate impact stems from fossil-based phenolic resin.	(Tingley et al., 2017; Kingspan Insulation, 2017)
Plasterboard	m^2	2.20	5%		77%	13%	5%	Average climate impact from references for gypsum plasterboard. Raw material emissions are from gypsum extraction.	(Lushnikova and Dvorkin, 2016; Pedreño-Rojas et al., 2020; Kurkinen et al., 2017; IVL Swedish Environmental Research Institute, 2019; Lasvaux et al., 2015; Gustavsson et al., 2010; Quintana et al., 2018; Saint-Gobain Gyproc, 2017a; Norgips Norge, 2020a; Kanuf, 2015)
Fire-resistant plasterboard	m^2	3.00	27%		56%	10%	7%	Average climate impact from references for fire-resistant gypsum plasterboard. Raw material emissions are from gypsum extraction and fire-protective coating.	(Lushnikova and Dvorkin, 2016; Pedreño-Rojas et al., 2020; Kurkinen et al., 2017; Lasvaux et al., 2015; Gustavsson et al., 2010; Quintana et al., 2018; Norgips Norge, 2020b; Saint-Gobain Gyproc, 2017b)
Plastic	kg	2.60	12%		71%	12%	5%	Average climate impact from references for the dominant plastic types used in construction. Raw material emissions from extraction of crude oil or natural gas.	(Material Economics, 2019; Andersson et al., 2018; Zabalza Bribián et al., 2011; Kurkinen et al., 2017; Chau et al., 2015; Lasvaux et al., 2015)
Aluminum	m^2	3.40	70%		85%	15%		Average climate impact from references for processed (extruded or rolled) primary aluminum; 90% of the climate impact is from primary aluminum production and 10% from processing.	(Bianco et al., 2013; Andersson et al., 2018; Chau et al., 2015; Fischedick et al., 2014; Sandberg et al., 2019)
Sawn timber	m^2	2.25		4%	85%	15%	6%	Average climate impact from references for sawn timber. Raw material emissions from forestry operations and transport emissions from log transports.	(Kurkinen et al., 2017; Otto et al., 2017; Chau et al., 2015; Gustavsson et al., 2010; Lolli and Hestnes, 2014; Norwegian Wood Industry Federation, 2015; Swedish Wood, 2018)
Cross-laminated timber	m^3	53.4	60%			14%	26%	Average climate impact from references for cross-laminated timber. Raw material emissions divided equally between timber and resin.	(Skullestad et al., 1876; Kurkinen et al., 2017; IVL Swedish Environmental Research Institute, 2019; Chen et al., 2019; Stora Enso, 2020; Martinsons Såg, 2019; Cross Timber Systems Ltd, 2017)
Windows	kg	1.20	92%			8%		Average climate impact from references for windows with a	

(continued on next page)

Table A 1 (*continued*)

Reference materials (*i*)	Unit	Emissions intensity Efi (kgCO2e/unit)	Emissions share Eshj					Details	References
			Raw materials	Manufacturing					
				Process emissions	Fossil fuels	Electricity	Transports		
								wood frame. Raw material emissions are two-thirds from glass and one-third from steel/aluminum	(Andersson et al., 2018; IVL Swedish Environmental Research Institute, 2019; Fönster, 2020; Vinduet, 2020)
Glass	kg	0.97		20%	75%	5%		Average climate impact from references for flat glass; 25% recycled glass on average.	(Lechtenböhmer et al., 2016; Zabalza Bribián et al., 2011; Chau et al., 2015; Gustavsson et al., 2010)
Façade plaster	kg	0.16	78%		5%	8%	9%	Average climate impact from references for façade plaster. Raw material emissions are predominantly from cement.	(Andersson et al., 2018; Kurkinen et al., 2017; Chau et al., 2015; Saint-Gobain Sweden AB Weber, 2019)

Table A 2
Current and estimated future emissions intensity factors for energy carriers.

Energy sources	Year	Emissions intensity ($kgCO_2e/kWh$)	Comment	References
Diesel (MK 1)	2019	0.275	Based on the composition of standard diesel in Sweden 2019 with 23% biobased content.	Energimyndigheten (2020)
HVO100	2019	0.048	Based on the composition of the second-generation biodiesel (hydrogenated vegetable oil, HVO) in Sweden 2019.	Energimyndigheten (2020)
Natural gas/LPG	2018	0.248	Including upstream emissions. According to the IPCC 2006 guidelines, the combustion emissions are 0.20 $kgCO_2e/kWh$.	(Naturvårdsverket, 2018; IEA, 2017b)
Fuel oil	2018		Including upstream emissions. According to the IPCC 2006 guidelines, the combustion emissions are 0.20 $kgCO_2e/kWh$.	
Electricity (Nordic)	2018	0.125	Average current Nordic electricity mix	Energimyndigheten (2020)
Electricity (Sweden)	2018	0.047	Average current Swedish electricity mix including imports and exports.	(Energimyndigheten, 2020; Moro and Lonza, 2018)
	2025	0.034	According to a linear reduction to the figure in 2045 from the emission factor in 2018.	
	2030	0.025		
	2035	0.017		
	2040	0.008		
	2045	0.003	According to the average figure in 2045 from the scenario analysis Four energy futures from the Swedish Energy Agency.	Statens energimyndighet (2016)
Electricity (Europe)	2019	0.267	Average current EU electricity mix	(European Energy Agency, 2018; Agora Energiwiende and Sandbag, 2020)
	2025	0.222	Calculated according to estimated EEA projections	EEA (2018)
	2030	0.177	According to the REmap scenario developed by the International Renewable Energy Agency for the European Commission.	IRENA and European Commission (2018)
	2035	0.118	Calculated according to a linear reduction from the estimated figure in 2030 to the estimated figures for 2040 as modelled by IEA.	
	2040	0.060	According to the Sustainable Development Scenario as modelled by IEA.	IEA (2020)
	2045	0.030	According to a linear reduction from the estimated figure in 2040 down to zero emissions in 2050	
District heating (Sweden)	2018	0.069	National average in Sweden	Naturvårdsverket (2018)
	2025	0.064	According to a linear reduction to the figure in 2045 from the emission factor in 2015.	
	2030	0.059		
	2035	0.055		
	2040	0.050		
	2045	0.045	According to the average figure in 2045 from the scenario analysis Four energy futures from the Swedish Energy Agency.	Statens energimyndighet (2016)

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