

Roadmap for climate transition of the building and construction industry – a supply chain analysis including primary production of steel and cement

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Abstract

Sweden has, in line with the Paris agreement, committed to reducing greenhouse gas emissions to net-zero by 2045. Emissions arising from manufacturing, transporting and processing of construction materials to buildings and infrastructure account for approximately one fifth of Sweden's annual CO₂ emissions. This work provides a roadmap with an analysis of different pathways of technological developments in the supply chains of the buildings and construction industry, including primary production of steel and cement. By matching short-term and long-term goals with specific technology solutions, these pathways make it possible to identify key decision points and potential synergies, competing goals and lock-in effects. The analysis combines quantitative analysis methods, including scenarios and stylized models, with participatory processes involving relevant stakeholders in the assessment process. The roadmap outline material and energy flows associated with different technical and strategical choices and explores interlinkages and interactions across sectors. The results show that it is possible to reduce CO₂ emissions associated with construction of buildings and transport infrastructure by 50 % to 2030 and reach close to zero emissions by 2045, while indicating that strategic choices with respect to process technologies, energy carriers and the availability of biofuels, CCS and zero CO₂ electricity may have different implications on energy use and CO₂ emissions over time. The results also illustrate the importance

of intensifying efforts to identify and manage both soft (organisation, knowledge sharing, competence) and hard (technology and costs) barriers and the importance of both acting now by implementing available measures (e.g. material efficiency and material/fuel substitution measures) and actively planning for long-term measures (low-CO₂ steel or cement). Unlocking the full potential of the range of emission abatement measures will require not only technological innovation but also innovations in the policy arena and efforts to develop new ways of cooperating, coordinating and sharing information between actors.

Introduction

Sweden has, in line with the Paris agreement, committed to reducing greenhouse gas (GHG) emissions to net-zero by 2045 and to pursue negative emissions thereafter (Ministry of the Environment and Energy, 2018). 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, are likely to be speculative. But due to the urgent need to start the transformation towards deeper emission cuts, decisions as to how to best manage the transition must be made now taking the future into account (Bataille *et al.*, 2016). This includes starting with the current situation to map mitigation measures to see which measures can be applied already at present and those which will require longer lead times to be implemented. There are already today known measures and technologies which can reduce emissions to zero, from circularity and material efficiency measures, bio-fuel or biomaterial substitution, electrification (direct or indirect) with renewable electricity and/or carbon capture and stor-

age (Davis *et al.*, 2018; Energy Transition Commission, 2018; Material Economics, 2019; Schneider *et al.*, 2020).

Thus, the challenge to meet climate targets is not only a technological challenge but related to economics and financial risk – in particular since current climate policy is too weak (Bonde *et al.*, 2020). Indeed, large scale demonstration of key processes is required to obtain confidence in technologies and gain experience and to reduce financial risk, but technologies are available at high maturity levels.

Seeing that the energy and climate performance of the user phase of the built environment in Sweden keeps improving, the climate impact of the construction process has increasingly come in to focus (Erlandsson *et al.*, 2018a). Emissions arising from manufacturing, transporting and processing of construction materials to buildings and infrastructure account for approximately one fifth of Sweden's annual CO₂ emissions (Naturvårdsverket, 2019; Naturvårdsverket & Boverket, 2019; SCB, 2019).

However, current estimates of the climate impact from construction of building and transport infrastructure in Sweden is associated with a significant degree of uncertainty, with estimates for 2015 ranging from 7 MtCO₂e based on a process-based bottom-up life cycle analysis (LCA) approach to 8.1 MtCO₂e for territorial emissions and 13.5 MtCO₂e including imports, with the latter two estimates based on environmentally extended input-output (EEIO) data (Naturvårdsverket & Boverket, 2019; Erlandsson, 2020). To enable analysis into the ongoing development in the construction sector and the opportunities for the sector to contribute to the national climate targets, better estimates are needed, including the main components of the supply chain making up those emissions, from the different materials used, transport of the materials, to the construction processes.

The focus of this study is on the path towards net-zero emissions in 2045, which necessitates not only looking at current emissions and the components thereof, but also require comprehensive assessments into current and future abatement options and potentials. An array of industry level studies on future carbon abatement options have been performed (see e.g. Fishedick *et al.* 2014; Jernkontoret 2018; Wörtler *et al.* 2013) for steel, (Favier *et al.*, 2018; IEA & CSI, 2018) for cement/concrete, and for heavy transport and construction equipment (CEMA & CECE, 2011; Swedish Transport Administration, 2012; IEA, 2017; Kluschke *et al.*, 2019). There have also been recent attempts to synthesise the perspectives from different industries (Rootzén & Johnsson, 2015; Wyns & Axelson, 2016; Bataille *et al.*, 2018; Energy Transition Commission, 2018; European commission, 2018a; Material Economics, 2019; Schneider *et al.*, 2020). However, there are limited examples in the literature of international or national assessments of future abatement options and potentials and the pathway towards close to zero embodied emissions in the building and construction sector (Grønn Byggallianse & Norsk Eiendom, 2016; WGBC, 2019), with most studies pertinent to the UK (Green Construction Board, 2013; Giesekam *et al.*, 2014).

In Sweden, within the government-initiated Fossil Free Sweden initiative (Fossilfritt Sverige, 2018), business sectors have developed roadmaps towards 2045, describing in varying details technological solutions, investment needs, and obstacles required to be removed to realise the roadmaps. These provide

some key information on abatement options within individual industry sectors with the construction sector roadmap to some extent capturing a cross-sectorial perspective. Some initial assessments have also been made on the expected resulting emissions reductions and energy needs for the year 2045 (Kungliga Ingenjörsvetenskaps Akademien, 2019; SWECCO, 2019). However, to explore critical factors on the pathway towards 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 chains involved in the building and construction sector.

In this study, we use material and energy flow analysis combined with an extensive literature review to provide further perspective on the current status of emissions from the Swedish building and construction industry to assess how different abatement technologies across the construction supply chain could reduce the GHG emissions if combined to its full potential. The ambition is to analyse the current and future GHG emissions reduction potential by considering the development, over time, of emission reduction measures in different parts of the construction supply chain. With support of the development of pathways, we create a roadmap 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 roadmap and its pathways provide a basis for identifying key decision points and potential synergies, competing goals and lock-in effects.

Method

This work combines quantitative analytical methods, i.e. scenarios and stylized mass and energy flow models, with a participatory process involving relevant stakeholders in the assessment process. Stakeholders include industry representatives and experts along the supply chain; material suppliers, contractors, consultants, clients and governmental agencies. Estimates are provided of the magnitude of current and future GHG emissions reduction potential across the supply chains in the building and construction industry by (i) estimating the current emissions, material and energy flows associated with the industry; (ii) identifying possible GHG abatement options relevant to the construction works and their estimated abatement potentials. In the next step (iii), we use (i) and (ii) to assess the impact of combining abatement measures along the supply chains to its full potential; (iv) crafting pathways to highlight challenges and possibilities up to 2045 given assumptions regarding external parameters.

The current emissions from the Swedish building and construction industry is analysed by comparing existing estimates with a mapping of the material and energy flow through the supply chain of building and transport infrastructure construction produced via a literature review of life cycle analyses and equivalent studies. With respect to construction of transport infrastructure, the Swedish Transport Administration (Trafikverket) 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 (Trafikverket, 2017). Coherent results for the total emissions for construction of transport infrastructure are also provided by detailed bottom-up analysis (Liljenström *et al.*, 2019) and EEIO data (Naturvårdsverket & Boverket, 2019).

As this coherence does not apply for building construction, an estimate for the national emissions associated with building construction was developed using data on the emissions share from different components and materials sourced from the literature review (see Table 1) combined with validated emission factors for each component and/or material. Where available, the literature review was concentrated to LCA studies in a Northern European setting as to account for equivalent design and construction techniques along with requirements stemming from climatic conditions. Since there are few studies describing separately material input, material transports and construction processes for refurbishments we have here adjusted the emissions share of the materials considered dominant in refurbishments in the few studies available.

The share of emissions for different materials for construction of different building types were calculated based on the estimates in literature for these building types and the estimated share of emissions per building type. The total share of emissions for different material/activities for building construction were subsequently calculated using estimates for different life cycle stages for the various building types. Validated emissions for construction equipment (as per data from the national EEIO data) was used to extrapolate total building construction emissions.

The literature review also provided emissions factors for materials, activities and fuels along with data for associated quantity and source of energy used for material production. The emission factors were divided into sources of emissions e.g. raw materials, production, transport where deemed feasible to enable the assessment of different mitigation measures.

The inventory of GHG abatement options is established by means of a comprehensive literature review including industry and governmental agency reports (grey literature) together with input from supply chain stakeholders. The main types of abatement options considered in the assessment are material efficiency and optimization measures together with 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. The inventory comprises both current best available technology and technologies assumed to be available over time to 2045.

A timeline is applied to test the potential implications to the climate impact when constructing the same assets while applying a combination of GHG abatement measures along the supply chain appraised to have reached commercial maturity at different points in time (over 5-year time periods until 2045). From this inventory, portfolios of abatement measures for the respective supply chain activities are constructed with selections of measures applied on a timeline up to Year 2045. Finally, the abatement measures are combined in pathways according to strategic choices (Amer *et al.*, 2013), namely access to biofuels and renewable electricity as well as enactment of material efficiency measures.

The portfolios are predominantly based around reaching the medium-high range of the emission reduction potentials for each selected abatement measure (as per Figure 2) 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 project (European commission, 2018b; Fossilfritt Sverige, 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).

In the pathway analysis, the emission factors were adjusted on the basis of the abatement options selected and applied in the assessment for each supply chain activity, applied in combination when the abatement measures reinforce each other; and applied in separation when mutually independent, e.g. cement clinker replacements and biofuel substitution in cement plants.

Appraisals of future levels of construction vary significantly, particularly depending on the basis of assessments of business cycles and economic conditions or based on the need for construction due to the expected growth in population along with refurbishments required to meet energy efficiency targets (Boverket, 2018; Peñaloza *et al.*, 2018; Erlandsson, 2019). For simplicity, an assumption of continuous levels of construction from the base year 2015 has been assumed in this study.

Results

CURRENT EMISSIONS FROM BUILDING AND INFRASTRUCTURE CONSTRUCTION

To validate the estimates of the current GHG emissions, and to specify emissions components, further analysis into the existing estimates were combined with a literature review focussed on relevant LCA studies detailing embodied emission sources for different construction types. Divergences in the current estimates of embodied emissions (ranging from 7 MtCO₂e based on a process-based bottom-up LCA approach to 8.1 MtCO₂e for territorial emissions and 13.5 MtCO₂e including imports based on EEIO data) partly stem from the varying scope of the different studies, where for instance a great majority of construction steel is imported, and while the cement market is mostly domestic (85 % of Swedish cement use), the concrete market is turning more international, at least pertaining to pre-cast elements. Table 1 gives the share of emissions components for building construction found in literature.

In the technology roadmap of this work, we focus mainly on the climate impact linked to construction of buildings and transport infrastructure, i.e. we do not include construction of for example utilities.

Focusing in on the components of building materials for new builds at a general level (non-residential and residential buildings combined as per A1–A3 in Table 1), the main emission sources are concrete and steel, with shares of around 35–65 % for concrete, 4–20 % for reinforcement steel and 6–33 % for construction steel, with the remainder mainly consisting of insulation, gypsum and plaster, plastics and chemicals along with other non-ferrous metals, glass and timber (Junnila *et al.*, 2006;

Table 1. Overview of the share of emission components from LCA literature.

		Share of total construction emissions (2015)	Share of emissions per life-cycle stage			References
			Building materials (A1–A3)	Transport (A4)	Construction process (A5)	
Non-residential buildings	Offices	34 %	86–93 %	2–3 %	7–12 %	(Junnilla <i>et al.</i> , 2006; Wallhagen <i>et al.</i> , 2011; Ylmén <i>et al.</i> , 2019)
	Industrial		97 %	0–1 %	2–3 %	(Bonamente & Cotana, 2015; Rodrigues <i>et al.</i> , 2018)
Residential buildings	Multi-family dwellings	35 %	74–86 %	3–9 %	13–17 %	(Liljenström <i>et al.</i> , 2015; Andersson <i>et al.</i> , 2018; Erlandsson <i>et al.</i> , 2018b)
	Single-family dwellings	12 %	82–96 %	2–4 %	0–16 %	(Monahan & Powell, 2011; Petrovic <i>et al.</i> , 2019)
Transport infrastructure	Roads	13 %	78 %		22 %	(Trafikverket, 2017; Liljenström <i>et al.</i> , 2019)
	Railways	6 %	69 %		31 %	

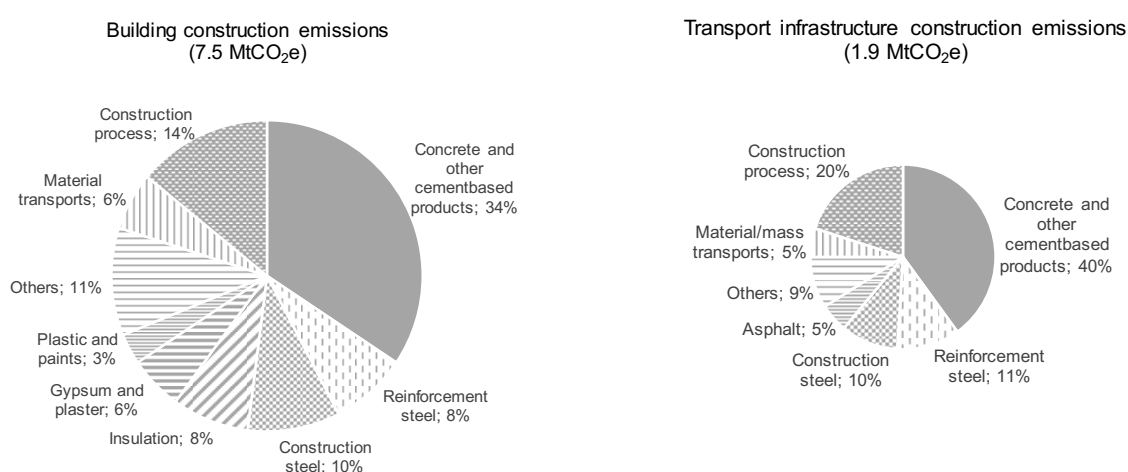


Figure 1. Carbon impact from construction of buildings and transport infrastructure with the size of the pie charts reflecting the relative magnitude of emissions.

Monahan & Powell, 2011; Wallhagen *et al.*, 2011; Larsson *et al.*, 2017; Andersson *et al.*, 2018; Malmqvist *et al.*, 2018; Hall *et al.*, 2019; Petrovic *et al.*, 2019; Ylmén *et al.*, 2019).

Around $\frac{2}{3}$ of the building construction emissions correspond to new buildings and $\frac{1}{3}$ to refurbishments and maintenance (Naturvårdsverket & Boverket, 2019). In addition, around 40–50 % 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 40–50 % arise from multi-family dwellings and the remaining 10–15 % from single family houses (Sveriges Byggindustrier & Iva, 2014; Naturvårdsverket & Boverket, 2019). Literature detailing refurbishments report the main embodied emissions resulting from insulation, windows and metals for new ventilation and heating systems (Almeida *et al.*, 2018; Moncaster *et al.*, 2019; Piccardo *et al.*, 2019).

Based on the various sources and approximations, we have estimated the total climate impact of building and transport infrastructure construction in Sweden to around 9.4 MtCO₂e per year, with building construction responsible for 80 % and transport infrastructure for 20 %. As can be seen in Figure 1,

this carbon impact derives predominantly from concrete and steel together with diesel use in construction processes and material transports.

ABATEMENT OPTIONS

The main emission abatement options currently available for cement/concrete comprise of biofuel substitution in the cement plant, reducing the amount of cement clinker by using alternative binders and optimising the concrete recipes to use less cement (Favier *et al.*, 2018; IEA & CSI, 2018). Other options include design optimization to slim constructions and material substitutions towards wood-based solutions (Material Economics, 2019). 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 required (Karlsson *et al.*, 2020a).

For primary steel production, the main options for deep emission reduction 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) (Fischedick *et*

al., 2014). Increasing the share of EAF production to produce higher quality products would be also an important abatement option for construction steel. For scrap-based steel production, emissions reductions result from improvements in the electricity emissions factor in line with progressive integration of renewables in the electricity system, together with refurbishments and upgrades of current electric arc furnaces providing potential for decreased electricity consumption. There is also potential for biomass substitution for chemical process energy needs, which are at current satisfied with coal powder and syngas (Bianco *et al.*, 2013).

High potential abatement measures for heavy vehicles and machinery in the short to medium term include biofuel substitution, energy efficiency measures, hybridization and optimization

of logistics and fleet management. Over the longer term, deeper emissions reductions would result from electrification of construction equipment, crushing plants and heavy trucks (CEMA & CECE, 2011; IEA, 2017).

With respect to measures to improve material efficiency, 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.

A summary of all abatement options and their identified emission reduction potential are described in Figure 2. The graph illustrates the range of GHG emissions reduction po-

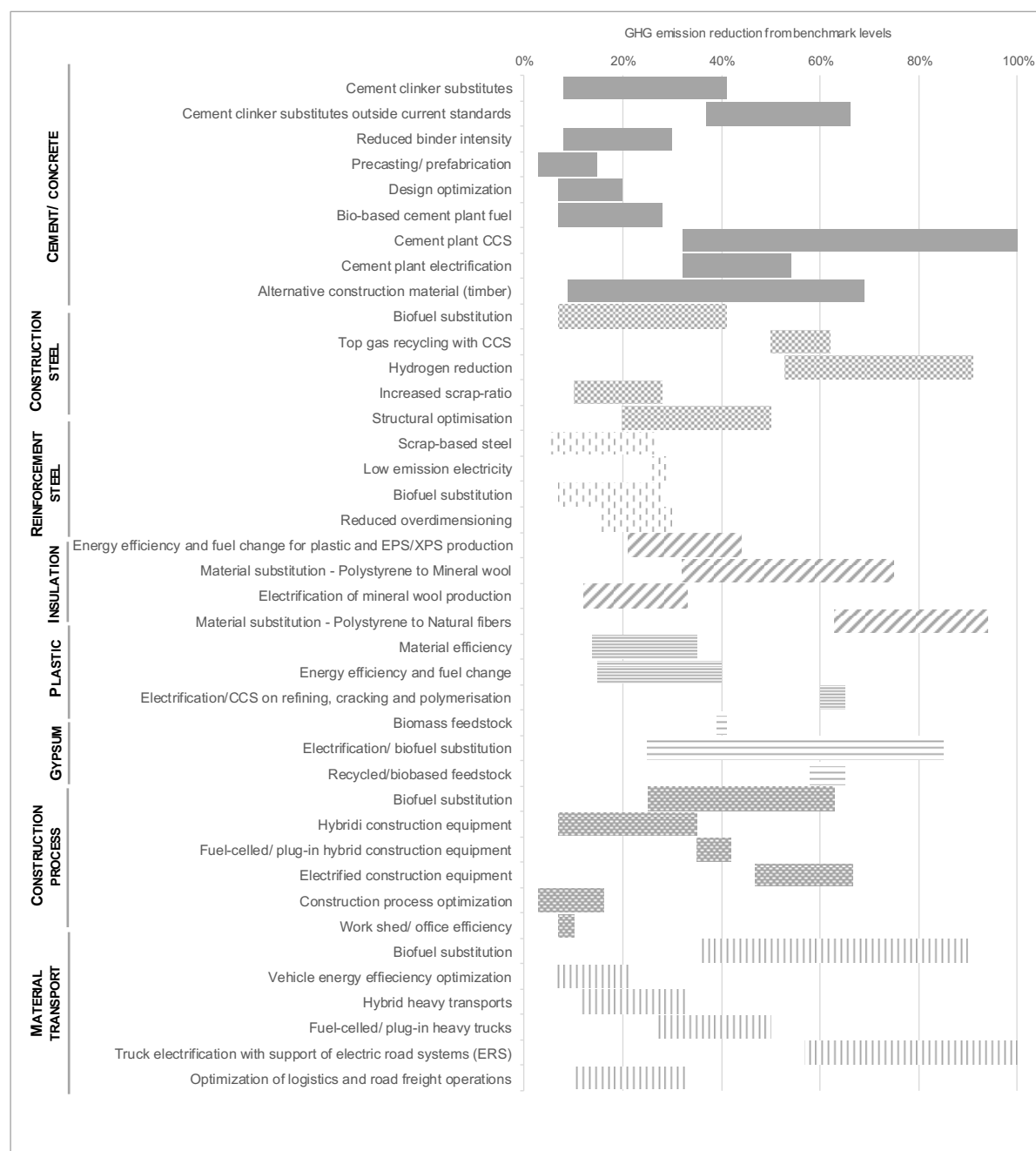


Figure 2. Tornado graph depicting the range of GHG emissions reduction potential for the abatement options identified in the literature review and stakeholder workshops for the central emissions sources.

tential recognised in literature for each of the abatement options explored (for references refer to Ida Karlsson et al. 2020; I. Karlsson, Rootzén, and Johnsson 2020), where the range may depend on the level of the abatement measure that is adopted, e.g. the degree of fuel or cement 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.

ALTERNATIVE PATHWAYS

Four pathways have been devised within the roadmap, describing different future trajectories of technological developments in the supply chains of buildings and transportation infrastructure in Sweden, two with a focus on bio-based measures together with CCS and two with an emphasis on electrification:

- Pathway 1: Biofuels and CCS
- Pathway 2: Electrification
- Pathway 3: Biofuels, CCS and material efficiency
- Pathway 4: Electrification and material efficiency

The second of the two within each focus explores the role material efficiency measures may play in the low-carbon transition.

Details of the emissions reduction measures applied over the timeline for the different pathway scenarios are displayed in Table 2.

For cement, the Bio/CCS pathway adopts post-combustion carbon capture with amine scrubbing, a commercially available technology which can be applied to existing plants, while the Electrification pathways uses the process explored in the CemZero project (Wilhelmsson *et al.*, 2018). In all pathways, a continuous increase in cement clinker substitution and reduction in cement demand from optimisation of concrete recipes is assumed. For primary steel production, the Bio/CCS pathways adopt a process modification enabling top gas recycling combined with CCS, 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 assumed to be refurbished and upgraded at a continuous rate in all pathways, alongside partial bioenergy substitution in the Bio/CCS pathways. Separate pathways have also been devised for construction equipment and heavy transports, while other materials follow the same development for all decarbonisation pathways (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).

Table 2. Details of abatement measures applied across pathways with percentage figures depicting the diffusion of the specific mitigation option.¹

	Pathway	2025	2030	2035	2040	2045
Cement/ concrete	All pathways	20% AB, 5% RB	25% AB, 12% RB	28% AB, 15% RB	32% AB, 22% RB	35% AB, 28% RB
	Biofuel + CCS	40% BS	45% BS, 45% CCS	50% BS, 45% CCS	52% BS, 80% CCS	55% BS, 90% CCS
	Electrification	40% BS	45% EL	45% EL	90% EL	100% EL
	ME	8%	15%	20%	25%	30%
Reinforcement steel	Biofuel + CCS	100% RE	10% EE, 7% BS	14% BS	25% BS	35% BS
	Electrification	100% RE	10% EE, 7% EL	14% EL	14% EL, 10% BS	14% EL, 21% BS
	ME	5%	10%	15%	20%	25%
Construction steel	Biofuel + CCS		20% BS	30% BS	30% CCS, 30% BS	60% CCS, 30% BS
	Electrification		20% BS	30% BS	50% HR	100% HR
	ME	10%	15%	20%	25%	30%
Construction equipment	All pathways	5% OP	10% OP	10% OP	10% OP	10% OP
	Biofuel + CCS	42% BS, 9% HY, 5% EL	63% BS, 14% HY, 9% EL	78% BS, 23% HY, 3% EL	85% BS, 31% HY, 15% EL	81% BS, 31% HY, 19% EI
	Electrification	42% BS, 9% HY, 5% EL	63% BS, 14% HY, 9% EL	78% BS, 23% HY, 24% EL	59% BS, 23% HY, 41% EL	50% BS, 23% HY, 50% EL
Heavy transports	All scenarios	5% EE/OP	10% EE/OP	15% EE/OP	20% EE/OP	25% EE/OP
	Biofuel + CCS	42% BS, 5% EL	63% BS, 10% EL	78% BS, 15% EL	80% BS, 20% EL	75% BS, 25% EL
	Electrification	42% BS, 5% EL	63% BS, 20% EL	70% BS, 30% EL	55% BS, 45% EL	40% BS, 60% EL
Insulation		2% EE; 20% MS	4% EE; 50% MS; 10% EL	6% EE; 70% MS 20% EL	70% MS; 30% EL/ CCS	70% MS; 30% EL/ CCS
Gypsum/ plaster		25% BS/MS	25% BS/MS 25% RE	25% BS/MS 50% RE	50% BS/EL 50% RE	100% BS/EL 75% RE
Plastic		20% EE & BS	40% EE & BS	40% EE & BS	50% EL/CCS	100% EL/CCS
	ME	5%	10%	15%	20%	25%

¹ Abbreviations: AB – Alternative binders, BS – biofuel substitution, CCS – carbon capture and storage, EE – energy efficiency, EL – electrification, HY – hybridization, HR – hydrogen reduction, ME – material efficiency, MS – Material substitution, OP – optimization, RB – reduced binder intensity, RE – recycling.

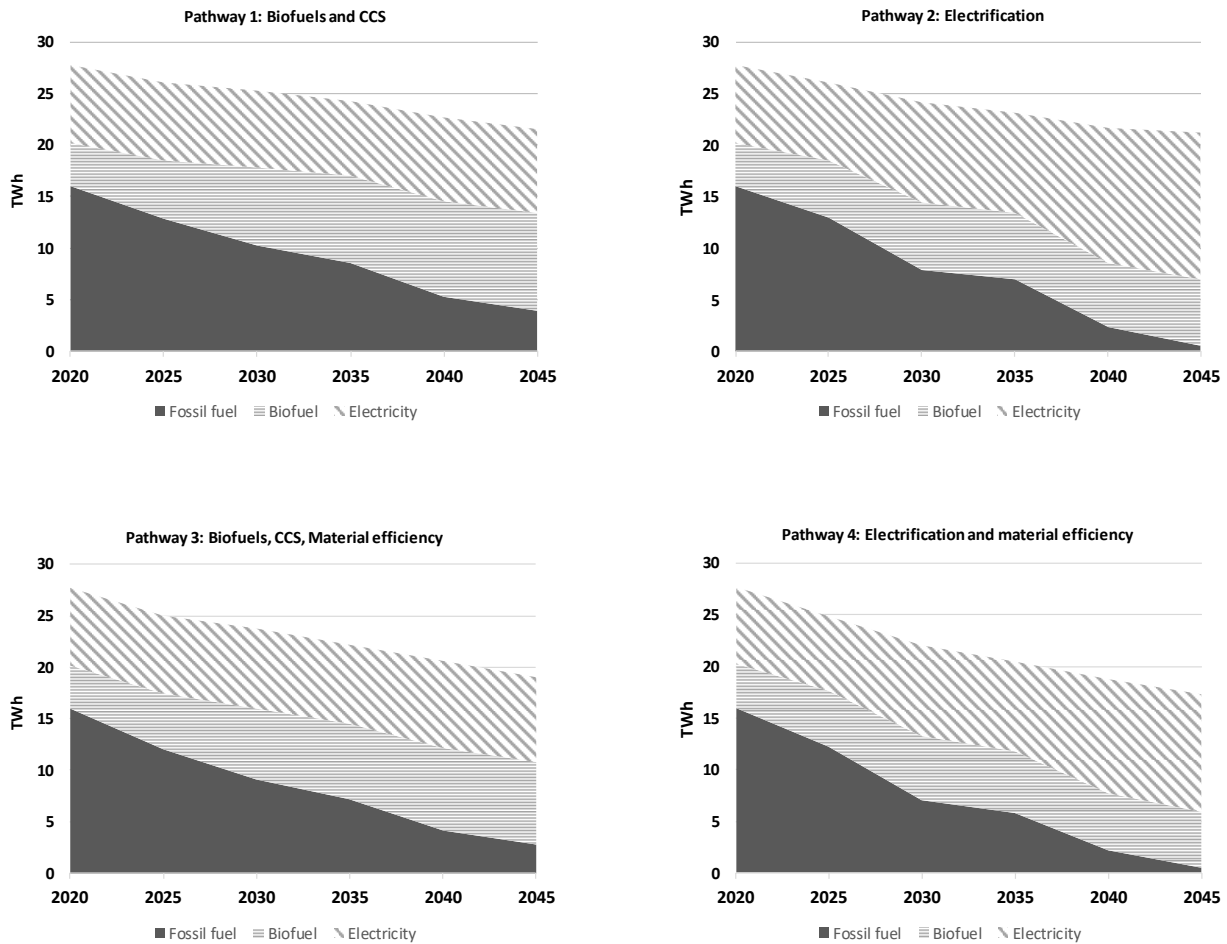


Figure 3. Energy use for each energy carrier over time for the buildings and transport infrastructure pathways.

Pathway results

Figures 3 and 4 depict the resulting energy use per energy carrier and carbon emission reductions for the construction of buildings and transport infrastructure in Sweden. The analysis demonstrates that construction of buildings and transport infrastructure currently use approximately 28 TWh energy, accounting for around 7 % of total Swedish energy use. All the pathways show a reduction in total energy use over time, with the reduction varying from 8–20 % to 2030 and 18–38 % to 2045. When comparing the total energy use in Year 2045, the Electrification pathways demonstrate a total energy use of around 4–7 % lower than the Bio/CCS pathways. 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 4 % up to 2030 and 14 % by 2045 for both the Bio/CCS and Electrification pathways (noting that the reduction potential would be even higher compared to a reference scenario).

Regarding biofuels, they are currently mainly used in the transport sector, and in asphalt and cement production. Over time, the use is set to expand with the overall share of biofuels increasing from 20 % of total energy use at current to around 40 % in the Electrification pathways and to 60 % in the Bio/CCS pathways by 2045. This would mean an increase from 4 TWh to

10 TWh, which can be compared with the current total bioenergy use of 89 TWh in 2017 (Energimyndigheten, 2019).

Electricity use remain almost constant in the Biofuel pathways reaching a share of around 40 %, while increasing from 8 TWh up to 14 TWh in 2045 in the Electrification pathways, reaching a share of 65 %.

As can be seen in Figure 4, all pathways reach close to zero emissions in 2045, with total emissions reductions of 90–96 %, with the highest emission reduction potential in the Electrification pathways. Up until 2030, we see potential emissions reductions of 49–50 % for Pathways 1 and 2. Before 2030, most emissions reductions stem from increased use of alternative binders combined with reduced binder intensity in concrete (25 %), optimisation and energy efficiency measures on the construction sites combined with biofuel substitution in construction equipment and material transports (36 %). The biofuel substitution partly ensues as a result of the Swedish reduction duty regulation, which specifies 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 (12 %) together with material and fuel substitutions regarding insulation materials (5 %).

A focus on material efficiency provides for additional reductions, particularly in the medium term. An additional 7–10 %

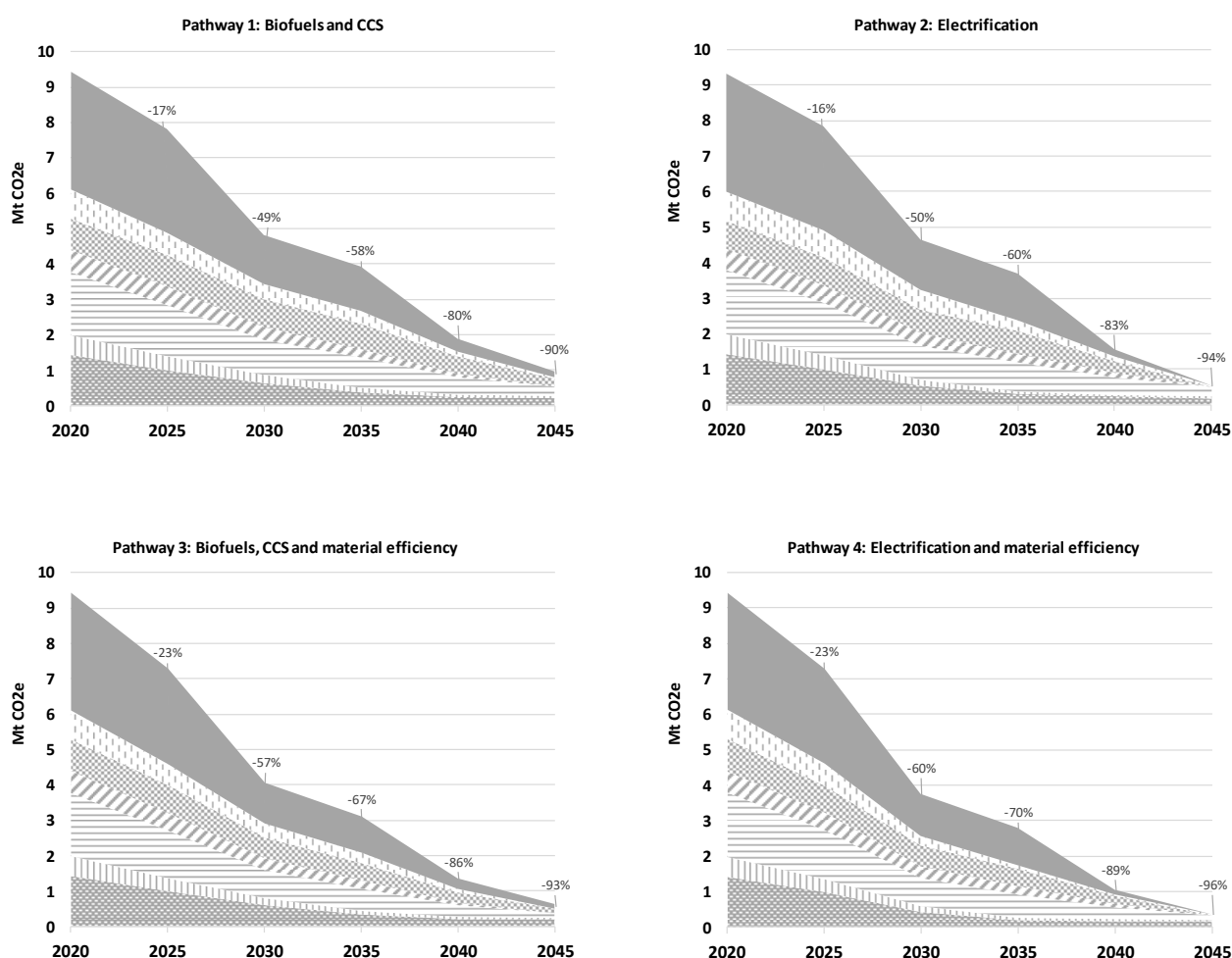


Figure 4. Resulting emissions for the buildings and transport infrastructure pathways.

brings the total emissions reductions down to around 57–60 % by 2030, implying a difference of 0.6–0.8 Mt CO₂ emissions per year.

After 2030, deeper emissions reductions come about as a result of continued biofuel substitution combined with hybridization and electrification for construction equipment and trucks (contributing to 35–42 % of the emissions reductions in 2030). Fuel substitution also plays a role in primary and secondary steelmaking (11–12 % of the emissions reduction 2030–2035).

In the Bio/CCS pathways, this fuel substitution is combined with CCS in primary steelmaking as well as in cement kilns (11 % and 33 % of the emissions reductions in 2040–2045, respectively). 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 in mineral wool production. (contributing to 36 %, 10 % and 9 % to the emissions reductions in 2040–2045, respectively with the last two combined). Electrification in the primary steelmaking (via hydrogen reduction) also contributes considerably in the Electrification pathway (30 % in 2045).

In view of the remaining carbon budget up to 2045, the Material efficiency pathways could reduce the total cumulative amount of CO₂ emitted from construction of buildings and transport infrastructure over the years 2020 to 2045 by

12–13 % compared to its corresponding Biofuel/Electrification pathways, equivalent to 14–15 MtCO₂.

Discussion

Cement and steel together with diesel use in construction processes and material transports account for the majority of the CO₂ emissions associated with building and infrastructure construction (cf. Figure 1). In this roadmap, we illustrate how the basic materials industry and supply chains for buildings and transport infrastructure construction are affected, in terms of energy and material use and associated GHG emissions, by different technical choices. The study also aims to illustrate the timing of measures needed to reach intermediary and long-term emission reduction targets.

Together with previous analysis, we demonstrate the increased importance of ensuring sufficient availability of sustainable biomass/bioenergy, electricity and hydrogen, particularly as experience shows that planning, permitting and construction of both support infrastructure (renewable-based electricity supply, electricity grid expansion, hydrogen storage, CCS infrastructure), and piloting and upscaling to commercial scale of the actual production, involves long lead times.

One of the key messages from this work is the importance of, on the one hand, not letting the pursuit of abatement meas-

ures available at current (e.g. material/fuel substitution and efficiency measures) be an excuse for not acting to lay the foundation for the high-cost long lead-time measures (zero-CO₂ basic materials) that will be required for decarbonisation, and, vice versa, not letting the promise of e.g. low-CO₂ steel or cement be an excuse to not act to unlock the potential for measures that that already exists today.

Successful decarbonisation of the supply chains for buildings and transport 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. Unlocking the full abatement potential of the range of emission abatement measures that are described in this study will involve 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.:

- **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-CO₂ 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).
- **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 long lead times for major infrastructure projects, planning for key support infrastructure therefore needs to be initiated as early as possible, even if not all uncertainties in cost and how the measures can be implemented will be fully resolved.
- **Ensuring sufficient availability of sustainably produced second-generation biofuels** and continued support for hybridisation and electrification of heavy transport and construction equipment.
- **Using public procurement** as a tool to spur innovation, creating markets for low-CO₂ 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. 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 umbrella organisation (public or private) with the responsibility to oversee and support the low-CO₂ transition; securing new competence by including low-CO₂ building and construction as a central part of the in upper secondary school and higher education; and training of active practitioners (engineers, architects etc.).
- **Continued development** and refinement of existing **climate policies** such as the EU-ETS and renewable energy policies, ensuring transparency and long-term predictability.

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