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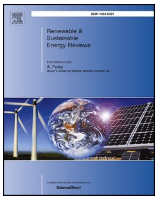

Reaching net-zero carbon emissions in construction supply chains – Analysis of a Swedish road construction project

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ABSTRACT

Recent estimates suggest that the construction sector accounts for approximately one quarter of global CO_2 emissions. This paper assesses the potential for reducing the climate impact of road construction. The study is structured as a participatory integrated assessment with involvement from key stakeholders in the supply chain, supported by energy and material flow mapping, an extensive literature review and a scenario analysis. The results indicate that it is technically possible to halve road construction CO_2 emissions with today's best available technologies and practices, to abate more than three quarters of the emissions by 2030 and achieve close to net zero emissions by 2045. Realising the current potential would rely on sufficient availability of sustainably produced second-generation biofuels, indicating a need to speed up the implementation of alternative abatement measures, including optimization of material use and mass handling requirements, increased recycling of steel, asphalt and aggregates and enhanced use of alternative binders in concrete. Policy measures and procurement strategies should be aligned to support these measures with a clear supply chain focus. For deep decarbonization several key opportunities and obstacles for realisation of breakthrough technologies for basic industry are highlighted – including electrification and carbon capture for steel and cement, and hybridisation and electrification for heavy transport and construction equipment. There is a clear need to prepare for deeper abatement and associated transformative shifts already now and to carefully consider the pathway of getting there while avoiding pitfalls along the way, such as overreliance on biofuels or cost optimizations which cannot be scaled up to the levels required.

1. Introduction

Anthropogenic greenhouse gas (GHG) emissions are a serious concern with recent climatic changes having already demonstrated widespread impacts on human and natural systems [1]. Limiting global warming to well below 2 °C will require drastic reductions of global GHG emissions up to 2050 with subsequent negative emissions [2]. Due to the urgent need to start the transformation towards deeper emission cuts, it is essential to map how mitigation measures can be allocated up to the mid-century to see which measures can be applied already at present and those which will require longer lead times to be implemented [3]. This, to avoid that only the low-hanging-fruit (incremental) measures are implemented, without necessary planning for the more transformative measures, which will be required to reach zero or near zero emissions by mid-century. Emphasis in this work is on the challenges associated with achieving net-zero carbon emissions from construction and construction supply chains within the next two to three decades - using a Swedish road construction project as a case study.

In pursuing a vision of becoming the world's first fossil free welfare state, Sweden has set a long-term goal of having no net GHG emissions by 2045, with a requirement of domestic emissions reductions of at least 85% compared to 1990 [4]. Seeing that the energy and climate performance of the user phase of the built environment keeps improving, the climate impact of the construction process has increasingly come in to focus [5]. The construction sector in Sweden (and globally) is responsible for around a quarter of all CO_2 emissions [6,7] with many activities essential to the construction sector, such as heavy transport and production of carbon-intensive structural materials, mainly steel and

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Abbreviations: BAT, Best available technologies; CCS, Carbon capture and storage; ERS, Electric road system; GHG, Greenhouse gas; HVO, Hydrogenated vegetable oil; PH, Plug-in hybrid; STA, Swedish Transport Administration (Trafikverket); TGR, Top gas recycling; WMA, Warm mix asphalt.

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cement, entailing emissions difficult to eliminate [8,9].

The total climate impact of building and construction processes in Sweden is estimated to be around 10 Mt CO_2e per year, with building construction accounting for approximately two thirds and civil engineering and public works for one third of the annual emissions. Recognising this, the Swedish Transport Administration ("STA") has set an aligned goal of no net GHG emissions by 2045. As a measure towards this goal, STA applies continuously strengthened climate requirements in its procurement of construction of major projects, materials used and future maintenance [10].

In this 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.

In general, a life cycle assessment (LCA), a methodology for detailing resource flows and associated environmental impacts, is used to appraise the climate impact of a product or service, such as transport infrastructure [11,12]. Numerous attributional LCA studies, the most commonly used LCA method, have been performed, which detail the carbon footprint of road construction or elements thereof [13–22]. The use of attributional LCA as the basis for decision making towards creating the conditions for climate change mitigation has been questioned in recent literature [23–25]. Suggestions are made of consequential LCA avoiding many of the limitations of attributional LCA, and there is evidence of literature which can be considered to be consequential LCA studies, wherein the impact of selected GHG abatement options linked to certain aspects or individual materials are investigated [26–30]. Further critique relates to limited system boundaries that do not encompass the full direct and indirect impacts, along with the LCA process, originally developed for manufactured products, having yet to be effectively adapted for large complex structures [31,32]. Thus, while the literature to date have contributed to providing a firm basis of road construction GHG emission hot spots [12], studies which can be considered to have taken a comprehensive view of abatement options along the entire road construction supply chain are lacking.

Also, whereas methods to better capture the effects of change in (and around) a studied system over time have been developed (for example dynamic [33] or prospective [34] LCA), the LCA framework has its limitations when trying to capture sectorial interlinkages and assess effects of transformative technical change over several decades.

Therefore, there is a need to complement traditional approaches with dimensions critical to lay foundations for the low-carbon transition in transport infrastructure construction supply chains, as argued also by Weidema et al. (2018) [25]. Whereas existing literature may be of benefit to decision making for projects taking place in the near term, these are insufficient basis for longer term policy making, which will require comprehensive assessments into not just current but also prospective future abatement options and potentials. This sentiment is also shared in other reviews, which argue that adapting to a more dynamic approach increases the usefulness of assessing complex systems in the context of variations in the surrounding industrial and environmental systems [35–37].

On future carbon abatement options, an array of industry level studies have been performed for individual sectors (see e.g. Refs. [38–42] for steel, [43–45] for cement/concrete and [46–49] for heavy vehicles) and there have also been recent attempts to synthesise the perspectives from different industries [9,50–58]. While these provide insights towards industry-level policy and decision making, a gap exists in literature of studies providing a holistic assessment of current and future abatement options and potential along and across construction project supply chains. The importance of taking a project level approach has been emphasised by for example Brander (2017) [23].

Consequently, to explore critical factors affecting the abatement potential up until 2045, including impacts from upscaling and the risk of lock-in effects, there is a need for studies that take both a broader perspective while combining a short and long-term perspective of abatement potential across the supply chain.

In this study, the aim is to identify the extent to which abatement technologies across the supply chain of road construction projects could reduce the GHG emissions if combined to its full potential. This provides the ability to put a broader lens on both opportunities and barriers, as these often transpire in the links between economic sectors and individual actors [25].

The objectives of this paper are thus to review and expand on existing literature by: assessing current and future GHG emissions reduction potential across the road construction supply chain; exemplify what this potential would imply for a typical transport infrastructure construction project; develop scenarios highlighting key strategic considerations and limitations around the identified technical potential and compare the identified reduction potential with what has been realised in the exemplified project.

In view of the stringent long-term climate objective and the project-based risk-averse construction industry, tending towards a slow uptake of innovations [59,60], the main value of this work is to add a time dimension to see when the different mitigation measures can, and must be in place, if emission reduction targets are to be met. By including the time dimension, the aspiration is to identify where in the supply chain the large shifts are needed, highlighting strategic choices needed already now to make the necessary provisions allowing for net-zero emissions to be reached in 2045 [61].

This paper is organized as follows: Section 2 describes the methodology, Section 3 makes an account of the types of abatement options considered, while Section 4 describes the main results of the analysis. Section 5 continues with a discussion on the results, including barriers, opportunities and strategic choices now and towards 2045, ending with concluding remarks.

2. Methodology

This work has been structured as a participatory integrated assessment, a systematic approach for developing theoretically coherent and practicable decarbonization strategies integrating key stakeholders in the process [62,63]. Quantitative analysis methods, including scenarios and stylized models, are combined with participatory sessions involving relevant stakeholders in the assessment process.

The study follows the flow depicted in Fig. 1. In the preparation stage (Stage I), the research team defined the initial scope of the assessment and engaged stakeholders for participation in the assessment. Stakeholders include industry representatives and experts along the supply chain; material suppliers, contractors, consultants, clients and governmental agencies. Framing of the study with stakeholders (Stage II) implied a high-level classification of challenges and potential solutions for the low-carbon transition in construction together with identification of a suitable benchmark case (i.e. the case study object).

With support of this benchmark case, estimates are provided of the magnitude of current and future GHG emissions reduction potential across the road construction supply chain (Stage III) by: (i) mapping the material flow through the supply chain of a road construction project; (ii) identifying possible GHG abatement options relevant to road construction works and their estimated abatement potentials by means of a comprehensive literature review and input from supply chain stakeholders; (iii) using (i) and (ii) to assess the impact of combining abatement measures along the supply chain for the construction of a functionally equivalent road but with lower GHG emissions; (iv) crafting scenarios to highlight challenges and possibilities up to 2045 given assumptions regarding external parameters; and (v) comparing the portfolio of current best available technologies with measures implemented in the real case study project.

The inventory of GHG abatement options include current best available technology and technologies deemed available over time to 2045. From this inventory, portfolios of abatement measures for the respective supply chain activities are constructed with selections of

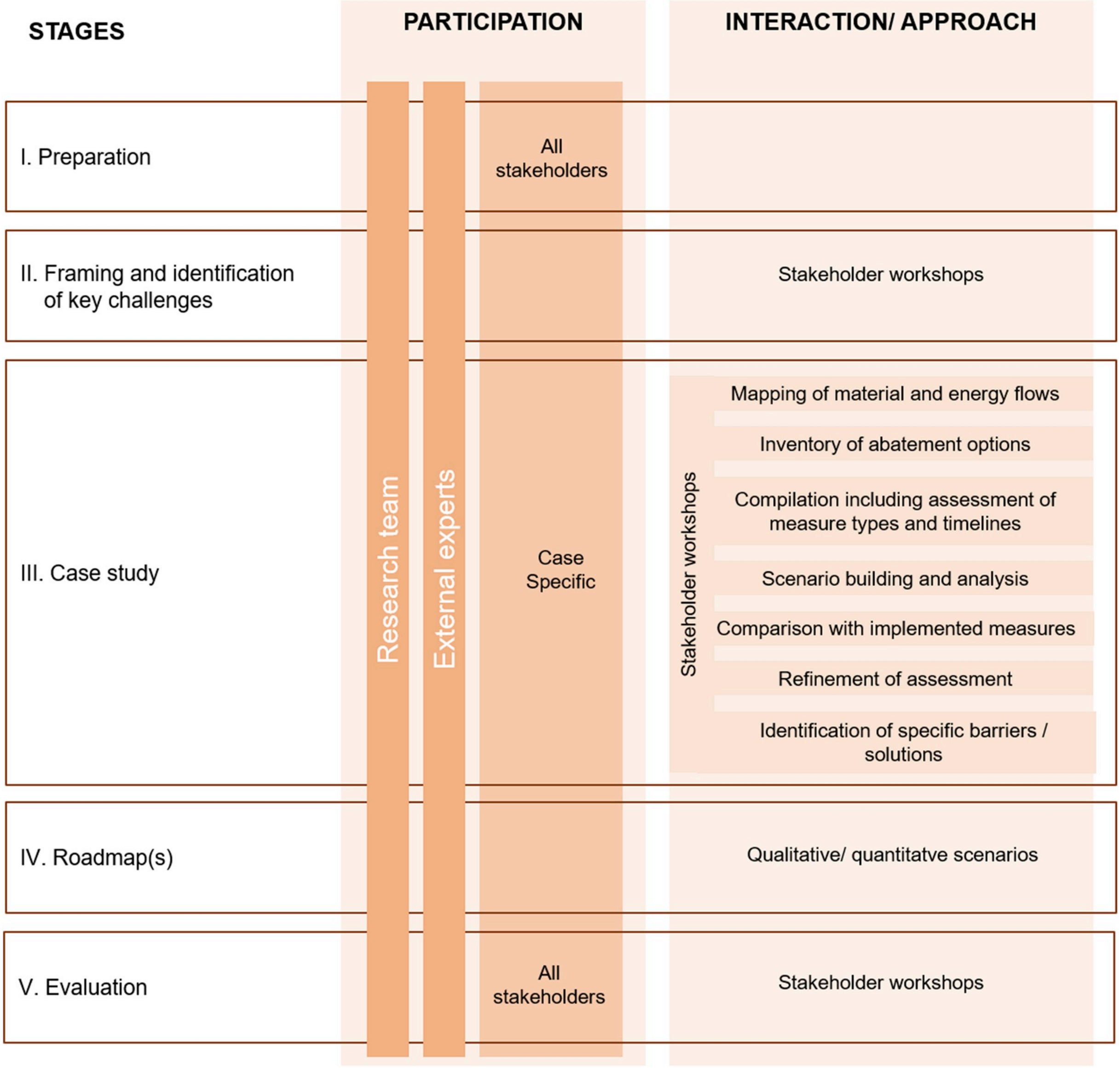


Fig. 1. *Outline of the methodological approach (adapted from Rootzén and Johnsson* [64]*).*

measures applied on a timeline. The timeline is applied to test the potential implications to the climate impact when constructing the same road in 5, 10 and 25 years' time while applying a combination of GHG abatement measures along the supply chain appraised to have reached commercial maturity at these points in time. The abatement measures are combined in scenarios according to specific conditions [65] with a focus on parameters that may impact strategic considerations, such as access to biofuels and enactment of transformative measures.

The outcomes from the study will be used as input in the development of decarbonization roadmaps (Stage IV) for the supply chains of buildings and infrastructure, which in addition to the timeline developed in this study will contain a more detailed assessment of pathway choices along with barriers, risks and enablers [66,67], flowing into a subsequent evaluation process (Stage V). The work has been supported by iterative stakeholder workshops and case study meetings enabling a continuous knowledge exchange and involvement of stakeholders in the analysis.

2.1. Case study object

The case study object is a representative road construction project in Sweden, a typical meeting-separated 2 plus 1 road with a centre rail (as illustrated in Fig. 2), including the construction of 9 bridges [68].

The project is part of National Road 44 and is built in a new 8 km stretch between Lidköping and Källby in the middle of Sweden, with construction completed in 2019 [69].

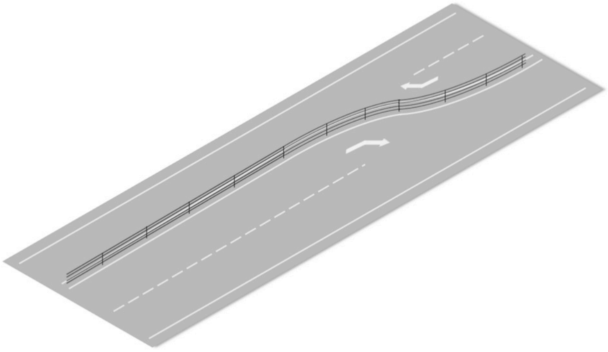


Fig. 2. Illustration of a meeting-separated 2 + 1 road with a centre rail.

2.2. Benchmark GHG emissions

The sources of GHG emissions from the Road 44 project were established in collaboration between STA and the contractor engaged for the construction in a dedicated ‘climate footprinting tool’, “Klimatkalkyl”. This tool was developed by STA to consistently calculate the energy consumption and climate impact generated by transport infrastructure projects. The model uses emission factors along with resource templates and project-specific inputs to calculate energy use and GHG emissions from an object or action [70]. Fig. 3 shows the estimated GHG emission, by category, from the construction of Road 44 in the benchmark case, i.e. before considering any measures to reduce the emissions.

2.3. Mapping of material and energy flows

The output from the Klimatkalkyl tool provides the basis for our mapping of the material and energy flows across the supply chain for the road construction works, including primary materials and energy/energy carriers used as input in the production and processing of construction materials, and energy/fuel use related to transport and construction services, as illustrated in Fig. 4.

Six categories of supply chain activities, with importance for the overall climate impact of the road construction, were identified:

- Steel production and use
- Cement and concrete production and use
- Asphalt production and paving
- Heavy transport
- Construction processes

In Fig. 4, arrows follow the material flow from sourcing of raw material (by extraction/recycling), via primary/secondary material production (with production plants indicated by coloured boxes) to construction of earthworks, pavements, and structures. Double-lined and block arrows signify supply chain links associated with substantial energy use (material/mass transport and energy-intensive material production processes, respectively). To illustrate supply chain effects, a few examples of abatement measures are shown, signposted by dashed arrows and boxes. These include using slag, a rest product from iron-making blast furnaces, substituting cement clinker as alternative binders in cement (reducing the need for virgin material and energy inputs to the cement production), use of reclaimed asphalt (reducing the need for virgin aggregate and bitumen), along with transport biofuel (reducing the need for fossil diesel).

The material and energy flow mapping demonstrate the importance of analysing abatement options from a supply chain perspective. An illustrative example is ballast/aggregate from quarries (see arrows going from the dark grey box at the bottom end of Fig. 4) which are used not only as filling materials and base layers, but also as aggregate for asphalt and concrete, accounting for approximately 15% of the total emissions, excluding associated transports.

2.4. Scope and boundary

The focus of the study is on emission reduction measures with less dependency on individual project parameters (e.g. concrete recipes, bridge types and logistics) together with those recognised as important in stakeholder workshops and meetings. As such, the main types of abatement options considered in the assessment are shifts in: material production processes, transport vehicles and construction equipment technologies, and fuel substitutions in both equipment and production plants. The options include certain reuse and recycling measures resulting in emissions reductions, but not for the specific purpose of resource conservation. Table 1 gives an overview of the scope of the included abatement measures as well as possibilities not included in the investigations such as alternative designs.

2.5. Scenario building and analysis

Five scenarios were investigated in the study, as outlined in Table 2, with the main *‘Transformative’* scenario, devised to represent an extensive portfolio of abatement measures across all supply chain activities with increasing scope of measures over time together with an increasing degree of abatement levels for several of the earlier introduced measures. In addition, four restricted scenarios were formulated to test the sensitivity in changes of certain critical aspects; *No transport biofuel*, *No biomass*, *Alternative* and *Non-transformative*.

The *Transformative* scenario is predominantly based around reaching the medium-high range of the emission reduction potentials for each selected abatement measure with measures and timelines largely compatible with roadmaps and pathways developed within the EU Commission long term climate strategy (combination of electrification and hydrogen scenarios) along with relevant industry roadmaps developed within the "Fossil Free Sweden" initiative [75,76]. A matrix of the reduction measures selected for different scenarios is depicted in Fig. 5, including the timeline for implementation.

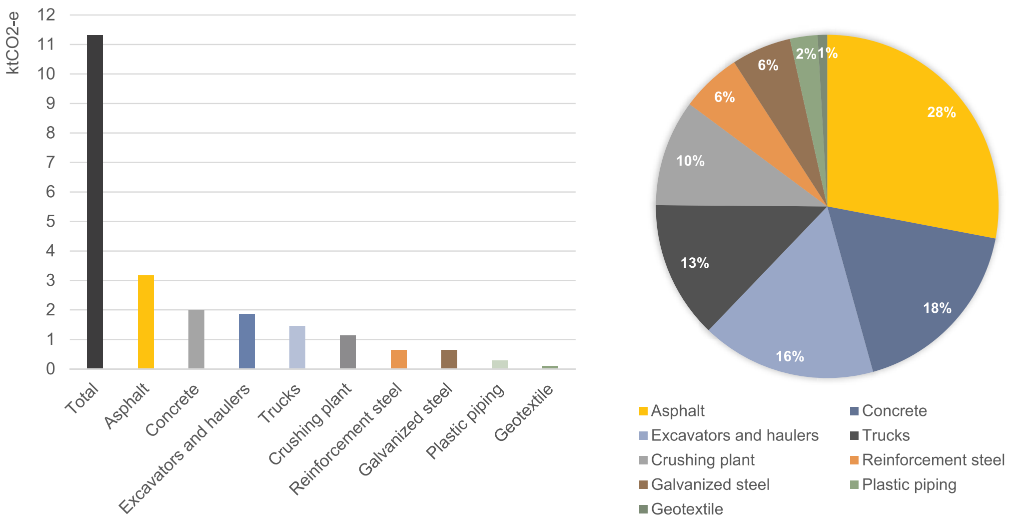


Fig. 3. Estimated GHG emission, by category, from the construction of Road 44 in the benchmark case, i.e. before considering any measures to reduce emissions.

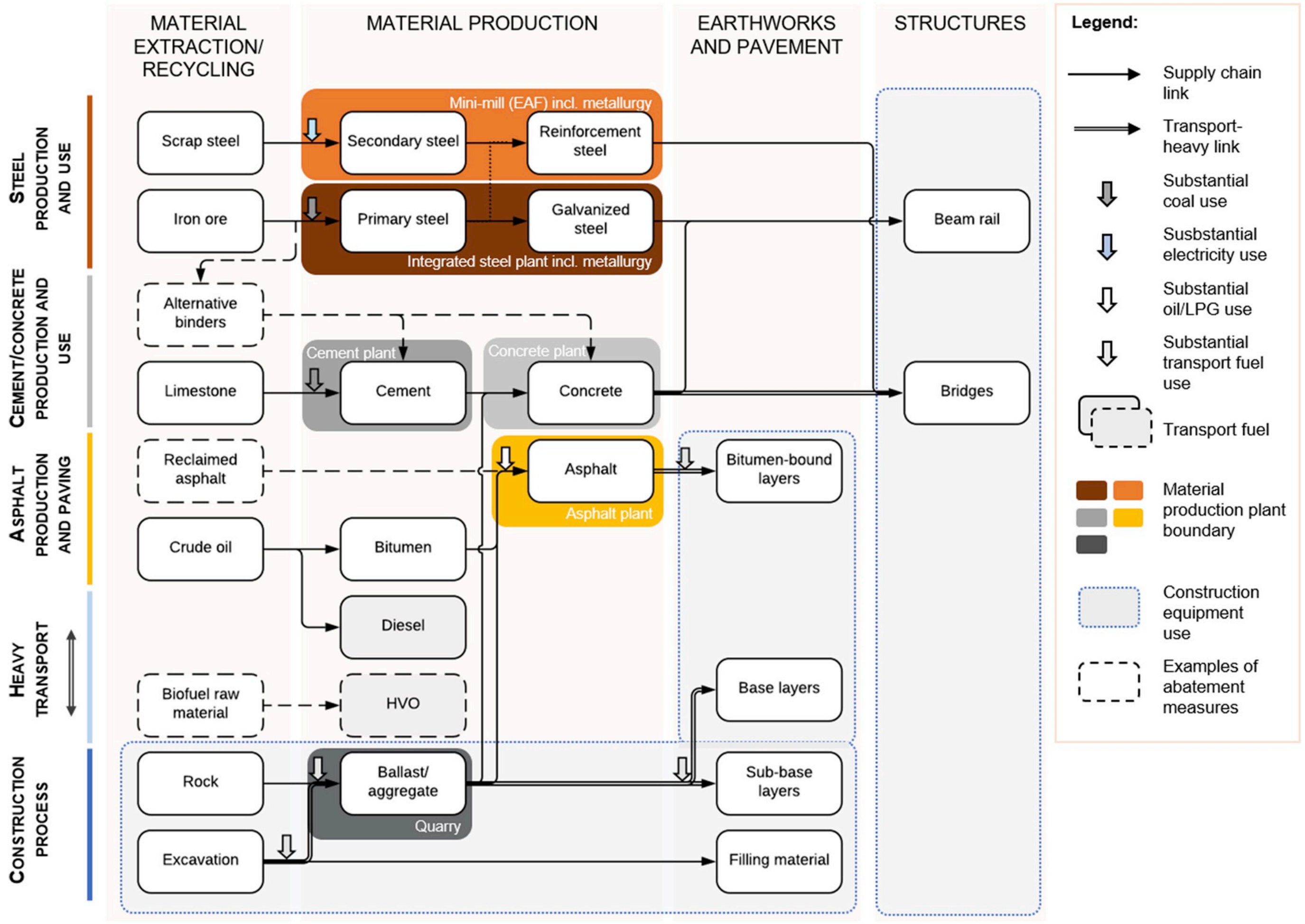


Fig. 4. Mapping of the material and energy flows for the key supply chain activities involved in road construction. Arrows map the material flow. Double-lined arrows indicate supply chain links with sizeable material transports, i.e. links associated with substantial fuel use from heavy transports. Block arrows indicate links with substantial energy use associated with material production (where the filling colour denote the main energy carrier). Blue-dotted grey background boxes indicate links associated with substantial fuel use from construction equipment. Finally, boxes and arrows with dashed lines represent a few examples of abatement measures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The multiple uses of biomass in the low carbon transition is likely to lead to intensified competition for sustainably produced biomass with effects such as increased prices and tightened regulations [9]. The extent to which biomass can supply transport and production fuels will thus depend not only on advances in conversion technology, but also on competing demands for bioenergy and land, feasibility of other fuel sources, and integration of biomass production with other objectives [8].

Consequently, the *No transport biofuel* and *No biomass* scenarios are used to assess the impacts from limited and costly biofuels, with the first of these scenarios eliminating transport biofuel as an abatement measure for construction equipment and heavy transport, while the second scenario tests the impact of also excluding biobased production fuels for asphalt, cement and steel plants.

The *Alternative* scenario tries to capture how large-scale GHG emissions reductions in the road construction supply chain could be achieved while limiting biomass demand increases. This scenario is based on the *No biomass* scenario, while further increasing the contribution of applicable technology options used in the *Transformative* scenario and adding supplementary abatement measures which are not necessarily reflected in industry roadmaps, i.e. top gas recycling with carbon capture and storage for primary steel production and plug-in hybrid (PH) or fuel-cell heavy duty trucks/haulers combined with electric road systems (ERS).

Large investments in zero-carbon electricity generation, transmission and distribution; hydrogen production and storage; and carbon transport and storage infrastructure, are required to transition heavy industry and heavy-duty transport to net-zero CO2 emissions. This is aside from the industrial assets needed to implement the abatement measures. The *Non-transformative* scenario aims to test what could be the result should these fall through, with CCS and electrification for cement and primary steel production together with large scale electrification of construction equipment not materialising.

2.5.1. *Climate impact calculations*

The total climate impact of the road construction project, for each scenario and in each time period, was estimated based on specific emission factors for the supply chain activities employed (Eq. (1)).

$$E_{tot} = \sum_{i=0,\ t=0}^{n} \left(M_i * Ef_{i,t}\right) \tag{1}$$

where E_{tot} is the total GHG emissions associated with the project; $Ef_{i,t}$ is the emission factor for activity type i in year t; M_i is the amount/use of each activity; $i = 1,2, \ldots,n$, is the activity types considered, i.e. asphalt use, concrete use, heavy transport etc.; $t =$ *Now, 2025, 2030, 2045.*

The emission factors were divided into components where deemed feasible to enable the assessment of different mitigation measures, as

Table 1
Details on scope and boundary of the case study assessment.

Step	Aspect	Inclusion	Comment
Mapping of material, energy and emission flows	Life-cycle stages of the road project	GHG emissions embodied in materials and released during the construction process	The assessment is concerned with emissions materialising up to the point of construction. Emissions associated with operation and maintenance of a road infrastructure project typically account for a smaller share of the total emissions over the lifetime of the project [71].
	Emissions embodied in concrete and steel	Cradle-to-gate	Transport of concrete and steel to site is not included as this varies considerably between individual producers, particularly for steel which is globally traded.
	Emissions embodied in rock filling materials, base layers and asphalt	Cradle-to-site	These materials are generally sourced locally. The amounts and types of rock and bitumen-bound layers used are project specific to a high degree.
	Emissions embodied in plastic and lining	Cradle-to-gate	Abatement options have not been analysed for these materials (as plastic-based materials together contributes to <5% of total emissions).
	Emissions associated with vehicle fuels	Cradle-to-tank	According to the life cycle assessments performed by the Swedish Energy Agency [72].
	Emissions from construction equipment and trucks	Operational emissions	Life-cycle emissions from production and end-of-life are not included due to the complexity of calculating and attributing these to a specific project.
	Emissions attributed to biogenic carbon (biomass used as plant fuels)	As per attribution made in references applied	Emissions attributed to biogenic carbon is a debated subject in literature (see e.g. Refs. [73,74]) and is dependent upon the raw material source and management thereof.
	Concrete carbonation	Not included	While concrete structures reabsorb some of the embodied CO_2 if exposed to air, this predominantly happens at the end-of-life phase [33]. This is not considered in the study as the focus is on emissions at the point of construction.
Inventory of abatement options	Abatement technologies in material production	Included	Focus of the assessment, including fuel substitutions, energy efficiency measures, electrification and carbon capture and storage.
	Optimization/alternative design	Not included	Design, material, work or transport efficiency measures are referred to in brief but are not included in the calculations for the case study assessment.
	Material substitutions	Partly included	Material component substitutions (e.g. alternative binders in cement/concrete or bio-based asphalt binders) are included while complete substitutions (e.g. to advanced concretes, wooden/composite bridges, different wirings etc.) have not been considered, as these could impact design and material amounts.
	Recycling/reuse	Partly included	Recycling of asphalt and steel are considered, but measures such as re-use of construction and demolition waste as aggregate are out of scope.

exhibited in Equation (2).

$$Ef_{i,t} = \sum_{j=0,\ t=0}^{n} \left(Esh_j * Ef_{j,t}\right) \tag{2}$$

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

Some abatement measures can be combined in the scenarios, such as lowering asphalt temperatures and increasing recycling rates or hybridization and biofuel substitution in machinery. Others are mutually exclusive, i.e. hydrogen reduced steel and steel production with CCS; or hybrid and electric construction equipment.

In the scenario analysis the emission factors were adjusted on the basis of the abatement options selected and applied in the assessment for each supply chain activity, as given in Equation (3a) and (b), where *a* is applied when the abatement measures reinforce each other.; and *b* is applied when abatement measures are applied in separation, e.g. cement clinker replacements and biofuel substitution in cement plants.

$$Ef^{*}_{i,j,t} = (A,\ b_1 * Ab_2 * Ab_n) * Ef_{i,j,t} \tag{3a}$$

$$Ef^{*}_{i,j,t} = ((1 - Ab_1) * Ab_2) * Ef_{i,j,t} \tag{3b}$$

where $Ef_{i,j,t}$ is the emission factor for material/activity type i and/or for component j where relevant in year t; $Ef^*_{i,j,t}$ is the amended emission factor; Ab is the share of emissions remaining after the specific abatement measure has been implemented; $1,2..n$ are the types of abatement measures investigated, e.g. product choice, energy efficiency, fuel substitution etc.

Table 2
Outline of assessment variations tested within the scenario analysis.

#	Scenario	Description
1	Transformative	Broad range of abatement measures, including transformative measures (electrification/CCS) across the supply chain activities considered in the analysis. Unlimited access to biomass/biofuels.
2	No transport biofuel	No transport biofuel available for construction equipment or heavy transports - Otherwise as per the Transformative scenario.
3	No biomass	No transport biofuel nor biomass-based fuel for asphalt, cement and steel plants – Otherwise as per the Transformative scenario.
4	Alternative	As per the No biomass scenario, but with deepening of alternative none bio-based measures, including early implementation of some measures.
5	Non-transformative	Bio-based as per the Transformative scenario but excluding transformative measures (electrification/CCS).

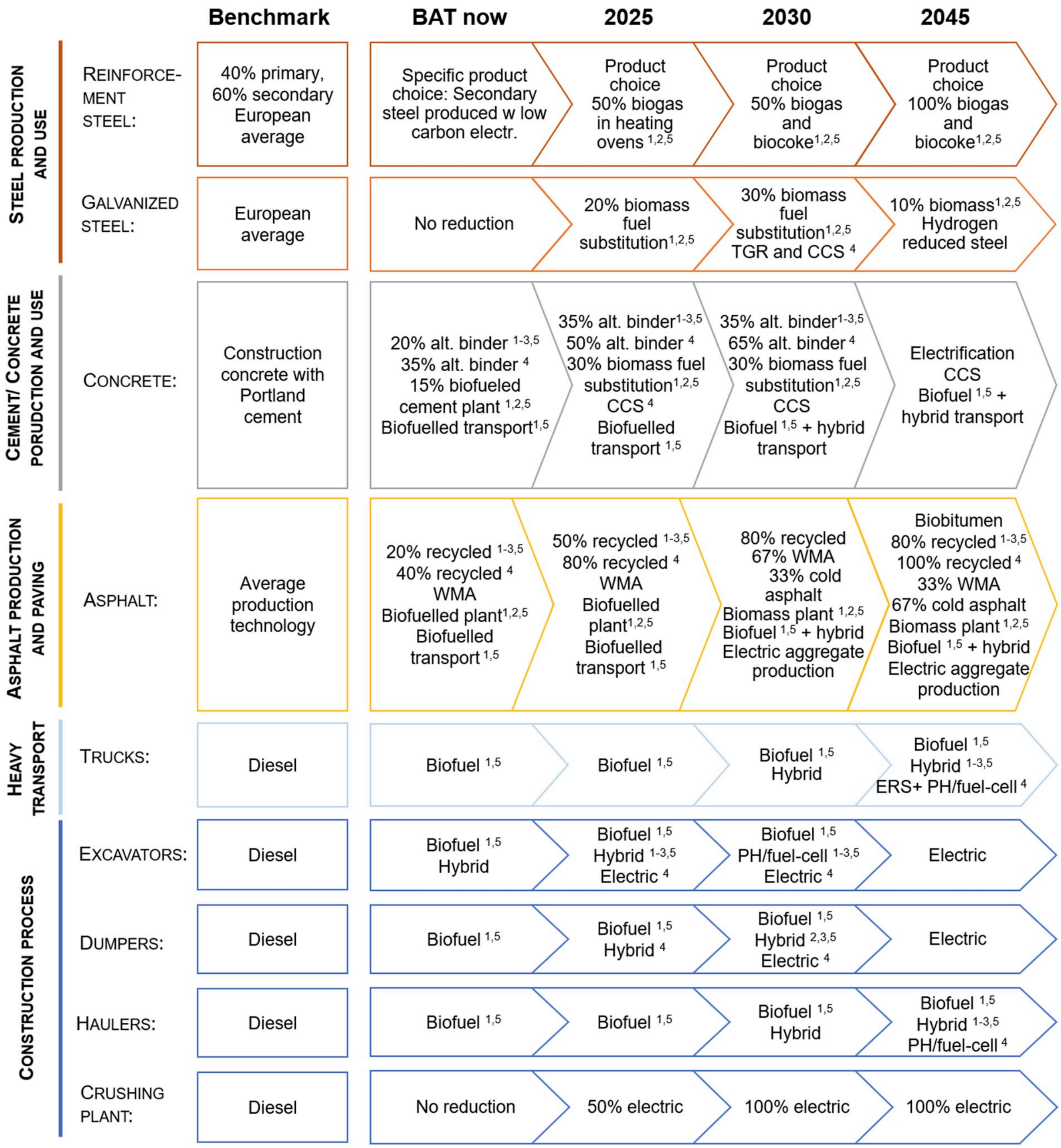
The adjusted emission factors were subsequently inserted into the initial energy and material flows to give an updated picture of greenhouse gas emissions associated with the case object.

The types of emissions reduction measures, probable timeline for implementation and identified abatement potentials applied are illustrated with full details of measures for all activities in the supplementary material.

3. Results

3.1. Inventory and compilation of abatement options

The GHG emissions reduction potential for the inventory of abatement options identified in the participatory assessment and literature review are depicted in Fig. 6. The graph illustrates the range of GHG emissions reduction potential recognised in literature for each of the abatement options explored, where the range may depend on the level of the abatement measure that is adopted, e.g. the degree of fuel or cement



		Benchmark	BAT now	2025	2030	2045
Steel production and use	Reinforcement steel:	40% primary, 60% secondary European average	Specific product choice: Secondary steel produced w low carbon electr.	Product choice 50% biogas in heating ovens ^{1,2,5}	Product choice 50% biogas and biocoke^{1,2,5}	Product choice 100% biogas and biocoke^{1,2,5}
	Galvanized steel:	European average	No reduction	20% biomass fuel substitution^{1,2,5}	30% biomass fuel substitution^{1,2,5} TGR and CCS ^{4}	10% biomass^{1,2,5} Hydrogen reduced steel
Cement/ Concrete poruduction and use	Concrete:	Construction concrete with Portland cement	20% alt. binder $^{1\text{-}3,5}$ 35% alt. binder ^{4} 15% biofueled cement plant ^{1,2,5} Biofuelled transport^{1,5}	35% alt. binder$^{1\text{-}3,5}$ 50% alt. binder ^{4} 30% biomass fuel substitution^{1,2,5} CCS ^{4} Biofuelled transport ^{1,5}	35% alt. binder$^{1\text{-}3,5}$ 65% alt. binder^{4} 30% biomass fuel substitution^{1,2,5} CCS Biofuel ^{1,5} + hybrid transport	Electrification CCS Biofuel ^{1,5} + hybrid transport
Asphalt production and paving	Asphalt:	Average production technology	20% recycled $^{1\text{-}3,5}$ 40% recycled ^{4} WMA Biofuelled plant^{1,2,5} Biofuelled transport ^{1,5}	50% recycled $^{1\text{-}3,5}$ 80% recycled ^{4} WMA Biofuelled plant^{1,2,5} Biofuelled transport ^{1,5}	80% recycled 67% WMA 33% cold asphalt Biomass plant ^{1,2,5} Biofuel ^{1,5} + hybrid Electric aggregate production	Biobitumen 80% recycled $^{1\text{-}3,5}$ 100% recycled ^{4} 33% WMA 67% cold asphalt Biomass plant ^{1,2,5} Biofuel ^{1,5} + hybrid Electric aggregate production
Heavy transport	Trucks:	Diesel	Biofuel ^{1,5}	Biofuel ^{1,5}	Biofuel ^{1,5} Hybrid	Biofuel ^{1,5} Hybrid $^{1\text{-}3,5}$ ERS+ PH/fuel-cell ^{4}
Construction process	Excavators:	Diesel	Biofuel ^{1,5} Hybrid	Biofuel ^{1,5} Hybrid $^{1\text{-}3,5}$ Electric ^{4}	Biofuel ^{1,5} PH/fuel-cell $^{1\text{-}3,5}$ Electric ^{4}	Electric
	Dumpers:	Diesel	Biofuel ^{1,5}	Biofuel ^{1,5} Hybrid ^{4}	Biofuel ^{1,5} Hybrid ^{2,3,5} Electric ^{4}	Electric
	Haulers:	Diesel	Biofuel ^{1,5}	Biofuel ^{1,5}	Biofuel ^{1,5} Hybrid	Biofuel ^{1,5} Hybrid $^{1\text{-}3,5}$ PH/fuel-cell ^{4}
	Crushing plant:	Diesel	No reduction	50% electric	100% electric	100% electric

Fig. 5. Timeline of GHG emissions reduction options applied for the supply chain activities in the case study assessment. Measures applied in the different scenario are depicted with subscript numbers: ^{1}Transformative; ^{2}No transport biofuel; ^{3} No biomass; ^{4} Alternative; ^{5} Non-transformative. Measures without numbers are applied across all scenarios.

clinker substitutions deemed feasible in literature. The abatement potential may also be deemed to move across the range over time along with technological development and/or streamlining of standards.

Key near-term abatement options include lowered temperatures and increased recycling rates for asphalt (Asphalt production and paving), using scrap-based steel (Steel production and use), using cement clinker substitutes in concrete (Cement/concrete production and use), conversion to biomass-based fuels for both machinery, transport (Construction process and Heavy transport) and production facilities (Asphalt production and Cement and Steel production) along with hybridization of construction equipment (Construction process).

Over the longer term, deeper emissions reductions could result from electrification of construction equipment (Construction process), hybridization or electrification of mass and material transports (Heavy transport), carbon capture and storage for cement clinker production and integrated steel plant emissions together with commercialisation of breakthrough technologies such as hydrogen direct reduction of iron ore with hydrogen produced by renewable electricity (Cement and Steel production).

3.2. *Transformative scenario*

Potential GHG emissions reductions from now to 2045 for the studied road construction case in the Transformative scenario is demonstrated in Fig. 7. The figure exhibits the GHG emission reduction for the road construction project from the combination of abatement measures applied in the scenario (see Fig. 5) compared with the benchmark. It depicts the combined abatement across the supply chain if applying the current best available technology and practices (BAT), along with the resulting abatement if applying the abatement measures deemed feasible in 2025, 2030 and 2045 respectively.

The Transformative scenario demonstrates that it is possible to halve the GHG emissions by using today's best available technologies, fuels and materials associated with the construction of a typical road. Fuel substitution in asphalt plants, excavators, haulers and trucks make up the largest share of these reductions.

For current BAT, the analysis demonstrates that changes in asphalt production and paving could contribute 35% of the total GHG emissions reduction, with production plant biofuel substitution supplemented by lower production temperatures and recycled content. These measures

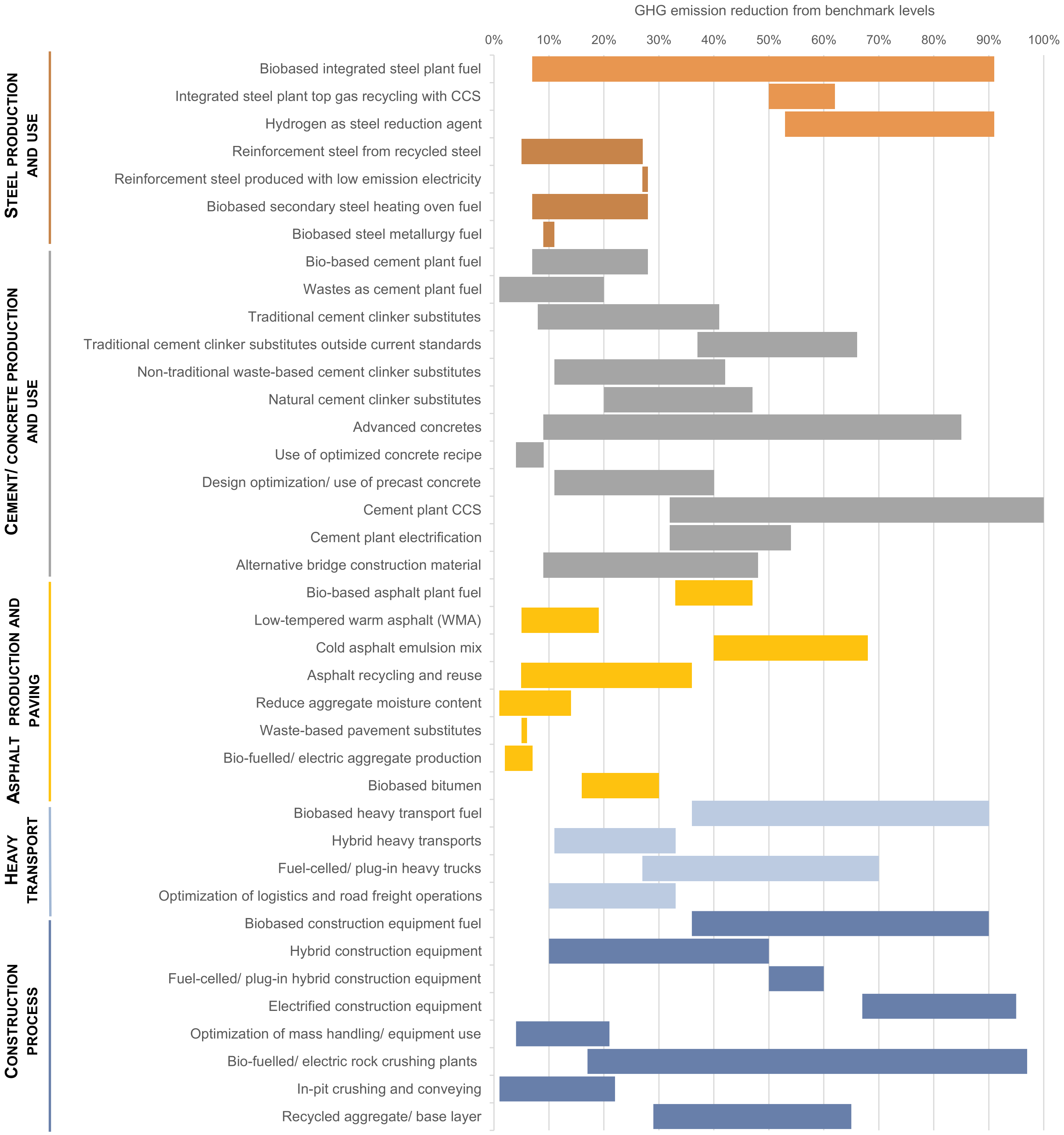


Fig. 6. Tornado graph depicting the range of GHG emissions reduction potential for the abatement options identified in the literature review and stakeholder workshops for the central supply chain activities (colour coded). Full details of measures for all activities, including timelines, potentials and references are available in the supplementary material. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

combined would result in asphalt emissions dropping by more than 60%. Fuel substitution to 100% hydrogenated vegetable oil (HVO100) for all construction machinery and heavy transports together correspond to half of the abatement from the benchmark to BAT in the assessment, given the Swedish raw material mix for HVO100 production reducing the GHG footprint by 86% compared to standard diesel (which in Sweden had a 17 vol% renewable component in the reference year of 2015). The remaining current abatement potential corresponds of material substitution (i.e. cement clinker substitution to alternative binders) and choosing reinforcement steel made from recycled steel produced by low-emission electricity.

The analysis further demonstrates that lowered asphalt production temperatures and increased shares of recycled content could produce large GHG emission reductions in every time step, with an additional 12% reduction from BAT to 2025. Reduced GHG emissions from concrete, due to further integration of alternative binders to reduce the cement clinker content and increased biomass fuel substitution in the cement plants, could add another 13% abatement to 2025 (with concrete emissions reduced by about 40% from the benchmark to 2025). A further 41% abatement from BAT (8% compared to the benchmark) would result from half of the crushing plants producing aggregate and ballast running on low-carbon electricity instead of diesel.

For the crushing plant, moving towards electrification yields a large impact also from 2025 to 2030, with full electrification to 2030. Over the same time period, implementation of carbon capture in cement production makes a large dent in the remaining concrete emissions.

In the final time step from 2030 to 2045, hydrogen-reduced iron for primary steel production (with hydrogen produced by electrolysis) would provide half of the additional abatement, supported by electrification of construction equipment and cement production, all with the prerequisite of zero-carbon electricity.

The analysis demonstrates the ability to reach the minimum domestic reduction target stipulated in the Swedish climate law (85% by 2045). This would however require comprehensive measures across-the-board, including breakthrough technologies for both cement and steel production.

In Fig. 8 we further highlight the types of reduction measures yielding the potential CO_2 emissions reductions over time in the *Transformative* scenario. In this figure, the influence of biomass and biofuel for GHG emissions reduction becomes clear, particularly in the short term (contributing to 70% of the BAT reduction). To halve the emissions at present would for example mean a reduction in overall diesel use of 80%. Similarly, biofuel conversion of asphalt plants has the potential to halve the emissions associated with asphalt production. The large share of emissions reductions from bio-based measures continues in 2025, levels out up to 2030, after which their importance is decreased with the expansion of electrification.

Abatement stemming from the energy efficiency measures included in the analysis (mainly lowered asphalt production and paving temperatures together with hybridisation of construction equipment and heavy transports) increase from 5% of the total abatement potential for current BAT to 12–13% towards 2030–2045. Recycling measures (steel and asphalt) could also become an increasingly important abatement measure with an estimated 10% of total GHG emissions reduction in 2030–2045.

Material substitution here refers to use of waste-based alternative binders to replace virgin cement clinker in concrete. Since availability of conventional alternative binders, i.e. fly ash and blast furnace slag, can be expected to diminish as coal power plants and steel industry blast furnaces are phased out in a carbon constrained world, increased use of these binders is predominantly considered as a short-medium term abatement measure, with a potential of around 6–7% out of total abatement in 2025–2030. It is worth noting however that these binders could potentially be replaced by either natural (e.g. calcined clay) or other waste-based supplementary cementitious materials or advanced geopolymer or alkali-activated concretes [43,77].

Electrification of construction machinery and crushing plants together with capture and storage of CO_2 emissions from cement production have the potential to contribute with 25% abatement to 2030. With the introduction of electrified cement production and steel works (with hydrogen as reduction agent), the abatement from electrification could reach over 35% in 2045.

3.3. Restricted abatement scenarios

A comparison of the restricted abatement scenarios with resulting potential GHG emission reductions for BAT and over time until 2045 is demonstrated in Fig. 9. In the *No transport biofuel* and *No biomass* scenarios, the importance of both transport biofuel and industrial biomass energy use to deliver large GHG emissions reductions, particularly until 2025, again becomes clear. For BAT, fuel substitution in asphalt plants contributes the predominant share, reducing over time as alternative abatement measures including recycling take over. The potential biofuel substitution in cement plants of 20–30% corresponds to around 10% concrete emission abatement, while biomass use in both primary and secondary steelmaking has the potential to reduce the associated GHG emissions by 10–20%.

The *Alternative* scenario aims to test to what degree a focus on earlier implementation and deeper alternative measures could make up for the downfall from the absence of bio-based measures. Lowering the asphalt

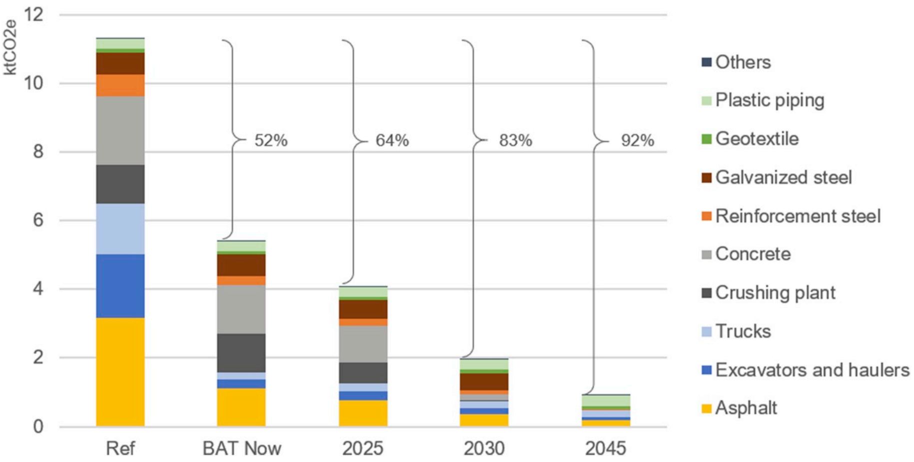


Fig. 7. Potential GHG emissions reductions from now to 2045 for the studied road construction case in the Transformative scenario. Note that no abatement analysis has been completed for geotextiles, plastic piping and the others category.

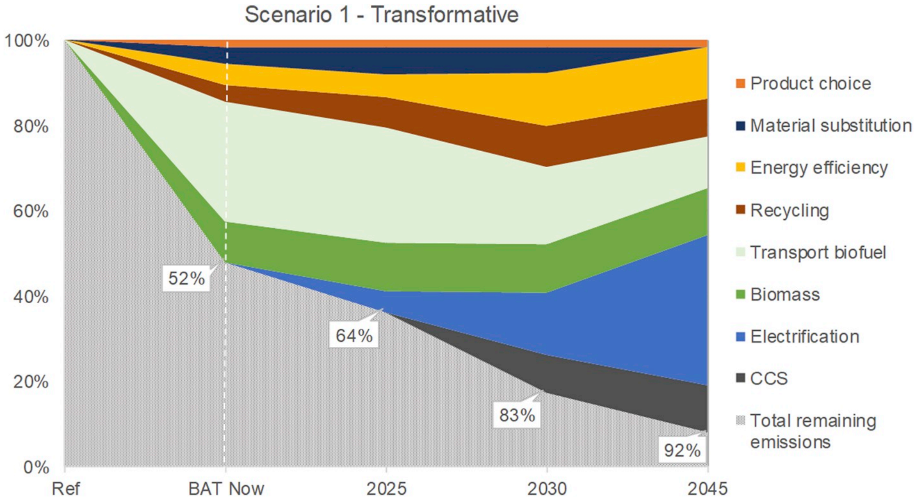


Fig. 8. Summary graph of emissions reduction measures and potential to reduce CO_2 emissions at present and over time until 2045 in the Transformative scenario.

production temperatures and increasing the recycling rate along with increased cement clinker substitution in concrete provide slight recompense in the short term, reducing GHG emissions by another 4% at present.

Early introduction of CCS in the cement production would do more to close the gap, bringing the emission reductions down to 40% in 2025. Introduction of CCS in primary steel production together with electrification of construction equipment by 2030, stretches the abatement down to 65%. However, even with all the measures introduced in this scenario, adding fuel-celled or plug-in hybrid combined with electric road systems for haulers and trucks in 2045, a gap of 17% remain compared to the range of measures in the *Transformative* scenario. Consequently, if bio-based measures are restricted, measures involving optimization of material, design, mass handling and transports as well as the use of alternative materials and design, will become central to reach the goal of close to zero GHG emissions by 2045.

The final scenario, the *Non-transformative* scenario tests the sensitivity to transformative measures, i.e. electrification of construction equipment, cement and steel plants, and CCS for cement CO_2 emissions. This scenario demonstrates an abatement plateau after 2025, with emissions reductions in 2045 remaining at 70%, thus between 15 and 30% off the stipulated emissions target.

3.4. Implemented emission reduction measures

To relate the assessment to the actual case, a comparison is made of

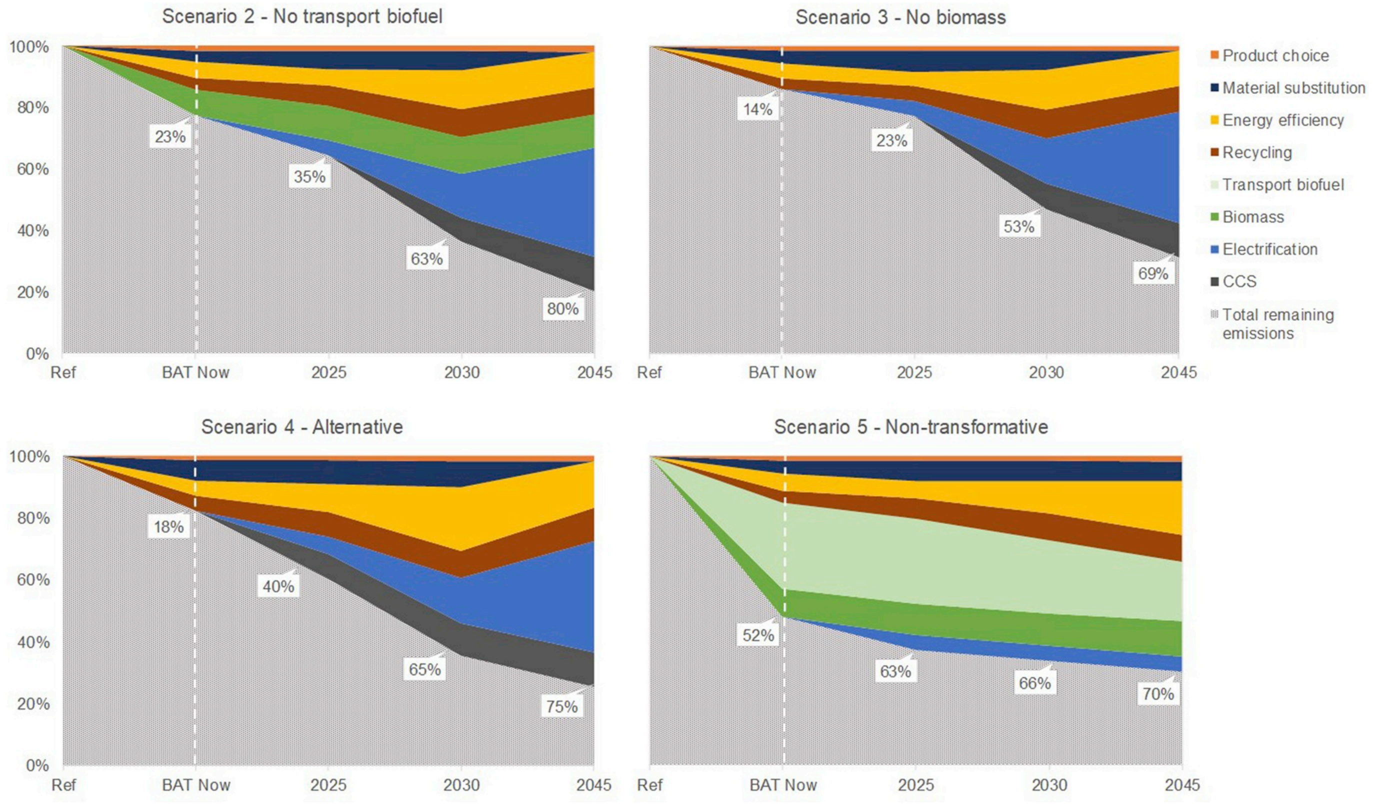


Fig. 9. Comparison of restricted abatement scenarios with the resulting potential GHG emission reductions at current and over time until 2045.

the BAT measures in the Transformative scenario to the measures that are being implemented in the real project and the predicted result of these. The contractor estimate gives an approximate 19% reduction in GHG emissions from the construction of the new stretch of Road 44, with the largest reductions realised by optimizing amounts in the planning phase, both of masses, asphalt and concrete.

By reducing more than half the volume of unbound base materials (together with minor reductions in rock and earth filling materials), the associated fuel consumption has been reduced by 15%, contributing to around 6% abatement. Regarding asphalt, measures include applying two instead of three layers in the overtaking lane, decreasing asphalt volumes by 35% and overall emissions by around 10%. Other measures being implemented relate to fuel substitution from standard diesel to HVO100 for a share of the excavators used along with an active product choice with 20% of reinforcement steel procured from scrap steel produced with low emission electricity.

Optimization towards cost reduction have played a key part in the project implementation, and the material efficiency measures applied in practice are alternatives complementary to those assessed in this study.

4. Discussion

This paper investigates the prospect for decarbonizing road construction over the next few decades. The results indicate that it is possible to halve GHG emissions associated with a road construction project already at present, to abate more than three quarters of the emissions by 2030 and to achieve close to net zero emissions by 2045. Through scenario analysis based on material and energy mapping, strategic aspects on choice of mitigation focus are highlighted, regarding availability of biomass for transport biofuels and combustion fuels for material production, early implementation and deepening of alternative none bio-based measures as well as realisation of breakthrough transformative technologies for cement, steelmaking and heavy machinery.

As the scenario analysis demonstrates, more than half of the current emissions reduction potential stem from substituting diesel use with transport biofuel (80% overall substitution). This would require sufficient availability of sustainably produced second-generation drop-in biofuels (e.g. hydrogenated vegetable oil, HVO). As previous research has demonstrated (see e.g. Refs. [8,78,79]), a shortage of biomass may be imminent unless production is ramped up or wood and agricultural products from other uses is directed to the manufacture of transport and combustion fuels.

In Sweden, consumption of HVO100 has been growing rapidly from close to zero in 2014 to being 524,000 m^3 in 2017 (with 95% of the raw materials imported), corresponding to around 5% of total road transport fuel use. Despite supply expansion, shortages are already experienced, while demand is due to continue increasing (e.g. owing to obligations on biofuel blending [80]). At the same time, the Swedish Energy Agency estimates that the total sustainable resource base for HVO production is limited to 1,480,000 m^3, decreasing to 830,000 m^3 if excluding palm oil and palm oil derivative PFAD [72]. The climate benefits of palm oil and PFAD are heavily debated due to the associated land use change. Indeed, the greenhouse gas emissions associated with the life cycle of biofuels vary widely dependent on fossil fuel inputs and changes in soil and aboveground carbon stocks [81–83].

On the one hand, use of biofuel in the transport and industrial sectors is a prerequisite for successful decarbonization, while on the other hand, there are limits on the available supply of truly sustainable biomass, linking to other Sustainable Development Goals such as SDG 15 Life on Land. Thus, while transport biofuels have a significant role to play to reach full climate mitigation potential in the short term, limits to upscaling and availability of transport biofuels, stresses the need to speed up the implementation of alternative abatement measures and to deploy biofuels only where there are no alternatives [9,55].

Moreover, in a world that advances in line with the Paris Agreement, the competition for, and thereby the value of, biomass will increase with time. In Sweden many industries see potential in using bio-based fuels as substitution for fossil fuels, with some already having started down this path, including the cement and asphalt industries. Although this fuel shift has climate benefits (for example halving emissions associated with asphalt production), a shortage of suitable and inexpensive biomass resources could hamper its prospect for wider adoption and bears a risk of leading to increased manufacturing cost if/when other sectors starts moving down the same path (as per sector roadmaps, see e.g. Refs. [42,43,76]). Given the increased value of biomass with increased deployment and its likely limitation in supply, the willingness to pay for the biomass could, and feasibly should, limit its use in sectors where alternatives exist [9].

Again, it is important to ensure that focus remains firmly on adopting and scaling up the range of alternative abatement measures. For asphalt, these include lowered production and paving temperatures, increased recycling rates and support towards additional circularity measures such as increased use of other recycled materials as aggregates, e.g. construction and demolition waste and slag from municipal waste incineration [30,84].

For construction equipment and heavy transports, this would mean an increased focus on development and deployment of hybrid and electric technologies for vehicles and crushing plants, given a prerequisite of low-carbon electricity (see e.g. Refs. [48,49,85,86]). While some examples of hybrid and electric machinery are already available on the market, their wider adoption would require collective agreements or incentive structures that cascade requirements down the supply chain as to assure construction equipment owners that investments in machinery with higher upfront costs will repay themselves.

Other high potential abatement measures for construction equipment and heavy transports include optimization of logistics and material efficiency, such as mass handling requirements. Already today a certain degree of optimization of base, filling and structural materials is taking place, as evidenced by the execution of the project used as a case study here (with a decrease in fuel consumption of around 15% as a result). However, implementation of its full potential would require greater collaboration between and beyond project stakeholders [49,87,88], and demand a change of Swedish waste regulation, which puts limitations on the reuse of for example excavation masses [89]. By attracting attention to resource efficiency and circularity principles, stronger linkages would be created to SDG 12 on Responsible Consumption and Production.

Next in the line of road construction GHG emission hotspots is concrete, where adoption of concrete with cement clinker substitutes is a key measure requiring further attention. In Sweden, regulations and national standards regarding construction concrete have historically been more restrictive than on a European level [90]. Despite an ease in this regard, the use of concrete with alternative binders in Swedish transport infrastructure projects remain limited [28]. Additional barriers have been raised by stakeholders during the study, ranging from easing of standards not being fully applied, via technical challenges around production control, potential changes in the concrete properties and whether durability can be guaranteed, to economic concerns on process adjustments with e.g. additional hardening times prolonging project timelines. While these barriers are confirmed by e.g. Benhelal et al. [91], other studies including Wesseling and Van der Vooren [92], also describe systemic lock-in effects, circled around vested interests and the lack of a business case for alternatives, noting coordinated policy efforts are needed with a focus on procurer-supplier knowledge diffusion and market creation support. In contrast, cement clinker substitutes are in wide use in transport infrastructure projects in Denmark, Norway and the Netherlands [90,93,94].

Nonetheless, raw materials for cement clinker substitutes will likely need to be replaced over time as fly ash from coal power plants and slag from steel production will diminish as coal power is phased out and blast furnaces are converted [43,95,96]. Even so, alternatives are proposed, including other industrial slags, agricultural waste ashes or calcined clays [45,97,98].

However, even if current abatement options are combined to its full potential, transformative technologies are still required to reach the goal of net zero emissions in the cement industry by 2045. Carbon capture technologies (CCS), with or without electrification of the cement kilns, are the main deep decarbonization alternatives. Similarly, the main options defined for deep emission reduction in the iron and steel industry are the use of carbon capture and storage (CCS) and electrification (either via hydrogen direct reduction or through electrowinning). While transformation of basic industry would entail positive links to SDG 9 on Industry innovation and infrastructure, it is worth remarking that the lead-times in these industries are long, with few investment cycles remaining to mid-century. In addition, such fundamental changes in industry processes are associated with high upfront costs.

Even so, increased electrification of the transport and industry sectors is a promising alternative, although it is important to remember that the impact of electrification of transport and industry will depend on how it is managed in terms of interlinkages and interactions across sectors. In addition, lead times related to planning, permitting and construction of both support infrastructure (RES energy supply, electricity grid expansion, hydrogen storage, CCS infrastructure) and piloting and upscaling to commercial scale of the actual production units will influence the speed of change. Realising these transformative measures would thus require a mix of long-term regulations and comprehensive policy measures, such as access to financial capital, risk sharing, standard requirements and public procurement [99]. Bataille et al. [50] state that each region needs a heavy industry decarbonization pathway focused on its particular competitive (dis)advantages and potential markets, e.g. reflecting access to biomass, zero carbon electricity and heat, and geological storage for carbon dioxide. The Swedish sector roadmaps for fossil free competitiveness [99] constitute a first step towards such pathways, which with support of national strategies and policy measures could lead to a holistic decarbonization pathway, including robust strategies for expansion of zero carbon electricity generation, transmission and distribution together with development of hydrogen supply chains and CCS infrastructure.

Another aspect to take into account for steel in particular, is the fact that steel is traded on a highly competitive global market, which is frequently emphasised as a barrier to realising its emission reduction potential (see e.g. Refs. [14,52,100]). Policy measures and investments towards transformation of the steel sector to allow for low-carbon construction steel will hence be needed at least on a European, if not a global level [101]. Various measures are put forward to manage this transformation, including industrial R&D, piloting of net-zero technologies, and demand support such as border carbon taxes, consumption-based carbon pricing, and/or cross-sectorial collaborations.

What emerges is a need to prepare for deeper abatement already now, to carefully consider the pathway for getting there while avoiding pitfalls along the way, such as over-reliance on biofuels or cost optimizations that cannot be scaled up to the required levels. Achieving the required transformative shifts will require holistic decarbonization pathways which ensure policy coherence for sustainable development.

Procurement could constitute an important enabler. Yet, in construction businesses, as in many other businesses, there are many companies involved in a project - developers, contractors, subcontractors and material suppliers, which all need to translate climate lean products/services into business opportunities. For procuring agencies, there is a balance between setting requirements too low (thus not incentivising the investments and shifts needed for deeper decarbonization) and setting the bar too high (and thus risk pushing smaller actors out of the market or end up with failed tenders). Procurers must thus find a strategy to formulate procurement requirements so that they do not lead to lock-in effects (i.e. only including incremental low-cost measures) while adapting and tightening the requirements at a pace and rate that incentivise rapid and extensive emission reductions on the supply side without being unattainable [64].

Incentives may thus prove critical and the Swedish Transport Administration has adopted an approach with functional requirements which set a minimum share of reduction as the baseline supported with a bonus structure down to 100% abatement, combined with material specific requirements strengthened over time [102]. This combination could indeed ensure not only that requirements are cascaded down the supply chain, but also serving to incentivise innovative or transformative solutions with deep decarbonization potential.

5. Conclusion

By mid-century, almost no carbon can be emitted to the atmosphere for compliance with the Paris Agreement. This study concludes that achieving close to zero emission road construction by 2045 is possible, although certain prerequisites must be met to realise the potential identified. Key priorities include: Upscaling of sustainable transport biofuel and industrial biomass fuel – in the short term (up to 2025–2030), together with a robust expanded climate neutral electricity sector; transformative shifts in basic industry (electrification and/or CCS in the steel and cement industry); and continued progress in hybridisation and electrification of heavy transport and construction equipment.

These challenges result in a need for transformative changes at different points along the supply chains. For the low-carbon transition to be realised, it is important to:

- Develop and monitor industry decarbonization pathways, and co-ordinate these plans nationally and internationally;
- Build on, support and strengthen cross-sectorial collaborations (such as the hydrogen-based steel making joint venture HYBRIT [103], the Volvo-Skanska Electric Site project on quarry electrification [104], and the Northern Lights CO_2 transport and storage project [105]).

Feedback from stakeholders throughout the case study work and beyond, indeed reaffirms the notion put forward by Bataille et al. [50], that the decarbonization is much more likely to succeed when involving most if not all supply chain actors.

Although the findings reported here draws primarily on Swedish experiences, and while some of the conclusions are valid only under certain conditions and circumstances, many of the challenges that have been raised here, and that must be overcome if to achieve a transition to zero-CO_2 production and practices in the construction supply chains, are universal [106–108].

From a global perspective, this is important, not the least, since there are still many regions of the world where much the of the infrastructure to provide mobility for people and goods, remains to be built. Estimates suggests that more than half of the urban infrastructure that will exist in 2050 has yet to be built [108,109].

In conclusion, unlocking the full abatement potential of the range of emission abatement measures that have been described in this study, will require not only technological innovation but also innovations in the policy arena and efforts to develop new ways of co-operating, coordinating and sharing information between actors in the supply chain. In support of this notion, further research would be needed concerning:

- Development of integrated industrial climate strategies including adaptation of legislation, policies and funding mechanisms aimed at transformative change [110];
- “Intangible” factors such as implicit or explicit constraints within organisations, inadequate communication between actors in the supply chain, overly conservative norms or lack of information;
- Strategies to increase coordination and collaboration along the supply chains, to facilitate collective action among stakeholders;

- The use of public procurement as a tool to spur innovation, create markets and open up for economies of scale, considering culture, policies and capabilities in the local context [112];
- Capacity building and information spreading (knowledge transfer, mainstreaming and securing new competences for the low-carbon transition, from higher education to active practitioners);
- Synergies, compromises and trade-offs when aiming to fulfil all the goals of the wider sustainable development agenda.

Author contribution section

Ida Karlsson: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing - Review & Editing, Visualization, Johan Rootzén: Writing - Review & Editing, Supervision, Filip Johnsson: Writing - Review & Editing, Project administration, Funding acquisition

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2019.109651.

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