Towards zero-CO2 production and practices in the supply chains for buildings and infrastructure – first experiences from a Swedish case study

(article starts on next page)

Towards zero-CO_2 production and practices in the supply chains for buildings and infrastructure – first experiences from a Swedish case study

Johan Rootzén & Filip Johnsson
Department of Space, Earth and Environment
Chalmers University of Technology
41296 Gothenburg
Sweden
johan.rootzen@chalmers.se

Keywords
construction industry, supply chains, climate change mitigation, buildings, infrastructure, greenhouse gas emission reduction, policies and measures, cement, steel

Abstract
This paper reports from initial case study work, with the aim to analyse transformative roadmaps for the supply chains for buildings and transportation infrastructure. The work is part of the Mistra Carbon Exit research programme, which addresses and identifies the technical, economic and political challenges for Sweden to reach the target of net zero greenhouse-gas emissions by 2045. The case study work gathers some 30 stakeholders, along the supply chain from building materials to end products in the form of buildings and infrastructure. The work is structured as a participatory integrated assessment and this paper provides an analysis based on the first stages of the assessment process. The aim of the first participatory workshop and case study meetings was to capture a wide range of perspectives with regards means available to tackle the challenge of radically reducing the climate impact from the building and infrastructure sector. This includes exploring:

1. Measures/tools to realise the potential of a 50 % reduction in the climate impacts from building and infrastructure construction processes that have been shown to exist already today, and,
2. Measures/tools to accelerate the transition towards zero-emission production and practices in the supply chains from raw materials to completed buildings and infrastructure.

The outcomes from the first stages of the case study work show the importance of:

- Increasing coordination and collaboration along the supply chains, so as to facilitate collective action among stakeholders in the supply chain from basic materials to buildings and infrastructure. This will include developing a common understanding, language and framework among the stakeholders.
- Public actors taking the lead in the transformation, for example by means of innovative procurement practices.
- Establishing markets for zero-CO_2 products and services, both for tapping the potential for early mitigation and for developing and deploying transformative shifts in production and practices, including: i) financing and de-risking investment in transformative technologies, ii) pricing emissions and de-meriting use/production of CO_2-intensive products, and iii) incentivizing demand reduction and substitution of materials.

Introduction
There is an increasing awareness that as the energy and climate performance of the user phase of the built environment keeps improving, the climate impact of the construction process and production and supply of building materials becomes increasingly important – this climate impact is sometimes referred to as embodied emissions or capital emissions. Previous studies (e.g. IVA, 2014; Boverket, 2015, Erlandsson, 2017) suggest that the total climate impact of building and

construction processes in Sweden is around 10 $MtCO_2$-eq per year, with housing projects accounting for roughly ⅔ and civil engineering and public works for roughly ⅓ of the annual emission. This is a substantial share of the total Swedish greenhouse gas emissions, which amount to around 53 $MtCO_2$-eq per year.

Figure 1 shows how the climate impact related to the heating of the Swedish building stock has been significantly reduced since 1993. Today GHG emissions from the construction process, including emissions related to production and supply of building materials, exceeds the emissions related to heating. Fuel- and carbon taxation in combination with improved access to district heating, heat pumps and pellets boilers has led to a gradual shift away from fossil fuels (mainly heating oil) and a consequent reduction of the carbon intensity of the fuel mix used to heat Swedish buildings. In parallel, enforcement of increasingly stringent energy performance standards, has helped lowering the energy intensity of the building stock.

Similar regulations and incentives targeting the climate impact of the construction process has, until recently, largely been lacking. This paper reports from the initial case study work within the Mistra Carbon Exit research programme –with the aim to identify and analyse measures/tools to incentivize transformative changes that could contribute to reducing emissions from the building process in line with the Swedish economy-wide emission reduction target, i.e. net zero greenhouse gas emissions by 2045. This includes:

1. Measures/tools to realise the potential of a 50 % reduction in the climate impacts from building and infrastructure construction processes that have been shown exists already today (see e.g. Uppenberg et al., 2017 and Erlandsson, 2017); and,
2. Measures/tools to accelerate the transition towards zero-emission production and practices in the supply chains from raw materials to completed buildings and infrastructure.

The wedges in Figure 1 illustrate the effects of full realisation of emission reduction measures that, at least theoretically, are realisable today (known measures) and of the more transformative measures and practices that are required to reach zero or near-zero CO_2 emissions from the building and construction processes. These measures require technologies which in many cases have not yet been demonstrated at scale and which, in some cases, require substantial technological development (innovation).

RELATED WORK

Efforts to increase the understanding of, and to reduce the climate impact of the construction process have traditionally typically been compartmentalized in accordance with traditional divisions of sectors and practices, e.g., focused on individual industrial processes, business areas and academic disciplines. This said, over the last few years several projects and initiatives have been launched aimed at bridging the knowledge gap and capturing a wider range of perspective on how to speed up efforts to reduce the climate impact of the construction process (e.g. Giesekam et al., 2014; Giesekam et al., 2016; Norman et al., 2016; UN Environment and International Energy Agency, 2017). Table 1 exemplifies this with an overview of four important initiatives in Sweden and the UK.

THE MISTRA CARBON EXIT RESEARCH PROGRAMME

The Mistra Carbon Exit programme (with a first phase 2017–2020) has the aim to analyse and demonstrate how the supply chains of buildings, infrastructure and transportation can be transformed to comply with the Swedish target of net zero

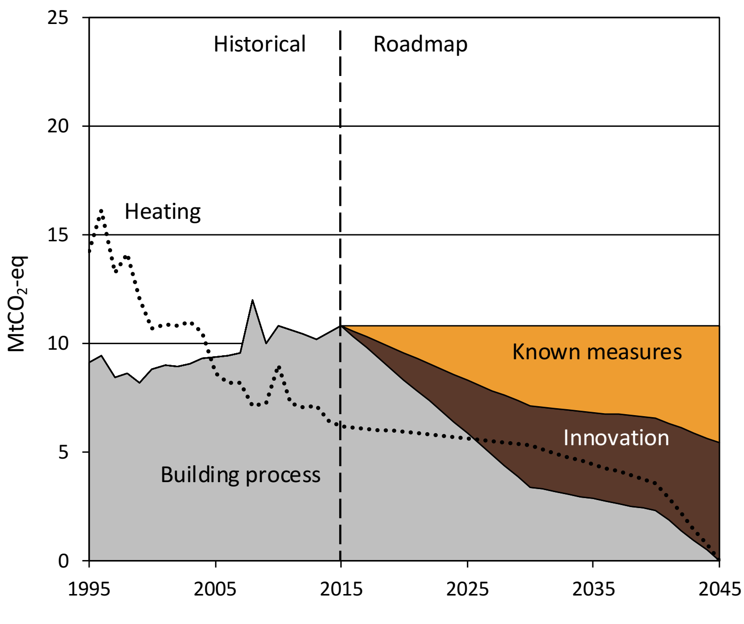

Figure 1. Historical climate impact related to the heating of buildings and from building and construction processes in Sweden and emission reduction required to meet the goal net zero greenhouse gas (GHG) emissions by the year 2045. Here, the demand (activity level) for building and construction work has been assumed constant in the future. Adapted from: Erlandsson et al., 2017.

Table 1. Overview of recent projects and initiatives aimed at improving the knowledge-base and reducing the climate impact from the construction process.

Project name	Description
Low Carbon Routemap for the UK Built Environment (UK)	A project developed by The Green Construction Board. Covers operational as well as embodied carbon emission from both the buildings and infrastructure sectors. Explores options to reduce GHG emissions from the user phase, supply chain and construction activities for the UK built environment (UKGBC, 2013).
PAS 2080:2016 Carbon management in infrastructure (UK)	Standard developed to assist infrastructure value chain participants to cooperate in the development of low carbon infrastructure projects. Provide a common language and framework aimed at delivering reductions rather than simply quantifying embodied emissions. Developed with the British Standards Institution by Arup and Mott MacDonald with guidance from the Green Construction Board (Enzer, 2016; DBW, 2017).
Roadmap for a carbon neutral and competitive building sector (Sweden)	Establishment of a roadmap for a carbon neutral and competitive Swedish building sector in the year 2045. Commenced 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 actions and key decision points required to achieve a carbon neutral and competitive building sector. The preparation of the roadmap involves a broad representation of actors across the Swedish construction sector.
Climate requirements on infrastructure (Sweden)	Since 2016 the Swedish Transport Administration applies climate requirements in its procurement of major projects and will gradually increase the requirements, with the aim of the infrastructure being climate neutral by the middle of this century (Swedish Transport Administration, 2015).

greenhouse gas (GHG) emissions by the year 2045. The supply chain approach involves analysis of opportunities and barriers for mitigating carbon emissions along the industry supply chains from the input of raw materials, over primary and secondary activities, to final products and services demanded by the end user. The concept of supply chain refers to the cross-sectoral networks of facilities and distribution channels that facilitate the sourcing and primary production of materials, as well as the further processing and assembly and delivery of products or services to the customer, see e.g. Stevens (1990). This is tightly linked to the concept of value chain, which focuses on the value creation and the margin which can be obtained from a certain supply-chain business (see original work by Porter, 1985 as well as Mentzer et al., 2001 with references).

The Mistra Case study work is carried out in close collaboration with actors involved in the respective supply chain and is supported by academic research work packages of the programme (MCE, 2018). The present work focuses on buildings and transportation infrastructure.

Method

The case study work has been structured as a participatory integrated assessment (see e.g. Stalpers et al., 2008 and Salter et al. 2010) involving five stages: I. Preparation, II. Framing and identification of key challenges and opportunities, III. Case study assessments, IV. Development of analysis of potential Roadmap(s), and, V. Evaluation. Figure 2 provides an overview of methodological approach.

The preparatory work (Stage I) involved identifying and inviting relevant experts and stakeholders, laying out a work plan and preparing the first stakeholder workshop (Stage II) which was dedicated to; i) jointly define and frame the problem, ii) create a common understanding of the current status and current best practices within different parts of the supply chains related to Buildings and Transportation infrastructure, iii) select relevant case study objects, and iv) to identify and rank key challenges and knowledge gaps that need to be overcome to meet the goal of net zero greenhouse gas (GHG) emissions by the year 2045.

The outcomes from the two first stages provide the basis of the continued work which will include inquiring into selected case study objects (Stage III), i.e., building or infrastructure projects in the planning or construction stage, to explore how challenges and opportunities related to the decarbonisation of the supply chains for buildings and transport infrastructure are manifested under different conditions and circumstances. In parallel, and informed by the previous stages, a number of different roadmaps will be developed and explored quantitatively and qualitatively to assess the measures, policies and key decision points required to achieve net-zero GHG emissions (Stage IV).

Whereas the academic research team, together with external experts, will have the main responsibility for the analyses work

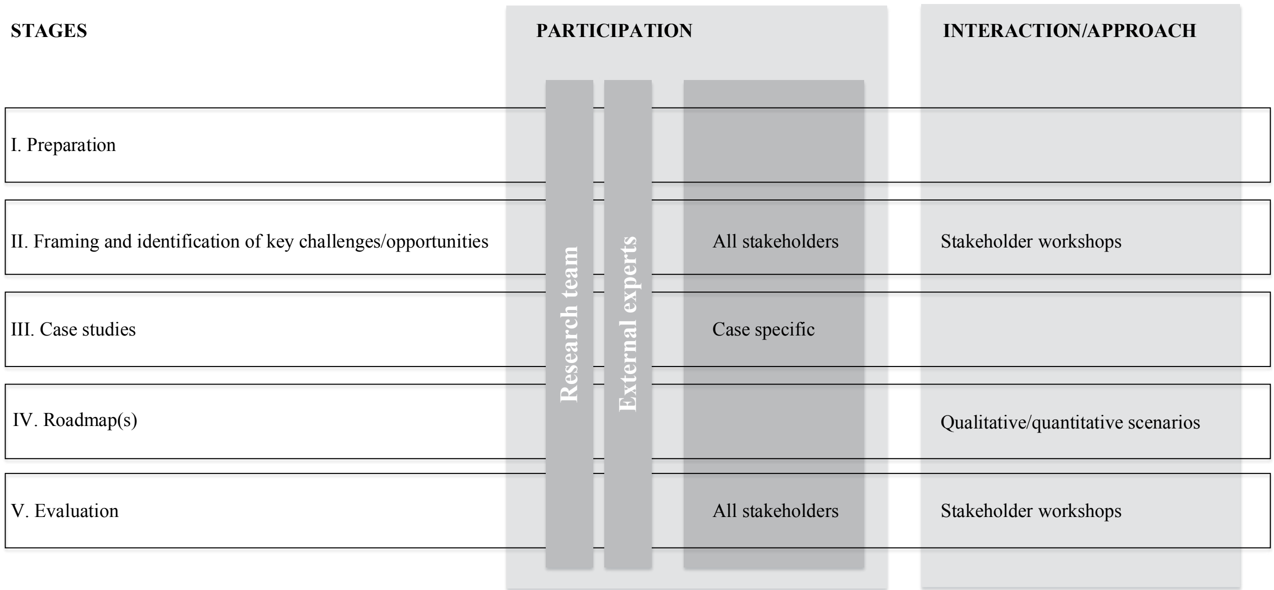

Figure 2. Outline of the methodological approach. Adapted from Stalpers et al., 2008 and Salter et al. 2010.

related to the construction projects short-listed for closer investigation and for designing the supply chain roadmaps iterative stakeholder workshops and case study meetings will ensure continuous knowledge exchange and the involvement of the stakeholders in the analysis and evaluation process (Stage V).

The work reported in this paper is based on initial analysis of the supply chains from cement and steel to buildings and infrastructure (cf. Rootzén and Johnsson, 2016; 2017a; 2017b) and the outcomes from the two first stages (Stage I and II) of the case study work, including a workshop and three case study meetings involving some 30 stakeholders along the supply chain; material suppliers, contractors, consultants, architects, clients, governmental agencies, municipalities research institutes and universities.

First outcomes from the case study work

CURRENT STATUS

The amount of GHG emissions associated with the construction of a specific building or an infrastructure project obviously varies depending on type of structure and the choice of material composition (e.g. type of infrastructure or choice of building frame). However, five categories materials/activities typically account for the majority of the GHG emissions associated with most construction projects:

- Concrete (mainly due to CO_2 emissions from the cement clinker production)
- Steel (reinforcement steel and construction steel)
- Heavy transports
- Construction machinery
- Asphalt (bitumen) and plastics

Figure 3 gives an approximation of the relative contribution from different categories of materials/activities to the total climate impact of building/infrastructure projects in Sweden.

It seems clear from the collective inventory work carried out within the case studies, that there is a number of emission reduction measures which, at least theoretically, are realisable today and if fully realised could contribute to halving the climate impact related to building and infrastructure construction in Sweden. Key measures include:

- Increased use of cement clinker substitutes
- Shifts to alternative fuels in heavy transport/construction machinery
- Material efficiency
- Recycling of asphalt
- Shifts to more CO_2-lean materials (e.g. wood)

It is also clear that reducing GHG emissions beyond a certain point (~50–100 %) will have to involve more transformative shifts in the way building materials are produced and sourced including, e.g.:

- Fuel shift and/or electrification in the cement industry
- Implementation of Carbon Capture and Storage (CCS) in the cement industry
- Alternative steel production process, e.g. hydrogen based steel making
- Shift to biomass based renewable bitumen
- Shifts to alternative drivetrains in heavy transport/construction machinery

MOVING FORWARD

The impression from the initial discussions with the stakeholders involved in the case study work is that there is a relative consensus with regards to the means available to tackle the challenge of radically reducing the climate impact from the building and infrastructure sector. Coordination and col-

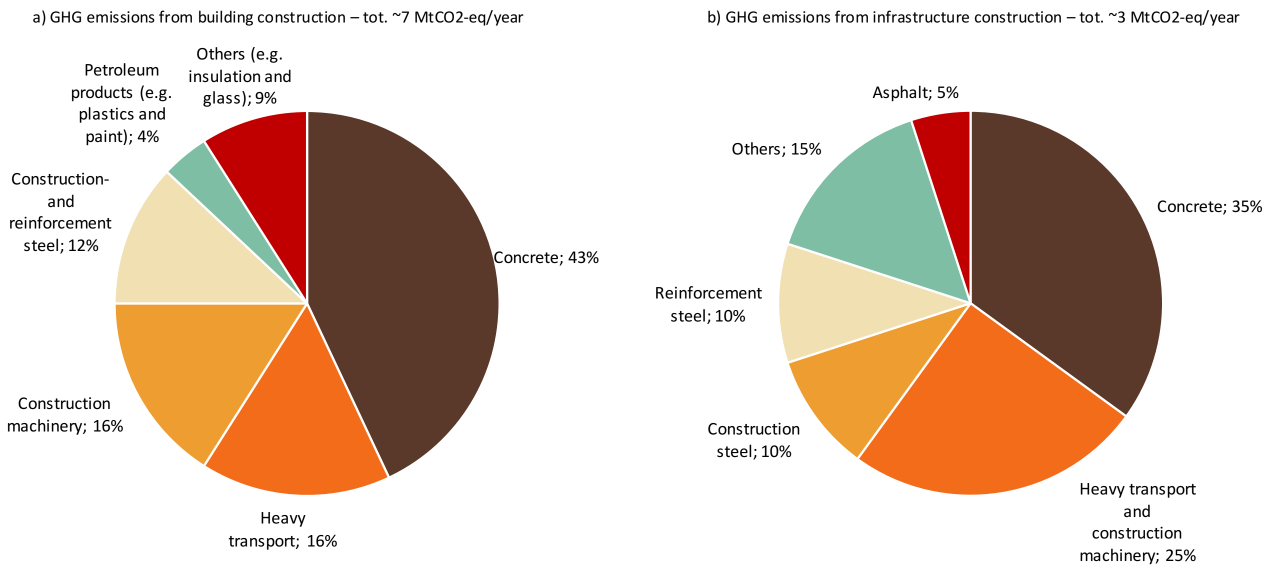

Figure 3. Relative contribution from different categories of materials/activities to the total climate impact of building or infrastructure projects in Sweden. Based on data from Boverket, 2017, Erlandsson et al., 2017 and Trafikverket, 2017a.

laboration along the supply chains are seen as central both for tapping the potential for early mitigation and for devising and implementing the mechanisms that can incentivise the development and deployment of transformative technologies required to achieve zero GHG emissions. At the same time, the challenge associated with the transformation required exhibits some of the features that often characterize collective action dilemmas (cf e.g. Ostrom, 2010). While sharing the same overarching goal one of the challenges will be for the different actors to find strategies to move forward at the same pace. The challenge may also appear different, depending on where in the supply chain a stakeholder/company is located. The basic materials producer needs some form of assurance that an investment in a mitigation measure will repay itself, i.e. that there will be a market for climate neutral materials. The contractor, while able to choose between materials and activities with different climate impacts, needs to translate climate lean products into business opportunities to create and capture the value of climate neutral products and services. The procurer must, for its part, find a strategy to formulate procurement requirements so that they do not lead to lock-in effects (i.e. only including incremental low-cost measures) and to adapt and tighten the requirements at a pace and rate that incentivize rapid and extensive emission reductions on the supply side without being unattainable.

In this context, it is also important to bear in mind that while infrastructure and building construction obviously have much in common when it comes to routines, equipment and key materials and products – concrete and steel in particular – there are also major differences with respect to possibilities for substitution materials and practices. An important issue is therefore to identify similarities and differences between the construction processes of buildings and infrastructure and analyse how the differences influence policy measures and procurement practices.

Key opportunities and challenges

As stated above two overarching questions guiding the case study work are:

> Q1. How to realise the potential of the emission reduction measures that have been shown to exist already today?
>
> Q2. How to, as soon as possible, create the economic and organisational conditions that will lay the foundations for reaching zero or near-zero GHG emissions in the entire supply chain – from raw materials to completed buildings and infrastructure?

Although related, the two questions tend to be associated with two quite different sets of opportunities and challenges. Whereas the failure to realise the potential for existing emission reduction measures (Q1) tends to be explained by factors such as, e.g., implicit or explicit constraints within the organisations of individual companies, inadequate communication between actors in the supply chain, overly conservative regulations and norms, or lack of information.

With respect to the second question (Q2) the task is to, already today, lay the foundation for a number of key technologies that will likely be required to achieve deep decarbonization with a couple of decades, e.g. electric construction machines, CCS and hydrogen reduced iron/steel. This involves, for example, adaptation of legislation, and innovative schemes to share the risk and costs associated with developing and implementing new technology.

An important part of the first stages of the case study work has been to identify and rank opportunities and challenges, key issues and strategic choices, from the different stakeholder. As a way of structuring the work opportunities/challenges has been categorised in five categories. Table 2 provides a list of examples of opportunities and challenges raised as particularly important in the first participatory workshop and in subsequent discussions. The following subsections describes, with somewhat more depth, three of the focus areas that will be part of the

Table 2. Examples of opportunities and challenges high-lighted in the initial scanning.

Category	Opportunities (+) and challenges (-)
Technology/materials	+ Breakthrough technologies/materials (e.g. 3D-printing and graphene-reinforced concrete) + Set requirements for fossil free transports/construction machinery/mobility solutions – Streamlined logistics – Possible limited supply of cement substitutes – Uncertainties related to key technologies, e.g., hydrogen reduction and CCS
Organisation	+ Organization/Business model innovation + Digitalisation of information flows + Cascading goals – Carbon management typically not prioritised in the early phases of a project – Compartmentalization
Policy/financing	+ Innovative procurement practices + New policies and funding mechanisms aimed at transformative change – Weak or no policy signals – Lack of predictability and long-term ground rules
Technical regulations and norms	+ Requirements for EPD:s and carbon performance in national/municipality-level legislation/regulations + Overhaul of regulations/norms hindering innovation/mitigation – New materials/products hindered by overly conservative regulations and norms – No standardized methods for assessing climate impact – Complex chains/interactions between standards/regulations → no one has the whole picture
Synergies/Conflicting goals	+ Avoid single policies for multiple goals + Cut carbon, cut costs, e.g., through efficient design + Design for recycling/reuse + Early movers could reap business opportunities abroad – Costs for carbon mitigation vs. competitiveness – Meeting the need for new construction vs. carbon mitigation – Shorter/less bridges → barrier effects – Limiting new construction (in the long term) vs. employment

[a] *See also the listing of key technical/material related emission reduction measures in the previous section 'Current status'.*

continuing case study work: method development, innovative procurement practices and the potential fallacy of low hanging fruits.

Method development for quantifying and reporting climate impact from building and construction

There is still a lack of standardization with regards to methods and tools for assessing, reporting the climate impact of building and infrastructure building process, on the project level as well as the sector- societal level. While the knowledge base is gradually growing, the lack of experience and standardization makes it difficult for customers to properly appreciate and compare the climate impact of the building process and to plan and formulate procurement requirements that could incentivise reductions in the climate impact.

Practitioners involved in climate assessments of buildings and infrastructure tends to rely on tools and schemes that were original developed for other broader purposes including Environmental Product Declarations (EPD), Life Cycle Analysis (LCA) tools, sustainability certification schemes like LEED, CEEQUAL, BREEAM Infrastructure and their national specific counterparts like Environmental building ('Miljöbyggnad') and 'Svanen' in the case of Sweden (see e.g. Raymond et al., 2013, Impres, 2017 for a more comprehensive review). All of these fill important roles as tools to assess, quantify and compare the climate impact of (i) individual products and building materials (EPD and LCA), (ii) components combinations and building elements (LCA), and (iii) the full building life cycle (LCA and sustainability certification schemes). Yet, these tools tend to be less equipped to address transformative shifts in technology and practices across multi-actor supply chains over a decadal timescale (Miller and Keoleian, 2015; Hanes and Carpenter, 2017), i.e. what relates to the research questions addressed in the Mistra Carbon Exit programme. One of the aims of the case study work is to develop and implement assessment tools to manage material and energy flows and corresponding GHG emissions and costs along the supply chains for buildings and infrastructure. This will enable analysts and stakeholders to assess the measures, policies and key decision points required to achieve net-zero emission. The tool will be based on an approach developed in previous works by the authors (Rootzén and Johnsson 2016; 2017a; 2017b) and developed further based on experiences from similar initiative and tools including the Low Carbon Routemap for the UK Built Environment (UKGBC, 2013), The Carbon Infrastructure Transformation Tool (CITT, 2017); the Materials Flow through Industry (MFI) supply chain modeling tool (Hanes and Carpenter, 2017), Environmental indicators for construction and property management (Boverkets Miljöindikatorer) (Boverket, 2014) and procurement requirements for road and rail installations, i.e. the Swedish Transport Administration climate calculation tool (Trafikverkets Klimatkalkyl) (Trafikverket, 2017b).

Innovative procurement practices

Total investments in buildings and infrastructures in Sweden amounted to approximately 40 billion Euro in 2014 (SBI, 2015), corresponding to around 10 percent of GDP. The split between private and public investment varies somewhat from year to year, but they each roughly account for half of the annual investments in buildings and infrastructure. The principle of public procurement has the primary starting point to safeguard competition and ensure compliance with the principles of equal treatment and non-discrimination, but also allows public procurers to influence, through procurement requirements, developments towards different social and environmental goals (SOU 2013: 12). Private actors have even greater freedom of action since their requirements and assessments do not have to withstand a judicial review (Bröchner and Kadefors, 2009). Overall, public procurers in governmental agencies, municipalities and county councils, 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 and to legitimize public strategies. As customers to the building and construction industry, this could for example involve to; (i) specifying climate requirements in a way that encourages incremental improvements within the framework of existing procurement strategies in, but also to, (ii) develop new procurement strategies that can support and drive the development of more transformative solutions. Such solutions can include both costly technological advances, innovative ways of organizing an activity as well as changing behaviours that make it possible to meet a specific need, but with radically reduced climate impact (Pamlin, 2013).

The Swedish Transport Administration has begun work in this direction by introducing climate requirements in its procurement of major projects and will gradually increase the requirements, with the aim of the infrastructure being climate neutral by the middle of this century (Swedish Transport Administration, 2015). The Swedish Transport Administration, which has an annual budget for maintenance and investment in new infrastructure of around 5 billion Euros, and is the single largest final consumer of basic materials in Sweden (mainly cement and reinforcement steel for Sweden's road and rail infrastructure) is well positioned to contribute to pursue development of carbon-lean materials. The Swedish Transport Administration's initiative already serves as an example of how to work with procurement as a tool for reducing climate impact from individual projects with a relatively complex supply chains.

The potential for public procurement as a tool to spur innovation, creating markets for low-CO_2 products and opening up for economies of scale generally remain underused (Chiappinelli, 2017). While both Swedish and EU legislation provide openings for green public procurement the lowest price criterion tends to continue to dominate. Realising the full potential would entail clearer political priority and governance structures as well as a building up of the administrative capacity and coordination and communication between authorities (Chiappinelli, 2017).

The potential fallacy of low hanging fruits

Much like in the discussions related to the technical potential for energy efficiency improvement the initial assessments of the opportunities for reducing the climate impacts from building and infrastructure tends to be optimistic. As have been described above, early assessments suggest that as much as 50 % of the climate impact from the construction process could be mitigated by measures/technologies that already exists today. There also seems to be a belief that many of these measures could come at a low- or in some cases negative cost, 'cut carbon – cut costs' (Enzer, 2016; DBW, 2017). While this may seem reassuring, it may be worth noting that experiences from similar analyses in the energy efficiency field has not seldom proven to be overly optimistic, i.e. the cost-effective level of energy use, as estimated using techno-economic bottom-up modelling, has not been realised under real market conditions (see e.g. Jaffe and Stevins, 1994; Murphy and Jaccard, 2011 and Ó Broin et al. 2015 and references therein). As the case study work proceeds with assessing the potential for early mitigation and with identifying means to realise this potential, to provide a realistic guide, and to neither inflate expectations nor unnecessarily underestimate the potential for emissions reductions, important insights may be gained from the literature discussing the so called 'energy efficiency gap. Concepts such as, transaction costs, principal-agent problems, bounded rationality, behavioural anomalies, consumer heterogeneity, opportunity costs and the risk aversion associated with the adoption of new technologies (Ó Broin et al. 2015) may prove to be applicable in the context of identifying opportunities and barriers to the efforts to reduce the climate impact of the construction process as well.

Concluding remarks

It is clear that no single actor has the means and tools required to achieve the goal of net-zero GHG emissions from Swedish construction and civil engineering projects. The case study work and the platform it provides have proven to be a valuable for exchanging information and experiences, to learn from each other, and co-produce new knowledge. Thus, the participatory inventory work performed within the work carried out so far, has resulted in a better collective understanding of the key opportunities, challenges and knowledge gaps that need to be overcome to meet the goal of net zero GHG emissions by the year 2045.

The next step in the case study work will be to begin probing into the construction projects that has been singled out as suitable for exploring how challenges and opportunities related to the decarbonisation of the supply chains for buildings and transport infrastructure are manifested under real market conditions. A number of cross-cutting focus areas that will be investigated throughout the Mistra Carbon Exit programme period have also been identified. First up is a study of the potential for and consequences of scaling up the use alternative binders in concrete production.

Although the findings reported in this paper 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 (cf. e.g. UN Environment and International Energy Agency, 2017). Whereas rapid improvements of the climate performance of the user phase 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.

References

Boverket, 2015. Miljöpåverkan från bygg- och fastighetsbranschen, 2014 Boverket (Swedish National Board of Housing, Building and Planning), Report no: 2014: 23.

Boverket, 2015. Byggnaders klimatpåverkan utifrån ett livscykelperspektiv Forsknings- och kunskapsläget. Boverket (Swedish National Board of Housing, Building and Planning), Report no: 2015: 35.

Bröchner, J. and Kadefors, A., 2009. Värden och värdekedjor inom samhällsbyggande. KK-Stiftelsen (The Knowledge Foundation), ISSN: 1652–5213.

Chiappinelli, O., 2017 Green Public Procurement for a low-carbon materials sector. Presented at: 'Policy Design for a Climate Friendly Materials Sector', COP23 Bonn, 7th November 2017, German Institute for Economic Research – DIW Berlin.

CITT, 2017. The Carbon Infrastructure Transformation Tool (CITT)– White Paper. Project executed by the Centre for Business and Climate Change at the University of Edinburgh Business School, together with industry partners Costain Group and Skanska UK.

DBW, 2017. PAS 2080 Carbon management in infrastructure, Designing Buildings Wiki (DBW). URL: www.designingbuildings.co.uk.

Enzer, M., 2016. Low carbon game-changer. Published by Institution of Civil Engineers, 10 March 2016.

Erlandsson, M., 2017. Blå Jungfrun version 2017 med nya cement inklusive potentiella förbättringar och karbonatisering. IVL Swedish Environmental Research Institute.

Erlandsson, M., Byfors, K., Sveder Lundin, J., 2017. Byggsektorns historiska klimatpåverkan och en projektion för nära noll. Swedish Environmental Research Institute (IVL), IVL rapport C 277 ISBN 978-91-88787-12-5.

Giesekam, J., Barrett, J., Taylor, P., & Owen, A., 2014. The greenhouse gas emissions and mitigation options for materials used in UK construction. Energy and Buildings, 78, 202–214. https://doi.org/10.1016/j.enbuild.2014.04.035

Giesekam, J., Barrett, J., and Taylor, P., 2016. Scenario Analysis of Embodied Greenhouse Gas Emissions in UK Construction. Engineering Sustainability, 169 (August), 1–13. https://doi.org/10.1680/jensu.16.00020

Hanes, R. J., and Carpenter, A., 2017. Evaluating opportunities to improve material and energy impacts in commodity supply chains. Environment Systems and Decisions, 37 (1), 6–12.

Impres, 2017. Implementation of Procurement Requirements for Sustainable Collaboration in Infrastructure Project (Impres) http://constructionclimatechallenge.com/research/impres-project/.

Jaffe A.B. and Stavins RN., 1994. The energy efficiency gap: what does it mean? Energy Policy. 1994; 22 (10): 804–10.

MCE, 2018. Mistra Carbon Exit. https://www.mistracarbonexit.com/about/.

Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D. and Zacharia, Z. G., 2001. Defining supply chain management. Journal of Business Logistics, 22: 1–25. doi:10.1002/j.2158-1592.2001.tb00001.x.

Miller, S. A., and Keoleian, G. A., 2015. Framework for analyzing transformative technologies in life cycle assessment. Environmental Science and Technology, 49 (5), 3067–3075. https://doi.org/10.1021/es505217a

Murphy R and Jaccard M., 2011. Energy efficiency and the cost of GHG abatement: A comparison of bottom-up and hybrid models for the US. Energy Policy 2011; 39 (11): 7146–55.

Norman, J. B., Serrenho, A. C., Cooper, S. J. G., Owen, A., Sakai, M., Scott, K., … Allwood, J. M., 2016. A whole system analysis of how industrial energy and material demand reduction can contribute to a low carbon future for the UK. CIE-MAP. Retrieved from http://ciemap.leeds.ac.uk/wp-content/uploads/2016/04/CIEMAP-Report.pdf.

Ó Broin, E., Mata, É., Nässén, J. and Johnsson, F., 2015. Quantification of the energy efficiency gap in the Swedish residential sector. Energy Efficiency (2015) 8: 975. https://doi.org/10.1007/s12053-015-9323-9

Ostrom, E., 2010. Polycentric systems for coping with collective action and global environmental change. Global Environmental Change, 20 (4), 550–557. https://doi.org/10.1016/j.gloenvcha.2010.07.004

Pamlin, D., 2013. Transformativa lösningar och offentlig upphandling (Transformative solutions and public procurement). Slutrapport för Upphandlingsutredningen (SOU 2013:12), 21st.

Porter, M., Competitive advantage: creating and sustaining superior performance, The Free Press, New York, 1985, ISBN 0-684-84146-0.

Raymond J. Cole & Maria Jose Valdebenito (2013) The importation of building environmental certification systems: international usages of BREEAM and LEED, Building Research & Information, 41: 6, 662–676, DOI: 10.1080/09613218.2013.802115.

Rootzén, J. and Johnsson, F., 2016. Paying the full price of steel – Perspectives on the cost of reducing carbon dioxide emissions from the steel industry. Energy Policy, 98, pp. 459–469.

Rootzén, J. and Johnsson, F., 2017a. Technologies and policies for GHG emission reductions along the supply chains for the Swedish construction industry. Paper ID 6-215-17, Proceedings of eceee 2017 Summer Study 29 May–3 June, 2017, Belambra Presqu'île de Giens, France.

Rootzén, J. and Johnsson, F., 2017b. Managing the costs of CO_2 abatement in the cement industry, Climate Policy, 17: 6, 781–800, DOI: 10.1080/14693062.2016.1191007.

Salter, J., Robinson, J., & Wiek, A. (2010). Participatory methods of integrated assessment – A review. Wiley Interdisciplinary Reviews: Climate Change, 1 (5), 697–717. https://doi.org/10.1002/wcc.73

SBI, 2015. Fakta om byggandet 2015, Sveriges Byggindustrier (SBI), The Swedish Construction Federation, Stockholm, Sweden.

SOU 2013:12. Goda affärer – en strategi för hållbar offentlig upphandling, Swedish Government Official Reports (SOU), SOU 2013:12.

Stalpers, S. I. P., Van Amstel, A. R., Dellink, R. B., Mulder, I., Werners, S. E., and Kroeze, C., 2008. Lessons learnt from a participatory integrated assessment of greenhouse gas emission reduction options in firms. Mitigation and Adaptation Strategies for Global Change, 13 (4), 359–378.

Stevens, G. C., 1990, Successful Supply-Chain Management, Management Decision, Vol. 28 Issue: 8, doi.org/10.1108/00251749010140790.

Trafikverket, 2015. Riktlinje TDOK 2015:0480 Klimatkrav i planläggning, byggskede, underhåll och på teknisk godkänt järnvägsmateriel, Trafikverket (The Swedish Transport Administration), Borlänge, Sweden.

Trafikverket, 2017a. Trafikverkets Miljörapport 2016. Publikationsnummer: 2017:090, Trafikverket (Swedish Transport Administration), Borlänge, Sweden.

Trafikverket, 2017b. Klimatkalkyl version 5.0 – Beräkning av infrastrukturens klimatpåverkan och energianvändning i ett livscykelperspektiv. Trafikverket (Swedish Transport Administration), Borlänge, Sweden.

UKGCB, 2013. Low Carbon Routemap for the UK Built Environment Prepared by WRAP in collaboration with Arup and the Climate Centre on Behalf of The UK Green Construction Board (UKGCB).

UN Environment and International Energy Agency, 2017. Towards a zero-emission, efficient, and resilient buildings and construction sector. Global Status Report 2017.

Uppenberg, S., Ekström, D., Liljenroth, U., Al-Ayish, N., 2017. Klimatoptimerat byggande av betongbroar. WSP och RISE. SBUF-projekt 13207.

Acknowledgements

Financial support from Mistra, the Swedish foundation for strategic environmental research, and VINNOVA (2016-03387), the Swedish innovation agency, is gratefully acknowledged. Thanks to the all the stakeholders involved in the case study whose engagement and generous sharing of experiences and knowledge has been instrumental in the process of completing this paper. We would also like to thank Ida Karlsson for proofreading and the two anonymous reviewers whose comments helped improve the readability of the manuscript.