Technical Roadmaps

Technical roadmap
Buildings and transport infrastructure

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MISTRA CARBON EXIT

About the authors

Ida Karlsson is a PhD student at the division of Energy Technology in the Department of Space, Earth and Environment at Chalmers University of Technology. Ida has a keen interest in research utilisation and bridging the gap between academia and centres of decision-making. Her research uses holistic systems thinking to analyse technological options and barriers, enablers and opportunities on the road towards zero carbon emission in the value chains of buildings and transport infrastructure.

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Abstract

This report explores different possible trajectories of technological developments in the supply chains of buildings and transportation infrastructure. By linking short-term and long-term goals with specific technology options, the Mistra Carbon Exit roadmaps describe key decision points and potential synergies, competing goals and lock-in effects. The analysis combines quantitative analytical methods, i.e. scenarios and stylized models, with participatory processes involving relevant stakeholders in the roadmap assessment process. The roadmaps outline material and energy flows along with costs associated with different technical and strategical choices and explore interlinkages and interactions across sectors. The results show how strategic choices with respect to process technologies, energy carriers and the availability of biofuels, carbon capture, transport and storage (CCS) and carbon neutral electricity may have very different implications on energy use and CO_2 emissions over time.

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The three reports: Technical roadmap Steel Industry, Technical roadmap Cement Industry and Technical roadmap Buildings and transport infrastructure.

Mistra Carbon Exit – Technical roadmaps

Introduction

Sweden has, in line with the Paris agreement, committed to reducing GHG emissions to net-zero by 2045 and to pursue negative emissions thereafter. The overarching goal of the Mistra Carbon Exit (MCE) research program is to identify and analyse the technical, economic and political opportunities and challenges involved in this undertaking.

With a time horizon of several decades, any notions as to the future development of the complex economic, social, and technical dynamics that govern demand for energy and materials, and the associated greenhouse gas emissions, are likely to be speculative. Nevertheless, decisions as to how to best manage the transition must be made taking the future into account.

In Mistra Carbon Exit we work with a set of Scenarios and Roadmaps as tools to assess interlinkages and interactions across sectors and to communicate internally between the project partners and externally to inform and engage relevant stakeholders. The MCE Roadmaps are aimed at exploring different future trajectories of technological developments in the supply chains for buildings and transportation infrastructure. By matching short-term and long-term goals with specific technology solutions, the MCE Roadmaps make it possible to identify key decision points and potential synergies, competing goals and lock-in effects.

Mistra Carbon Exit research investigates External scenarios (described in WP1, related to global development in "Shared Socioeconomic Pathways", SSPs), Internal scenarios (described in WP1, referring to the development of the Swedish energy system meeting national targets) and Roadmaps that explore different technological pathways for the supply chains for buildings and transportation infrastructure (*cf.* Figure 1). The latter, i.e. the Roadmaps, will be used in an iterative approach to be included in the narratives for the internal scenarios, which means that there for example should be consistency between the development of the Swedish demand for electricity and the development of transforming Swedish steel industry to using hydrogen as reduction agent in the reduction of iron ore. Thus, Roadmaps are an important part of describing drivers that give rise to new demand that need to be included in the Internal scenarios. The aim is to find clear timelines for scenarios and roadmaps and finding combinations of roadmaps that fit a certain scenario narrative. Thus, it may take iterations to find both coherence in terms of timing of measures and which measures that fit what scenario.

Roadmap description

This report describes the initial work with the Mistra Carbon Exit roadmap for the construction of Buildings and transport infrastructure. The following subsections are described for each of the Mistra Carbon Exit roadmaps:

- Technological options
- Alternative pathways (Key decision points and investments, technological specifications, assumed activity levels, energy carriers)
- Timeline (Describing production mix/ market shares, resulting energy mix and CO_2-emissions)
- Description of risks, barriers and enablers linked to the respective roadmap

To find all the roadmap reports, please visit www.mistracarbonexit.com.

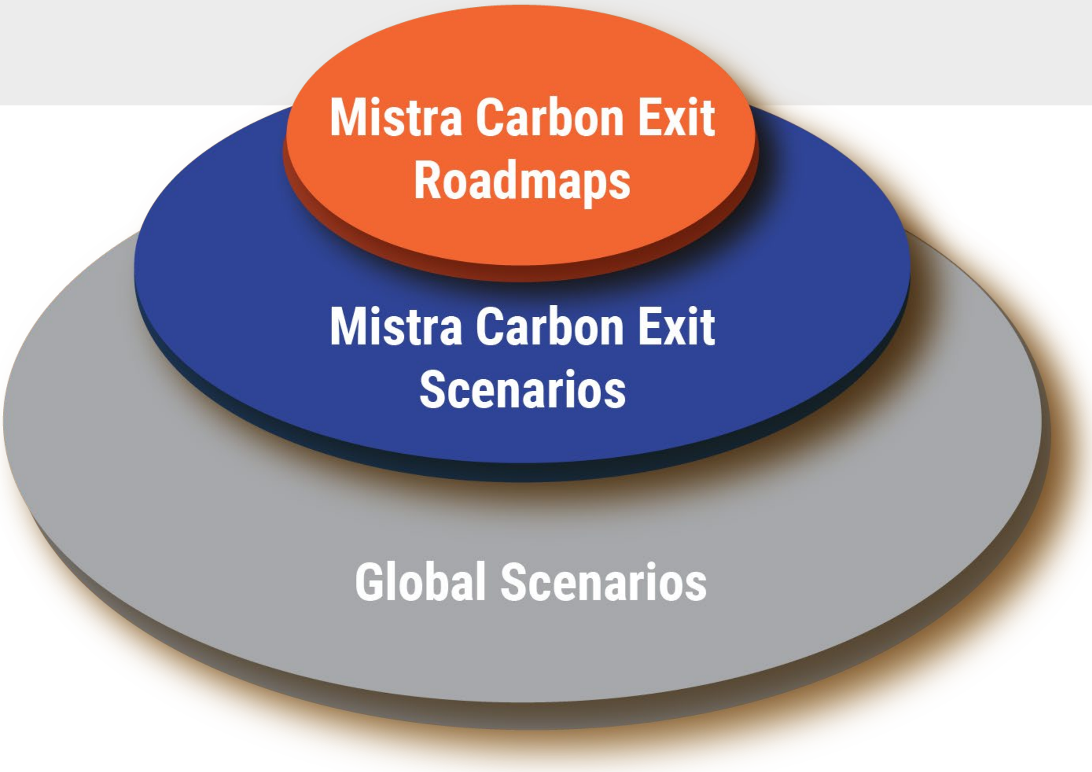

Figure 1. Mistra Carbon Exit use External scenarios to describe global development to meet a low carbon future, Internal scenarios to describe the development of the Swedish energy system and Roadmaps to describe how different technology options may impact the Internal scenarios.

Mistra Carbon Exit Roadmap

Buildings and transport infrastructure

Current status

Estimates of the climate impact from building and construction processes in Sweden is associated with a significant degree of uncertainty. Boverket, the Swedish National Board of Housing, Building and Planning, made an initial calculation of the sector's greenhouse gas emissions as early as 2009, which was the starting point for its development of environmental indicators, reported since 2011 with a methodology review in 2014. The environmental indicators are based on environmentally extended input-output data from SCB (Statistics Sweden). The reporting cover both domestic emissions and emissions associated with imported goods. Another estimate was made by the Royal Swedish Academy of Engineering Sciences (IVA) in 2014. Erlandsson et al (2018) combined the input-output data from Boverket with calculations for infrastructure construction from IVL Swedish Environmental Research Institute.

Most recently, Boverket and Naturvårdsverket (the Swedish Environmental Protection Agency) with support from IVL, have concluded a joint effort to develop a method to better chart future emissions from the construction and real estate sector. This includes a new bottom up method, where statistics detailing new net area from newbuilds and refurbishments are combined with life cycle analysis (LCA) data per building type. These figures are further combined with simplified calculation methods for gross refurbishments, repair, replacement and demolition. The various estimates are detailed in Table 1.

Table 1. Details on estimates for the carbon emissions associated with building and transport infrastructure construction in Sweden

Method	**Input-output**	**Input-output**	**LCA**	**Input-output and IVL**	**LCA and investment analysis**
Reference	Naturvårdsverket and Boverket, (2019)	Naturvårdsverket and Boverket, (2019)	(Erlandsson 2019; 2020)	Erlandsson, Byfors and Lundin (2018)	(Sveriges Byggindustrier and Iva 2014)
Scope	Domestic + Imports	Domestic	Domestic + imports	Domestic + imports	Domestic
Reference year	2015	2015	2015	2015	2012
B/TI combined (Mt CO_2)	**13.5**	**8.1**		**10.7**	**7.5**
Building construction (Mt CO_2)	11.6	6.6	5.5	7.6	4.5
Transport Infrastructure construction (Mt CO_2)	1.9	1.5		3.1	3
Comments			Excluding agricultural properties.		Plus 3 MtCO_2 for other infrastructure (e.g. ports, airports, power stations)

The range of estimates are notable, with potential variances including different system boundaries and possible overstating of the importance and emissions intensity of imports in the input-output analysis. Differences naturally also stem from the scope of the estimates, where for instance only 4% of the output from the Swedish steel industry is used in the Swedish construction industry. A great majority of steel is thus imported. Swedish steel imports correspond to 3.5-4 Mton per year with research demonstrating that around 25-50% of steel consumption goes to the construction industry. However, more work is needed to unravel the large differences between the estimates.

In terms of the sources of emissions, Naturvårdsverket and Boverket detail an approximate sector division for the building and real estate sector (domestic emissions), with 1.5 Mt CO_2 from transports, 0.9 Mt CO_2 from construction equipment, 2.4 Mt CO_2 from the mineral industry (predominantly cement) and 1.5 Mt from other sectors (refineries, other metals, paints and chemicals). It is also estimated that around 40-60% of the annual climate impact from building construction stem from construction of non-residential buildings, such as offices, schools and other premises. A growing share of around 30-40% arise from construction of multi-family dwellings and the remaining 10-15% from single family houses. In terms of where in the lifecycle the climate impacts arise, the estimates indicate that around 2/3 stem from new buildings and 1/3 from refurbishments and maintenance.

In terms of construction of transport infrastructure, the figure of 1.9 Mt CO_2 annually from domestic plus imports is equivalent to other recent research into the topic by Liljenström, (2018). Trafikverket (the Swedish Transport Administration) provides a detailed breakdown of the emission share from various materials and activities which is here used as a proxy, noting that around half of the transport infrastructure investments in Sweden are made by regional and local government.

Based on these various sources and approximates, we have estimated the total climate impact of building and construction processes in Sweden to be close to 10 Mt CO_2 per year, with building construction accounting for roughly three quarters, and civil engineering and public works for around one quarter of the annual emissions. In this technology roadmap, we focus mainly on the climate impact linked to construction of buildings and transport infrastructure, thus we do not include construction of for example utilities. As can be seen in Figure 2, this carbon impact derives predominantly from concrete and steel together with diesel use in construction processes and material transports.

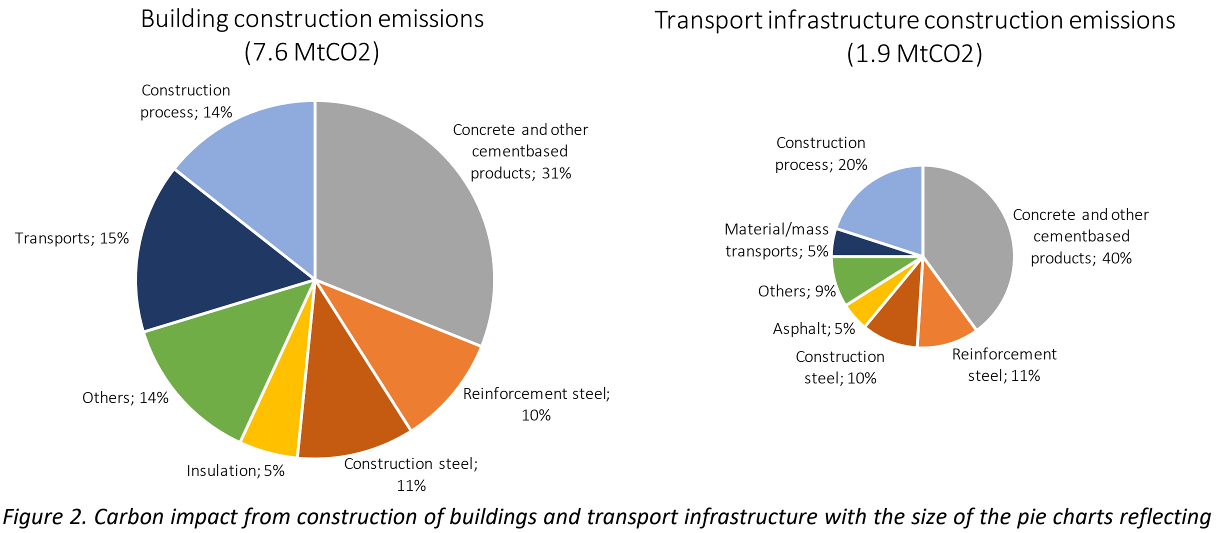

Figure 2. Carbon impact from construction of buildings and transport infrastructure with the size of the pie charts reflecting the relative magnitude of emissions. Based on data from Sveriges Byggindustrier and Iva, (2014); Naturvårdsverket and Boverket, (2019); Trafikverket, (2017); Junnila, et al, (2006); Wallhagen et al , (2011); and (Erlandsson, Byfors, and Lundin 2018).

Technological options

Related to concrete use, the cement clinker production is responsible for the majority of GHG emissions with around 65% of the CO_2 emissions stemming from the calcination process and 35% emanating from the fuels used in the cement ovens, the so-called kilns. The main current emission abatement options comprise of replacing fuels in the cement kilns with waste- or bio-based fuels, reducing the amount of cement clinker by using alternative binders and optimising the concrete recipes to use less cement. Other options include design optimization to slim constructions and material substitutions towards wood-based solutions.

Even if current abatement options are combined to its full potential, transformative technologies are still required to reach the goal of close to or net zero emissions in the cement industry by 2045. Carbon capture technologies (CCS) with or without electrification of the cement kilns are key deep decarbonisation alternatives. The Swedish cement industry roadmap is targeting climate neutrality by 2030, with the main focus being on biofuels together with CCS. However, Cementa is also pursuing electrification together with Vattenfall through its CemZero project, with a pre-feasibility study released in 2018 (Wilhelmsson et al. 2018).

For primary steel production, about 80% of the CO_2 emissions stem from the reduction of iron ore, while in scrap-based steel production, the main emission sources steel is produced by steel scraps that are melted in electric arc furnaces. These mainly use electricity but are also fuelled by natural gas (25-30%) and a smaller share of coal (<5%). Refurbishments and upgrades of current electric arc furnaces provide potential for decreased electricity consumption, and there is also potential for biomass to substitute fossil process energy in EAFs, both as a reducing agent and as fuel in reheating furnaces. The main options for deep emission reduction in primary steel production are electrification with renewable electricity (either via hydrogen direct reduction or through electrowinning), use of biomass to replace coke as fuel and reducing agent, and/or use of carbon capture and storage (CCS). Partial CO_2 capture is a mature and low-cost technology that can be implemented in the coming 10-15 years without major changes to the existing process and which can be combined with biomass substitution.

Key near-term abatement options for both construction processes and material transports include substitutions to biomass-based fuels and efficiency measures including hybridisation and operational measures such as eco-driving and logistics optimisation. Mass handling optimisation and material efficiency is another abatement measure with large emissions reduction potential linked to both construction machinery and heavy transport. Over the longer term, deeper emissions reductions would result from electrification and/or CCS for steel and cement clinker production together with electrification of construction equipment, crushing plants and heavy trucks. For the latter, options include plug-in hybrid or fuel-celled heavy-duty trucks/haulers potentially in combination with electric road systems. Model shifts for heavy transport to rail and ship is also an abatement measure with large potential. While such shifts have been out of scope for this analysis, this is an important level towards a more transport-efficient society (Kungliga IngenjörsVetenskaps Akademien 2019b).

High potential abatement measures for other materials include energy efficiency measures and biofuel substitution in other material production facilities (asphalt, mineral wool, chemicals), recycling, material substitutions such as wood-based solutions and change of insulation materials towards use of rockwool, glass wool and potentially renewable-based insulation (e.g. cellulose, wood fibre, straw) instead of cell plastics. In the longer term, measures such as electrification for heating in material production facilities and/or CCS for cracking and polymerisation for plastics production are potential deep decarbonisation measures for other materials.

Material efficiency is another key abatement measure for all construction materials, and a measure that in general deserves more attention in policy and climate mitigation discussions. Evidence (see e.g. Allwood and Cullen, 2012; Energy Transition Commission, 2018; Material Economics, 2019) suggest that, on average, one-third of all material use could be saved if designs were optimised for material use rather than for cost reduction, since downstream production (and design) are generally dominated by labour costs and not material costs. In addition, manufacturers are motivated to use excess material by an asymmetry in the costs of product failure compared with the costs of over-specification, and by the fact that many products experience higher loads prior to use (in installation or transport) than in use. Detail on some material efficiency and circularity measures are described in Table 2.

Table 2. Specifications of abatement potential and costs of selected circularity and material efficiency measures for construction of buildings and transportation infrastructure.

Technology	Demand/emissions reduction	Costs	References
Concrete			
Reduced overdesign	7-20% CO_2 reduction	€16-28/ t CO_2 (€40-70 /t cement)	(Shanks et al. 2019; Energy Transition Commission 2018; Favier et al. 2018; Material Economics 2019; Lindgren et al. 2017)
Precasting/ prefabrication	3-15% CO_2 reduction	€0-27/ t CO_2	(Shanks et al. 2019; Andersson et al. 2018; Favier et al. 2018)
Reuse elements	4-20% CO_2 reduction	€42/ t CO_2	(Favier et al. 2018; Energy Transition Commission 2018; IEA and CSI 2018)
Steel			
Structural optimisation of construction steel	20-50%	€48/ t CO_2	(Energy Transition Commission 2018; Material Economics 2019; Allwood and Cullen 2012; Moynihan, Allwood, and Allwood 2014)
Avoid steel downgrading	10-20% reduction in crude steel production	- 4€/ t CO_2	(Energy Transition Commission 2018; Fleiter et al. 2019)
Reduced over dimensioning of reinforcement	15-30%		(Allwood and Cullen 2012)
Plastics			
Plastics material efficiency	14-35%	€32/ t CO_2	(Material Economics 2019; Energy Transition Commission 2018)

The analysis assumes emission factors for electricity and district heating declining in accordance with scenario analysis from the Swedish Energy Agency, implying that GHG emissions related to electricity generation are close to zero in 2045. (Energimyndigheten 2017).
The abatement options for building and transport infrastructure construction have been roughly divided in three categories, depending on their cost and lead times, as described in Figure 3.

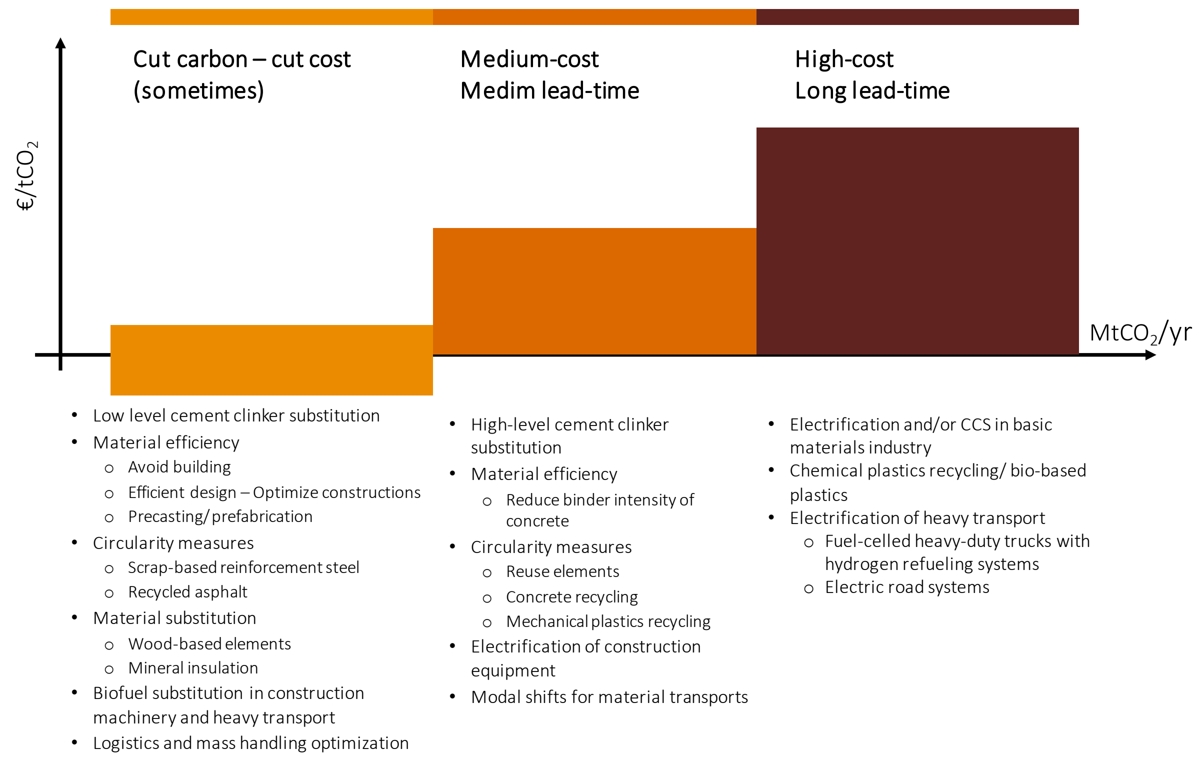

Figure 3. Categorisation of abatement options within the buildings and transport infrastructure roadmap

Alternative pathways

Four pathways have been devised for buildings and transport infrastructure, two with a focus on bio-based measures together with CCS and two with a focus on electrification. The second of the two within each focus explores the role material efficiency measures may play in the low-carbon transition. For cement and steel, the buildings/transport infrastructure pathways build on the cement/steel roadmaps with some variations to account for expected developments on the European level (for details, refer to Mistra Carbon Exit Steel and Cement Roadmaps).

For primary steel production, the Bio/CCS pathways adopt process modification enabling top gas recycling combined with carbon capture and storage, while the Electrification pathways pursue a hydrogen direct reduction (H-DR/EAF) steelmaking process. Current electric arc furnaces for scrap-based secondary steel production are being refurbished and upgraded at a continuous rate in all pathways, alongside partial bioenergy substitution in the Bio/CCS pathways.

For cement, the Bio/CCS pathway adopts post-combustion carbon capture with amine scrubbing, which is the technology tested by HeidelbergCement in Breivik in Norway, while the electrification pathway pursues plasma heating according to the CemZero concept. In all pathways, a progressive realisation of cement clinker substitution and cement demand reduction from optimisation of concrete recipes is assumed. It is worth noting that while the cement market is mostly domestic, the concrete market is turning more international, particularly pertaining to precast concrete, but there is a lack of data and reporting to determine the extent of concrete imports. However, the precast concrete market is regional and mainly limited to northern Europe, while steel on the other hand is traded on a global market. Nevertheless, the abatement alternatives proposed in the cement and steel roadmap pathways are deemed applicable for developments on a European level.

In addition to cement and steel, the main climate impact of building and transport infrastructure construction stem from the use of construction equipment together with heavy transports. Separate pathways have been devised for these, with a focus on Biofuel substitution and Electrification, respectively. Various international and national assessment and analyses (see e.g. Skinner *et al.*, 2010; Swedish Transport Administration, 2012; Sköldberg, Holmström and Löfblad, 2013; SOU, 2013; Bondemark and Jonsson, 2017; IEA, 2017; Energy Transition Commission, 2018; Kungliga IngenjörsVetenskaps Akademien, 2019a) have given diverging views on the potential for biofuel substitution and electrification for the low-carbon transition of heavy transport and construction equipment, which has been the basis for the respective pathways and associated potential over time. Details of the emissions reduction measures applied for the key emission posts over the timeline for the different pathway scenarios are displayed in Table 3.

Table 3. Timeline for key abatement measures in the buildings/ transport infrastructure roadmap

	Scenario	2025	2030	2035	2040	2045
Cement/ concrete	All scenarios	20% alternative binders 5% reduced binder intensity	25% alternative binders 12% reduced binder intensity	28% alternative binders 15% reduced binder intensity	32% alternative binders 22% reduced binder intensity	35% alternative binders 28% reduced binder intensity
	Biofuel + CCS	40% biofuels	45% biofuels 45% CCS	50% biofuels 45% CCS	52% biofuels 80% CCS	55% biofuels 90% CCS
	Electrification	40% biofuels	45% electrification	45% electrification	90% electrification	100% electrification
	Material efficiency	8%	15%	20%	25%	30%
Reinforcement steel	Biofuel + CCS	100% recycled steel	10% energy efficiency 50% biogas	100% biogas	100% biogas 50% biocharcoal	100% biogas 100% biocharcoal
	Electrification	100% recycled steel	10% energy efficiency 50% plasma heating replacing gas	100% plasma heating replacing gas	100% plasma heating replacing gas 50% biocharcoal	100% plasma heating replacing gas 100% biocharcoal
	Material efficiency	5%	10%	15%	20%	25%
Construction steel	Biofuel + CCS		20% biofuel substitution	30% biofuel substitution	50% TGR-CCS 30% biofuel	100% TGR-CCS 30% biofuel
	Electrification		20% biofuel substitution	30% biofuel substitution	50% hydrogen-reduction	100% hydrogen-reduction
	Material efficiency	10%	15%	20%	25%	30%
Construction equipment	All scenarios	5% optimization[1]	10% optimization	10% optimization	10% optimization	10% optimization
	Biofuel + CCS	42% biofuel[2] 9% hybridization 5% electrification	63% biofuel 14% hybridization 9% electrification	78% biofuel 23% hybridization 13% electrification	85% biofuel 31% hybridization 15% electrification	81% biofuel 31% hybridization 19% electrification
	Electrification	42% biofuel 9% hybridization 5% electrification	75% biofuel 14% hybridization 9% electrification	76% biofuel 23% hybridization 24% electrification	59% biofuel 23% hybridization 41% electrification	50% biofuel 23% hybridization 50% electrification
Heavy transports	All scenarios	5% efficiency/ optimization	10% efficiency/ optimization	15% efficiency/ optimization	20% efficiency/ optimization	25% efficiency/ optimization
	Biofuel + CCS	42% biofuel 5% electrification	63% biofuel 10% electrification	78% biofuel 15% electrification	80% biofuel 20% electrification	75% biofuel 25% electrification
	Electrification	42% biofuel 5% electrification	63% biofuel 20% electrification	70% biofuel 30% electrification	55% biofuel 45% electrification	40% biofuel 60% electrification

[1] *Efficiency comprises technical measures including hybridization and operational measures such as logistics optimization and eco-driving.*

[2] *The biofuel share for construction equipment and heavy transports is a combination of biofuel blending in conventional diesel together with pure biofuel (e.g. HVO100).*

Other materials follow a common decarbonisation pathway devised centred on the measures described in the technological options section (based on e.g. Schneider et al., 2020; Material Economics, 2019; Hill, Norton and Dibdiakova, 2018; Zabalza Bribián, Valero Capilla and Aranda Usón, 2011; Pedreño-Rojas et al., 2020).

Appraisals of future levels of construction vary significantly, particularly depending on the basis of assessments being of business cycles and economic conditions or on the need for construction due to expected growth in population combined with refurbishments required to meet energy efficiency targets (Erlandsson 2019; Boverket 2018; Peñaloza et al. 2018). For simplicity, an assumption of continuous levels of construction has been assumed in this study.

Results

The resulting energy use per energy carriers and carbon emission reductions for the construction of buildings and transport infrastructure are depicted in Figure 4 and Figure 5.

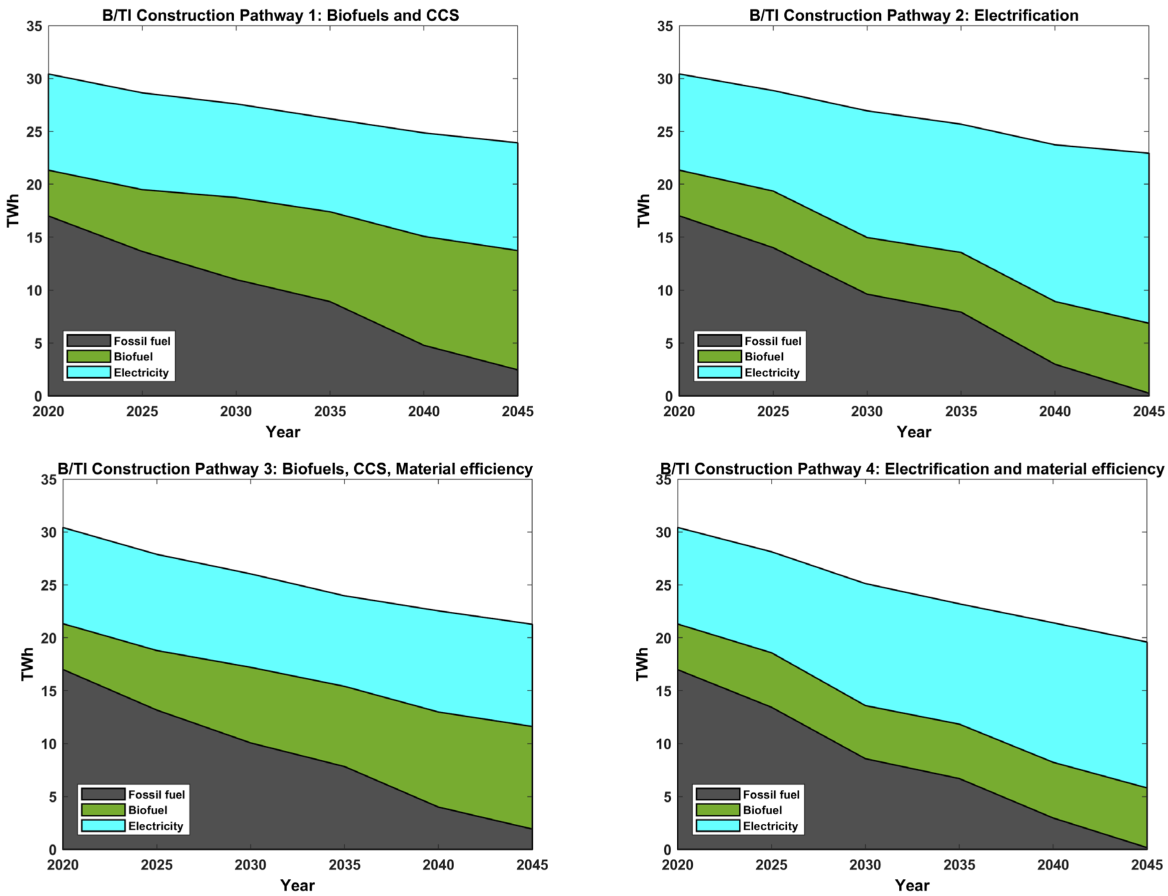

Figure 4. Energy use for each energy carrier over time for the buildings and transport infrastructure pathways.

The analysis demonstrates that currently, construction of buildings and transport infrastructure use about 30 TWh energy, which can be compared to the total energy use in Sweden of 378 TWh, thus accounting for around 8% of total Swedish energy use. All pathways exhibit a reduction in total energy use over time to 2045, with the reduction varying from 9-17% to 2030 and 21-36% to 2045. When comparing the total energy use, the Electrification pathways demonstrate a total energy use of 5-8% lower than the Bio/CCS pathways in by 2045. This is mainly a result of the lowered energy requirements from electric propulsion compared to combustion engines for construction equipment and heavy-duty trucks combined with the energy penalty for post-combustion carbon capture for cement production.

A focus on material efficiency has the potential to reduce total energy use by 6% to 2030 and 11-14% by 2045 for the Bio/CCS and Electrification pathways by 2045 (Pathway 3 vs 1 and Pathways 4 vs 2, respectively), implying reductions of around 5 TWh.

Regarding biofuels, they are currently mainly used in the transport sector, and in asphalt and cement production. Over time, biofuel use is set to expand with the overall share of biofuels increasing from 14% of total energy use at current to around 30% in the electrification pathways and to around 45% in the biofuel pathways by 2045. Electricity use remain almost constant in the Bio/CCS pathways, while increasing from 9 TWh to 14-16 TWh in 2045, reaching a share of around 70% in the Electrification pathways.

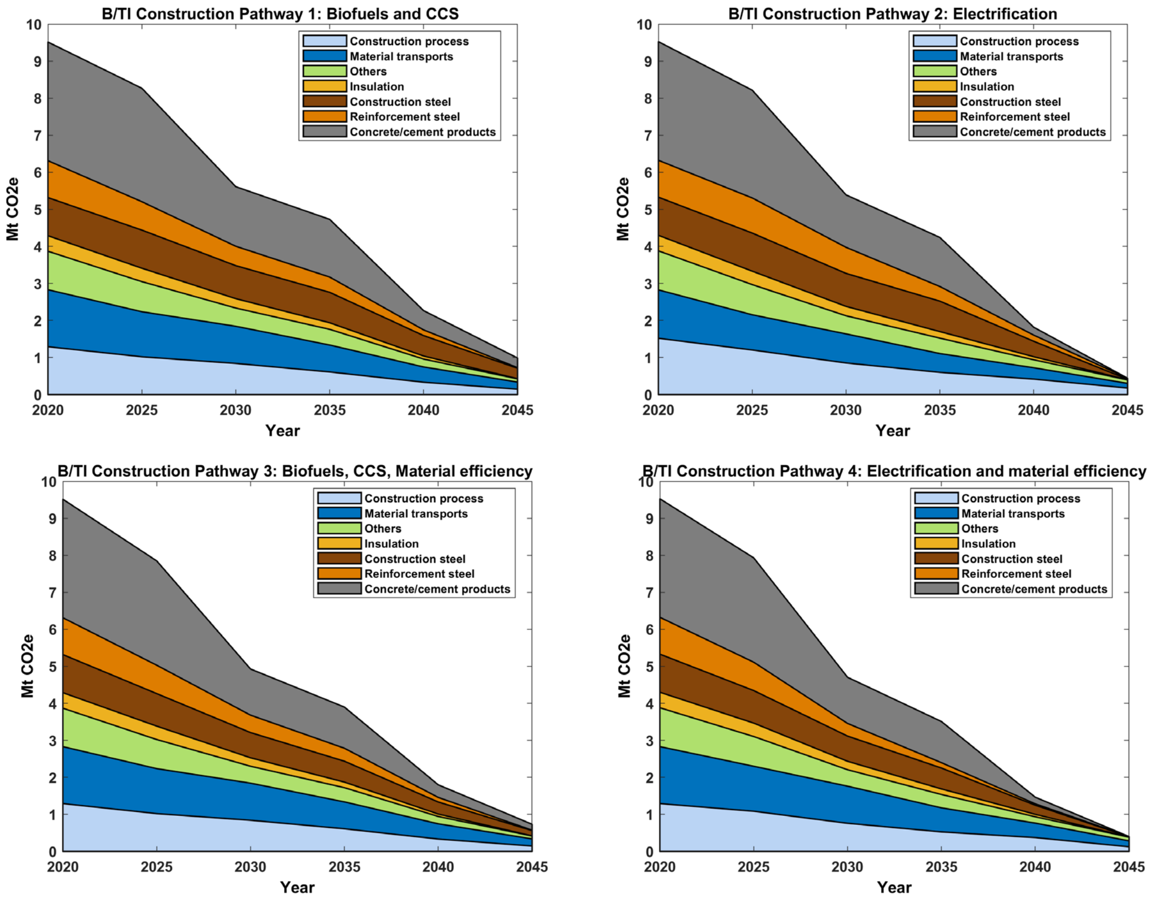

Figure 5. Results on emissions for the buildings and transport infrastructure roadmaps.

As can be seen in Figure 5, all pathways reach close to zero emissions in 2045, with total emissions reduction of 90-96%, with the highest emission reduction potential in the Electrification pathways. Up until 2030, we see potential emissions reductions of around 43-45% for Pathways 1 and 2.

Before 2030, most emissions reductions stem from increased use of alternative binders combined with reduced binder intensity in concrete optimisation and energy efficiency measures on the construction sites combined with biofuel substitution in construction equipment and material transports.
The biofuel substitution partly ensues as a result of the Swedish reduction duty regulation, which specifies a set and increasing emission reduction in line with a growing share of renewable content in

diesel fuel. The emission reduction up until 2030 is also supported by the use of reinforcement steel produced only from recycled steel combined with improved electricity emissions factors together with material and fuel substitutions regarding insulation and plaster materials.

After 2030, deeper emissions reductions come about as a result of continued biofuel substitution combined with hybridization and electrification for construction equipment and trucks. Fuel substitution also plays a role in primary and secondary steelmaking. In the Bio/CCS pathways, this fuel substitution is combined with CCS in primary steelmaking as well as in cement kilns.

In the Electrification pathways, plasma heating is instead used to create the necessary temperatures in secondary steelmaking, cement kilns, in cracking and polymerisation for plastic production as well as mineral wool production. Electrification in the primary steelmaking in the form of hydrogen reduction also contributes considerably in the electrification pathway.

A focus on material efficiency provides for additional reductions, particularly in the medium term. An additional 8-15% brings the total emissions reductions down to around 50% by 2030, implying a difference of around 0.5-0.8 Mt CO_2 emissions per year. In view of the remaining carbon budget, up to 2045 the material efficiency pathways could reduce the total cumulative amount of CO_2 emitted from construction of buildings and transport infrastructure over the years 2020 to 2045 by around 9-14% compared to its corresponding biofuel/electrification pathways.

Risks, enablers & barriers

An illustration of some of the main uncertainties related to the Building and Transport Infrastructure roadmap is depicted Figure 6, categorised according the assumed cost and lead times of the corresponding abatement measures (as per Figure 3).

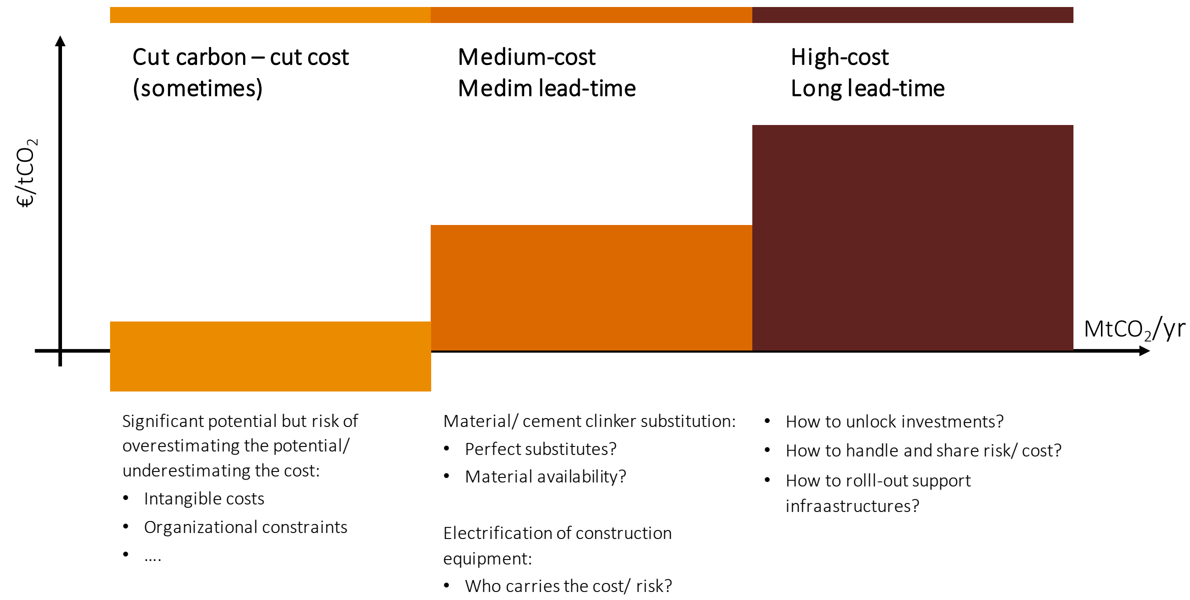

Figure 6. A qualitative categorisation of risks and barriers according to the categorisation of abatement costs and lead times for the Buildings and Transport infrastructure roadmap.

The main risks, enablers and barriers perceived for the buildings and transport infrastructure roadmap are further detailed in Table 4. The input for this compilation is drawn from the industries' own Roadmaps for fossilfree competitiveness, stakeholder input and feedback gathered from workshops and conferences within Mistra Carbon Exit and associated project collaborations together with inspiration from other relevant national and international studies (see Appendix 1: Overview of relevant roadmap studies and reports).

Table 4. Risks, enablers and barriers for the Buildings and Transport infrastructure roadmap.

Technological development and diffusion	Risks and uncertainties	Enablers
Carbon-lean materials and processes	Lack of a coordinated climate strategy; Conservatism and 'belts and braces' policies, standards and norms;	Ambitious, long-term and predictable legal requirements from the basis of the net-zero climate target - including active and continuous public policy coordination; Evaluate whether the mandate of public agencies needs to be reviewed to enable the facilitation of learning and innovation, e.g. financing/cost sharing, scale up of technology/ best practices; Appoint an agency with responsibility for national and sector-wide follow-up of progress and alignment to national goals, sector goals and industry roadmaps;
	Fragmented industry with complex value chains - complicates knowledge sharing and mainstreaming pilot/project results; Unclear responsibility structure leading to sub-optimisation and lost opportunities;	Utilise procurement types and/or strategic partnerships which stimulate increased collaboration and dialogue between actors in the value chain; Establish a continuous chain of responsibility motivated by collective incentives for all parties by using innovative contracting models with balanced risk sharing, e.g. long-term strategic alliances; Develop standardized and progressive procurement criteria and definitions through dialogue with the market - 'Procurement roadmaps' linked to industry roadmaps; Integrate system level climate requirements – Avoid sub optimisations and require interactions between suppliers and contractors; Plan carbon-smart and engage the value chain from the beginning of construction projects - Provide architects, constructors and consultants with means to propose and/or prescribe low climate impact resource-efficient solutions; Digitalise the entire planning and construction process; Establish means of cascading procurement requirements and incentives down the value chain, e.g. combinations of functional and specific requirements;
	Insufficient competence level on life-cycle climate reduction options across chain actors	Strengthen knowledge of the Swedish Public Procurement Act and the role and potential of procurement as a driver of the low-carbon transition - throughout client organisations; Increase the competence on the responsibility and opportunity to reduce climate impacts throughout the planning and construction process across the construction value chain; Provide incentives and motivation to establish a greater role for communication, public awareness and education; Establish an open-source method for visualisation of carbon emissions in value chain transactions from suppliers of raw materials to consumers; Key actors setting the standard - by ambitious carbon goals, continual monitoring and reporting of carbon emissions, climate and competency requirements internally and on suppliers, architects, consultants and subcontractors; Establish support systems and forums for outreach and dialogue towards sharing of case studies, best practices and knowledge development to effectively roll over learning from project to project, targeting the entire value chain;
	Lack of market demand for low-carbon products;	Lower capital adequacy requirements and other incentives for green financing solutions aimed at stimulating investments with lower carbon emissions;

		Allocate funding to and require sustainable retrofitting of existing property portfolios; Requirements for carbon impact declarations from a life-cycle perspective for buildings, infrastructure and construction products; Open database of representative generic carbon data that is life-cycle-based and quality-assured; Requirements and incentives in public procurement based on function and carbon footprint - Adjust incentive structures to project steering towards both carbon and cost; Where feasible, use carbon-linked procurement evaluation criteria to move towards climate being an integral part of decision making, e.g. life-cycle costing or criteria around competency within climate smart constructions; Provide resources for and prioritize procurement follow-up as strict as procurement requirements; Develop cross-sectoral initiatives to develop demand for low/zero-carbon products
Circularity	Lack of clear regulatory cross-sectoral framework; Unclear responsibility structure leading to sub-optimisation and lost opportunities; Unclear and hindering waste regulation; Lack of financial incentives towards material efficiency and circularity	Change regulations for the classification of waste to remove obstacles to – and instead drive – circular business models; Produce End-of-Waste (EoW) criteria and create financial thresholds for recycling; Produce industry guidelines and provide implementation support; Prioritize circular material flows during legal and permitting assessments; Establish »Policylabs« for industry regulations; Create obligations for materials separation and recycling at decommissioning, e.g. extended producer responsibility; Develop scalable production methods that enable use of materials with low climate impact, increased re-use and closed material flows during new production, refurbishing and demolition; Require re-use of materials if/when it is advantageous from a life-cycle perspective, for example in refurbishments and regarding mass handling.
Material efficiency	Lack of incentives and value chain collaboration; Inflexible design process; Labour cost overshadowing material costs; Split incentives due to construction industry fragmentation	Clarify the overall responsibility and capacity to influence for each actor along and across the value chain, Engage the value chain from the beginning of construction projects; Develop measurement and reporting of material use per functional unit - using digitalisation and visualisation tools; Use parametrization, digitization and collaborative working methods for an efficient and iterative design and construction process; Create standards on materials efficiency; Establish policies and procurement requirements and incentives towards material efficiency - early engagement and cascading of requirements along the value chain; Provide further opportunities for industrialised processes such as prefabrication and precasting
Transport efficiency	Lack of incentives and value chain collaboration	Digitalization for logistics optimisation; Greater coordination between companies in the value chain, facilitated by big data computing; Evaluate options to and invest in solutions to overcome inter-modal transportation bottlenecks and other obstacles - Allowing more goods to be transported by train and ship

		Examine the possibility of transitioning current fuel taxation to an environmentally differentiated distance-based tax (Eco tax)
Biofuel adoption in transport and industry	Unclear biofuel strategy; Uncertainty around access and availability; Consequences for other environmental targets - Biomass as carbon storage and provider of biodiversity;	Develop a national bioenergy strategy and action plan for access to and distribution of sustainable biofuels; Establish a regulatory cross-sectoral framework for biomass use; Develop tightly defined sustainability standards for biofuels; Secure well-functioning market for biofuels; Cascade requirements/incentives to subcontractors towards biofuel use/hybridisation - e.g. requirements for fossil free construction equipment; When and where alternatives exist, transition public support of biomass use toward high priority sectors;
Electrification in transport and industry	Lack of coordinated electrification strategy; High upfront investment costs for hybrid/electric vehicles/machinery; Demand for sufficient power generation/ transmission/ distribution; Uncertainty around electricity prices; Need for carbon neutral electricity;	Develop a national electrification strategy and action plan for access to and distribution of low/zero CO_2 electricity; Create conditions for transformation of industry and transport through financing, risk sharing, innovation support and policy instruments; Active and continuous public policy coordination, including direct investment support, where appropriate; Secure continued government support for initiatives such as 'Industriklivet', the "industrial leap" and 'Klimatklivet', the "climate leap"; Set requirements for fossil free construction equipment; Political engagement to secure grid stability, access to and availability of zero-carbon electricity; Establish and implement plans for demand integration in line with expansion of supply from renewables; Efficient and predictable permitting processes (e.g. by using learnings from the development of wind power permitting processes); Support system for continued fast deployment renewable energy generation capacity; Secure a well-functioning electricity market focussing on energy system flexibility to minimise system cost; Speed up and secure the electrification of major roads;

Summary and discussions

As discussed in this report, the current best estimates of the climate impact from building and construction processes in Sweden is associated with a significant degree of uncertainty. The Swedish Environmental Protection Agency has together with the Swedish National Board of Housing, Building and Planning and the Swedish Transport Agency initiated processes to improve the methods used to report and track emissions from the construction sector. To provide well-grounded decision support, it is important that sufficient resources and competence are allocated so that development of emissions can be properly evaluated and so that the effects of planned measures and policies can be assessed before implementation.

Everything now

Cement and steel together with diesel use in construction processes and transports account for the majority of the CO_2 emissions associated with building and infrastructure construction (*cf.* Figure 2). One of the key messages from this work (Figure 7) is the importance of, on the one hand, not letting the pursuit of 'low-hanging fruits' (e.g. material substitution and efficiency measures) be an excuse for not acting to lay the foundation for the high-cost long lead-time measures (zero-CO_2 basic materials) that will be required for decarbonisation. Vice versa, it is also vital to not let the promise of e.g. low-CO_2 steel or cement be an excuse to not act to unlock the potential for measures that already exists today.

Successful decarbonisation of the supply chains for buildings and infrastructure, including the production of basic materials, will involve the pursuit - in parallel - of emission abatement measures with very different characteristics. Consequently, to facilitate the transition, the support tools box will need to encompass a variety of policies and strategies.

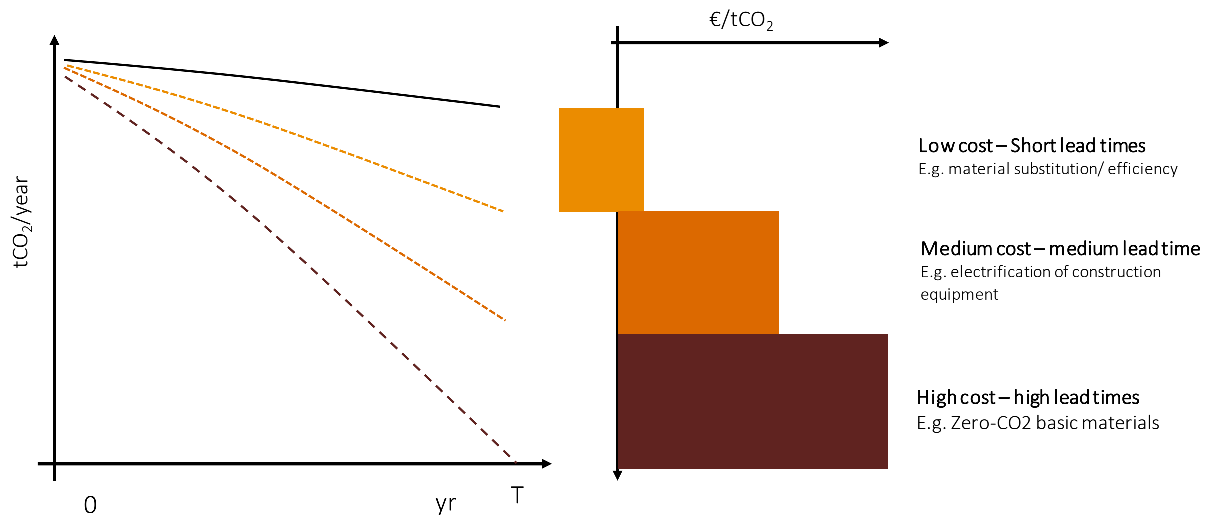

Figure 7. Successful decarbonisation of the supply chains for buildings and infrastructure in less than three decades will require the parallel pursuit of emission abatement measures with very different characteristics. Figure adapted from Vogt-Schilb and Hallegatte (2014)

Unlocking the full abatement potential of the range of emission abatement measures that are described in this report 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. Key priorities include, e.g.:

- **Providing policy coordination** and clear responsibility for monitoring and follow up of progress. Significant public and private resources are allocated to industry-level initiatives such as the Fossile Free Sweden roadmaps and the climate policy framework. However, stakeholders from both industry and public agencies have raised concerns about a lack of coordination and sub optimisation between different priorities and goals on a national level. Sufficient resources needs to be allocated so that development of emissions can be properly evaluated.

- **Continued and continuous effort** to reduce the climate impact from basic materials and construction through material efficiency, material substitution and continued process optimisation. This would include efforts early on, in all planning process and among all actors, to:
    - avoid building (where possible),
    - re-using old assets,
    - recycle building materials and components,
    - optimise material use, and
    - shift to low-CO_2 materials and services

- **Development of an integrated industrial climate strategy** including adaptation of legislation, and innovative schemes to share the risk and costs associated with developing and implementing new process technology and infrastructures (see e.g. Neuhoff *et al.*, 2019; Rootzén and Johnsson, 2019).

- **Strategic planning for support infrastructure**. The precise timing, location and nature of the technological shifts that will be required to decarbonise the basic material industry remains uncertain. Yet, given the speed of change required and the long lead times for major infrastructure projects, planning needs to take place even if not all uncertainties will be fully resolved. This could for example involve strategic planning for net-zero support infrastructure including, e.g. electricity transmission, hydrogen, carbon transport and storage, and sustainably sourced biomass/biofuels. Similar planning processes, including identification of designated strategic areas/zones, have previously been carried out for wind and hydro power (Swedish Energy Agency 2013; Energimyndigheten; and Naturvårdsverket 2018).

- **Ensuring sufficient availability of sustainably** produced second-generation **biofuels** and continued support for hybridisation and electrification of heavy transport and construction equipment (as called for in e.g. I. Karlsson, Rootzén, and Johnsson 2020).

- **Using public procurement** as a tool to spur innovation, creating markets for low-CO_2 products and opening up for economies of scale. Overall, public procurers in governmental agencies, municipalities and county councils and property owners, by virtue of their significant purchasing power, play an important role as drivers and by setting examples. In addition, private actors can help to increase the volume of demand for low-CO_2 products and to legitimise public strategies. At the same time it is important to realise that the applicability of procurement requirements for carbon reduction depends on how well these requirements are aligned with industry culture, policies and capabilities in the local context (see e.g. Kadefors *et al.*, 2019).

- **Capacity building** and information spreading through for example:
  - Establishment of an (public or private) umbrella organisation with the responsibility to oversee and support the low-CO_2 transition
  - Securing new competence by including low-CO_2 building and construction as a central part of the in upper secondary school and higher education
  - Training of active practitioners (engineers, architects…).

It is of course also important to continue to find ways to sharpen existing climate policies such as the EU-ETS and renewable policies, most important being to make them as long term as possible.

Transition speed

There is no guarantee that investments in the development and implementation of hydrogen direction reduction in the steel industry, CCS in the cement industry or other low-carbon technologies for industrial applications will pay off. However, choosing not to, or failing to act within the next few years, to create the economic, organisational and infrastructural conditions that could facilitate a shift towards low-CO_2 production and practices will severely compromise the chances of a successful decarbonisation of the steel and cement-industries, and the supply chains for buildings and transport infrastructure up to the year 2045.

Lead times related to planning, permitting and construction of both support infrastructure (renewable electricity 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. Table 5 provides an overview of some of the areas that have been identified throughout the preparation of this study where development is urgently needed.

Table 5. Overview of actions to facilitate planning, permitting and construction.

General	• Ensuring efficient and transparent permitting processes (for electricity generation, transmission, distribution, charging and storage, support infrastructure for CCS and hydrogen etc.) through e.g.: o Improving coordination between permitting authorities o Removal of procedural barriers o Ensuring resources and capacity in the authorities responsible for permitting process o Increasing the flexibility in the permit design
CCS	• Feasibility and routing studies to dimension transport infrastructure. • Inventory of potential areas of national interests for CO_2 infrastructure, e.g. harbours, hubs, pipelines, intermediate storage (*cf.* existing dedicated areas of national interest for energy production, wind power, energy distribution). • Developing a strategy for ramping-up CO_2 transport capacity over time. • Long term signals and incentives for potential transport operators (that would own and oversee the everyday operation of the transportation infrastructure). • Regional cooperation to plan and manage the development of: o Primary infrastructure (e.g. pipelines, shipping terminals and back-up storage sites) o Institutions, legislation and processes to manage the risk and liability with CO_2 storage

	• Models for financing/risk sharing. Capital costs related to proceeding to pilot/demonstration (in the order of tens of millions of €) and commercial (in the order of several hundreds of millions of €) in the steel and cement industries
Electrification	• Continuous efforts to assess and improve the interlinkages and interactions across sectors (energy/electricity supply, transports, industry and buildings) • Inventory of potential areas of national interests for electricity and hydrogen (generation distribution/transmission, storage) • Models for financing/risk sharing. Capital costs related to proceeding to pilot/demonstration (in the order of tens of millions of €) and commercial (in the order of several hundreds of millions of €) in the steel and cement industries

Lessons from historical transition processes also show the importance of, beyond the physical planning, early on ensuring transparency, broad participation and fairness (e.g. acceptable distributional effects) and agility and endurance in the face of the unforeseen (e.g. delays, changing market conditions).

Global outlook

Although the findings reported in this report 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 supply chains for buildings and infrastructure, are universal (Wang Cai et al. 2017; WGBC 2019; IRP and UN Environment 2019). Whereas rapid improvements of the climate performance of the use phase (i.e. related to heating and cooling) of the existing and new building stocks is a key priority in many parts of the world, it is equally important to take measures to reduce the climate impact of the construction process and the production and supply of building materials.

From a global perspective, this is important, not the least, since there are still many regions of the world where much the of the buildings and the infrastructure to provide shelter from the elements, mobility for people and goods, and infrastructures for the supply of water, electricity and heat, remains to be built. Estimates suggest that more than half of the urban infrastructure that will exist in 2050 has yet to be built (UNEP 2013; IRP and UN Environment 2019) and that total global floor area of buildings will double within the next three or four decades (Wang Cai et al. 2017; WGBC 2019).

While most of these investments in new buildings and infrastructure will appear outside Europe, re-investments, maintenance and renovation of ageing infrastructures and building stocks in combination with large scale deployment of renewable and low carbon technologies in the energy system are likely to uphold the demand for basic materials and construction services over the next decades. The energy system requires investments on both the supply side (e.g. solar panels, wind turbines, transmission) and the demand side (e.g. electric vehicles, battery storage). In addition, there will be a need for investments to improve resilience towards impacts of climate variability and climate change (e.g. water storage, flood defences, erosion control water supply and sanitation (OECD 2018).

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Appendices

Appendix 1: Overview of relevant roadmap studies and reports

	Description	Geographical scope	Reference(s)
Basic industry			
The "Fossil Free Sweden" initiative development of "Roadmaps for fossil free competitiveness"	Initiative in which Swedish business sectors (including cement, concrete, steel and building and construction) have developed roadmaps towards zero GHG emissions. Roadmaps have been developed for: the Aggregates Industry, the Aviation Industry, the Cement Industry, the Concrete Industry, the Construction and Civil Engineering Sector, the Digitalisation Consultancy Industry, the Food Retail Sector, the Forest Sector, the Heating Sector, the Heavy Haulage Industry, the Maritime Industry, the Mining and Minerals Industry, and the Steel Industry.	Sweden	(Fossil Free Sweden Initiative 2018)
Klimatneutral konkurrenskraft - Kvantifiering av åtgärder i klimatfärdplan	Quantifies the increased requirements for electricity and bioenergy in 2045 resulting from the combined measures of the industry roadmaps developed within the Fossilfree Sweden initiative, together with other parts of the Transport sector and the Chemical industry.	Sweden	(SWECO 2019)
Så klarar svensk industri klimatmålen	Survey of technological and process abatement options in the Swedish industry sector up until 2045. Coverage: Iron and steel, Cement, Petrochemicals/Chemicals, Non-Ferrous metals, Forestry, Oil Refining, Mining and minerals.	Sweden	(Kungliga IngenjörsVetenskaps Akademien 2019a)
Hinder för klimatomställning i processindustrin	A report within the government assignment *Innovation-promoting efforts to reduce greenhouse gas emissions in the process industry*. Details technical, market, regulatory, resource and infrastructure barrier to a low-carbon transition for the Swedish process industries: Iron and steel, non-ferrous metal, Cement, Petrochemicals/Chemicals and Oil Refining.	Sweden	(Swedish Energy Agency 2019)
Statens roll för klimatomställning i processindustrin	Provides an overview of the role of the government and other public and private actors in facilitating a climate transition in the Swedish process industry. Coverage: Iron and steel, Cement, Petrochemicals/Chemicals and Oil Refining	Sweden	(Karltorp et al. 2019)
A Steel Roadmap for a Low Carbon Europe	Industry association assessment of abatement options for the steel industry and conditions required for its realisation. Also details the role of steel for low carbon solutions in other societal sectors.	Europe	(Eurofer 2013)
Cements for a low-carbon Europe	Industry association report focusing on the diverse solutions applied by the cement industry across Europe to reduce the carbon footprint of its products through the production of low clinker cements.	Europe	(Cembureau 2013)
A sustainable future for the European cement and concrete industry	Summarises the practices and technologies that can be implemented to significantly reduce CO2 emissions from the cement and concrete sector in Europe by 2050. Details the potential and need for reduction efforts along the complete value chain.	Europe	(Favier et al. 2018)
Towards A Flemish Industrial	Puts forth a proposal on the possible scope and blueprint of a future facilitative framework towards a Flemish low-carbon economy taking into account the	Flanders and Belgium	(Wyns et al. 2019)

Transition Framework	interactions and possible synergies between energy intensive industries and the rest of the economy.		
Decarbonising Europe's energy intensive industries	Sketches the blueprint of an industrial strategy towards climate neutrality in the EU. The study provides an integrated structure that scrutinizes a broad set of policy instruments and provides ideas for making the whole policy set as tangible as possible.	Europe	(Wyns et al. 2019; Wyns and Axelson 2016)
Building Blocks for a Climate-Neutral European Industrial Sector	Outline an integrated industrial climate strategy for the EU and describes five policy options to facilitate decarbonisation of the basic materials industry by 2050.	Europe	(Neuhoff et al. 2019)
Industrial Innovation: Pathways to deep decarbonisation of Industry	Investigates the extent to which key EU industrial sectors can benefit and contribute to a climate-neutral future. The project takes a perspective to 2050 and beyond and analyses the technologies, pathways to 2050 and the policy mix needed for implementation.	Europe	(Fleiter et al. 2019; Chan et al. 2019)
Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry	Characterises how net zero emissions can be achieved by 2050 from the largest sources of 'hard to abate' emissions: Steel, Plastics, Ammonia, and Cement. Starts from a broad mapping of options to eliminate fossil CO2-emissions from production and integrates these with the potential for a more circular economy.	Europe	(Material Economics 2019)
Mission Possible - Reaching Net Zero Carbon Emissions from Harder-to-abate sectors by Mid-century	Outlines the possible routes to fully decarbonize Cement, Steel, Plastics, Trucking, Shipping and Aviation. Combines technical abatement options with materials efficiency, recycling, logistics efficiency and modal shifts.	World	(Energy Transition Commission 2018)
Construction			
Roadmap for a carbon neutral and competitive construction and civil engineering sector	Ongoing initiative, with the ambition to increase the awareness of the building sector's climate impact and highlight trends, motivations, barriers and business opportunities; and ultimately establishing a common view of responsibilities and actions required to achieve a carbon neutral and competitive building sector.	Sweden	(Fossilfritt Sverige 2018)
The Property Sector's Roadmap Towards 2050	Recommendation to Norwegian owners and commercial building managers regarding their short and long-term choices in ensuring that the property sector contributes to a sustainable society by 2050.	Norway	(Grønn Byggallianse and Norsk Eiendom 2016)
Finnish Ministry of Environment's Low Carbon Construction Roadmap	Plan for how to reduce GHG emissions related to building materials and the construction industry in general, with the goal of regulating buildings' emissions via legislation by mid 2020s.	Finland	(Finnish Ministry of Environment 2019; WGBC 2019)
Low Carbon Routemap for the UK Built Environment	A project exploring options to reduce GHG emissions from the user phase, supply chain and construction activities for the UK built environment. Covers operational as well as embodied carbon emission from both the buildings and infrastructure sectors.	UK	(Green Construction Board 2013; Steele, Hurst, and Giesekam 2015)
Bringing embodied carbon upfront	Call for coordinated action for the building and construction sector to tackle embodied carbon.	World	(WGBC 2019)

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