



City-based Carbon Budgets for Buildings

Lütken, Søren; Wretlind, Per Harry

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Lütken, S., & Wretlind, P. H. (2016). *City-based Carbon Budgets for Buildings*. UNEP DTU Partnership. UNEP DTU Partnership Working Paper Series 2017 No. 13

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

UNEP DTU
Low Carbon Development
Working Paper Series
No.13
May 2016

City Based Carbon Budgets for Buildings

Søren E. Lütken
and
Per Harry Wretling

Low Carbon Development Programme
UNEP DTU Partnership



CITY-BASED CARBON BUDGETS FOR BUILDINGS

A city-driven, industry-led bottom-up global response to emissions reduction

by Søren Lütken and Per Harry Wretling

Abstract

The construction of buildings consumes about 50% of all materials produced globally measured by weight. Materials such as cement, ceramic tile and steel are among the most carbon intensive materials to manufacture, and come with a carbon footprint of their own. This is called embodied carbon.

Accounting for embodied carbon is a different way of visualizing the emission effect of the consumer rather than the generator of emissions. Bringing the consumer, and the related production value chains, into play can engage powerful market drivers in the combat against GHG emissions. The building sector, with its vast resource consumption, is the ideal place to start. This working paper provides concrete ideas on how to proceed.

Currently, there is scant regulation addressing embodied carbon. Cities have great potential influence over the construction industry, as nearly all construction of buildings requires city government approval. Energy efficiency is the usual focus, though recent policy development regarding embodied carbon emissions in buildings has been observed in a number of cities and countries. Moreover, industry has been pushing the development of standards for calculation and reporting of embodied carbon in buildings. Embodied carbon is also addressed by several green building certification schemes. The development, however, needs to speed up.

The construction sector and cities together are ideally positioned to establish a local up-scalable regime that will curb greenhouse gas emissions from within. This working paper suggests concretely how to design and implement a model in which cities use existing construction approval processes to allocate a carbon budget that combines emissions from operational and embodied carbon - and make usage permits for buildings constructed under this restriction contingent upon documented compliance - leaving it up to the sector itself to document its carbon footprint. A parallel is drawn to the dissemination of ISO standards 9001 and 14001, where quality and environmental demands from decisive commercial actors spread through the supply chain. The paper explores principles and specific limits regarding e.g. calculation of the carbon budget over time and the method of budget allocation in order to repeat this experience with the purpose of emissions reduction. The working paper also reveals that cities have a firm ground to stand on and that in curbing emissions through carbon budgets for construction they would act in their own self-interest. Adopting the model they would and will ultimately deliver a ground breaking initiative for cutting global emissions at scale – beyond that of the construction sector. If the ISO experience has any merit, it suggests less than a decade for the effects of carbon budgets to show themselves.

Table of Contents

Abstract.....	1
Acknowledgements.....	2
Introduction	3
Life Cycle Assessments for Buildings.....	4
Materials Responsible for Embodied Carbon	6
Current Regulation of the Sector	9
Cities' Potential Role	10
The Model: Carbon Budgets for Buildings	11
What is in a Budget?	11
Calculation of carbon budgets	12
Allocation of Budgets	13
Trading	14
New Versus Existing Buildings	14
What is in it for Cities?	14
The Industrial Response.....	16
Drivers for ISO Certification	18
Challenges and Perspectives.....	19
Bibliography	23

Acknowledgements

This paper has benefited greatly from the contribution of Federico Antonio Canu, as well as the comments and suggestions by colleagues at UNEP DTU Partnership who have attended the Research Forum where it was discussed. The paper is also indebted to Ksenia Petrichenko, whose review offered insightful and valuable comments and suggestions.

Introduction

Global greenhouse gas (GHG) emissions have been on a rising trend for decades. While GHG emissions in developed countries seem to have peaked (at least momentarily), developing countries' emissions are skyrocketing (UNEP, 2014). Major reasons for this are rapidly increasing wealth and fast growing middle classes whose desires are met by an increasing production of consumer goods and significant improvements of living conditions, partly in terms of better living accommodations. This creates an impetus for constructing better buildings. A high rate of urbanisation adds to the construction pressure (Lucon et al., 2014). Billions of square meters of residential buildings, offices, public service institutions and industrial facilities are being built every year, not only keeping pace with population growth, but also responding to demands for larger dwellings¹. Industry experts predict that the construction industry will grow by 70% until 2025 (Global Construction Perspective, 2013). These trends are unlikely to be reversed or even reach maturity in the foreseeable future.

The global construction sector has significant environmental impacts. Once constructed, buildings – or those who use them – consume about 32% of all energy produced (Lucon et al., 2014). This is called operational energy, and the associated carbon emissions are thus called operational carbon. The growth of energy use is a natural consequence of growing wealth and increasing demands for comfort.

But there are other more significant emission effects of construction. In constructing, the rise in energy use is a consequence of growing wealth and increasing demands for comfort, and a large and growing cause of energy consumption is attributable to passive installations - mainly the buildings' climatic envelope. During the building of inner and outer structures, walls and roofs, the construction sector consumes about 50% of all materials produced globally measured by weight (Adriaanse et al., 1997). Moreover, these materials (e.g. cement, steel, ceramic tiles and insulation) are carbon intensive in manufacturing (Circular Ecology, 2015). Hence, the construction materials come with energy and carbon footprint of its own from manufacturing.

This is called embodied carbon. Embodied carbon encompasses the emissions from resource extraction, material production, the construction of buildings, as well as the transportation required for these activities. It stems from applying life cycle thinking to buildings (Liljenström et al., 2015). Some construction materials also have a direct influence on the operational carbon. Simply put, if 200 mm of insulation is good, 400 mm is not twice as good, because the insulating effect decreases exponentially (Bolattu, 2010). At some point, the energy (and emissions) it would take to produce that extra insulation would outweigh the reduction of emissions from the reduced energy consumption from operating the building – depending on the lifetime of the installation.

¹ Recently, though, an opposite trend towards micro-dwellings in high-priced metropolises (Hong Kong, London, New York and a number of other developed country cities) has taken root, although still a microscopic fraction of the activities in the construction sector.

A singular focus on operational carbon will disregard the embodied carbon, and the only limiting factor, for instance the thickness of the insulation, will become the price. However, the application of life cycle assessments (LCA) changes this isolated approach. For buildings, LCA has come later than in many other industrial sectors mainly due to the nature of the building sector, with very long life cycles of buildings and the resulting complexities of conducting an LCA (Khasreen, Banfill, & Menzies, 2009).

This, however, is changing as the building sector increasingly applies a life cycle perspective. Currently, this is mainly driven by the industry itself, but in order for it to become common practice, policy instruments are needed. This paper suggested a city based carbon budget model as a way to achieve lower levels of embodied carbon in buildings, which also reaches beyond the construction sector, promoting a decarbonisation of production value chains as a whole.

Life Cycle Assessments for Buildings

The standard EN 15978 issued by the European Committee for Standardisation (CEN) delineates how to conduct an LCA for a building and how to calculate the emissions from each stage of the life cycle - product, construction, use and end-of-life stage (Liljenström et al., 2015). An illustration of the delineation is shown in Figure 1. Embodied carbon include Stages A and C, as well as B1-5. Operational carbon covers B6-7, thus coming from emissions created when generating the energy consumed for space heating and cooling, water heating, conditioning, and lighting as well as appliances and equipment (elevators, pumps, ventilation etc.). The unnumbered box below the Use Stage, also titled 'Operational

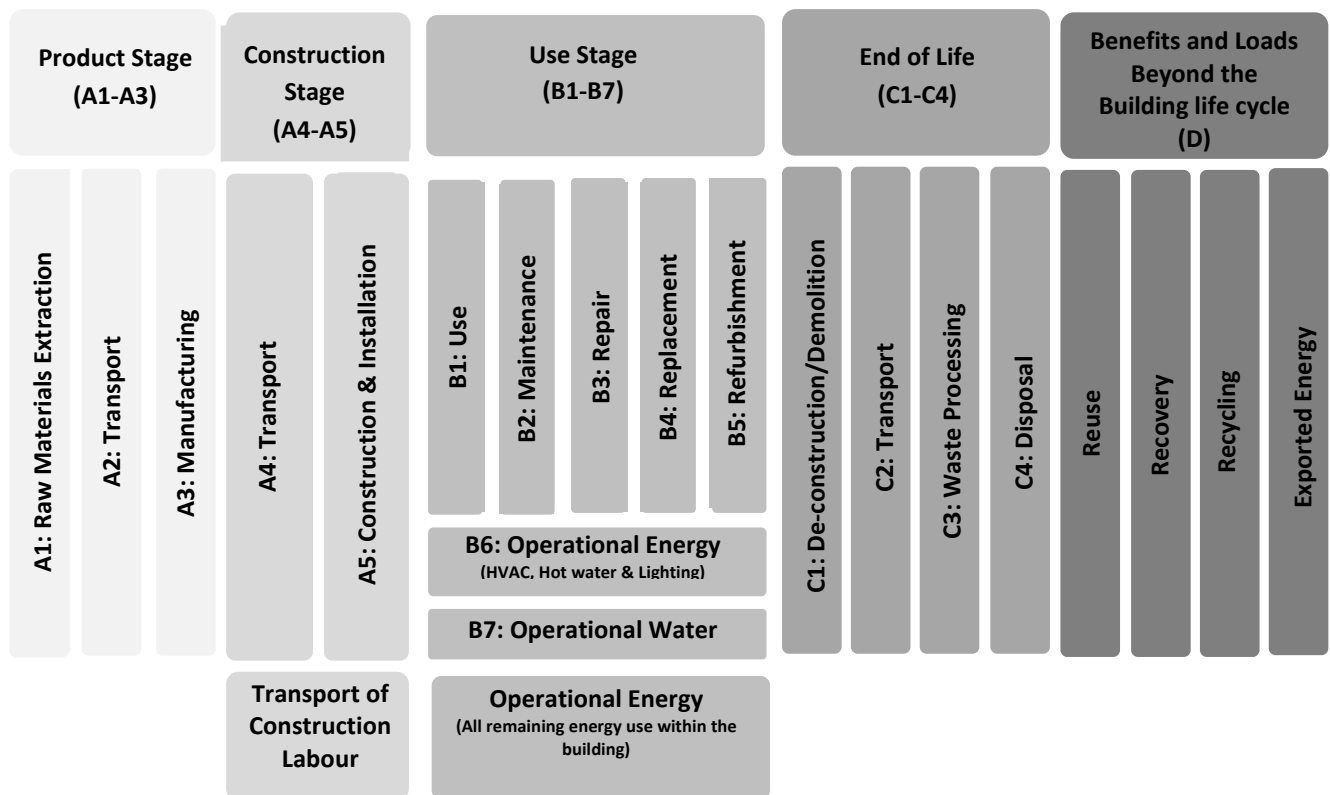


Figure 1. Standard EN 15978 delineates the different stages of a LCA of a building, providing a standard way of conducting a LCA (CEN - TC, 2011).

Energy’, represents the energy used by appliances such as computers, televisions and refrigerators. This is beyond the scope of the instrument, and is besides targeted more effectively by a number of other instruments. The last stage, D, is an optional stage that can be included within an LCA to show potential benefits with a certain material or way of building.

The conventional understanding of the split between embodied and operational carbon is a 20/80 split (see e.g. Adalberth, Almgren, & Holleris Petersen, 2001). However, as the stringency of the construction standards is continuously increasing in terms of their requirements for energy consumption, the carbon content of construction materials become increasingly prominent in the carbon footprint of buildings. In the United Kingdom, studies conducted by industrial actors such as the UK Embodied Carbon Industry Task Force and the UK Green Building Council (UKGBC) show that the current levels of embodied carbon within buildings in the UK cover 30-70% of the lifetime carbon emissions (Embodied Carbon Industry Task Force, 2014). The span depends on building type and use – for example, for a warehouse with a low need for heating, embodied carbon can account for 70% of the total life cycle climate impact. In a semi-detached residential house, however, the split is approximately 35/65, with operational carbon taking the larger share (Lockie & Berebecki, 2012).

Total Operational and Embodied Carbon Split in different scenarios (OC/EC in tCO _{2eq})							
100 m ² apartment used for 60 years		Energy consumption (kWh/m ² /year)	Embodied carbon (tCO _{2eq} /m ²)				
Grid emission factor (kgCO _{2eq} /kWh) ²	0.7		0.85	0.6	0.5	0.25	0.1
		150	630/85	630/60	630/50	630/25	630/10
		100	420/85	420/60	420/50	420/25	420/10
		60	252/85	252/60	252/50	252/25	252/10
		35	147/85	147/60	147/50	147/25	147/10
	20	84/85	84/60	84/50	84/25	84/10	
	0.35	150	315/85	315/60	315/50	315/25	315/10
		100	210/85	210/60	210/50	210/25	210/10
		60	126/85	126/60	126/50	126/25	126/10
		35	73.5/85	73.5/60	73.5/50	73.5/25	73.5/10
20		42/85	42/60	42/50	42/25	42/10	

Table 1. Displays the total carbon emitted by both the operational and embodied phases of a 100m² apartment used for 60 years in different scenarios. The energy consumption scenarios are chosen to reflect current as well as future levels of energy consumption. The range of embodied carbon/m² is derived from what Balson, Lowres, & Johnson, 2011 as well as Liljenström et al., 2015 finds in their studies.

² The grid emission factor refers to the average GHG emissions from all generation units on the grid that are caused by the production of 1 kWh of electricity delivered to the grid, whether the grid is electrical or heated or cooled water. Grid losses are not included and should in principle be added.

Table 1 is meant to illustrate the split between operational and embodied carbon, and its dependency on the grid emission factor of energy. It is a simple calculation based on reasonable options for construction and operational carbon. The figures are naturally under significant influence of the emission factor³ for the energy consumed by the building. For ease, the electric grid emission factor is used. In a setting with a relatively high grid emission factor of 0.7 (corresponding to the average of Africa or Central & Eastern Europe, but less than China), the embodied carbon only starts becoming significant if construction standards prescribe less than 100 kWh/m²/year. This is the upper bounds of the current level of the building code in, for example, Sweden – the Swedish regulation limits energy consumption for multi-family houses with electrical heating to 85-45 kWh/m²/year depending on climatic zone (Boverket, 2015a) – but significantly above the standard in Denmark (2015: 30 kWh/m², 2020: 20 kWh/m²; Bygningsreglementet.dk, 2016a, 2016b). However, as grid emission factors keep falling due to increasing penetration of renewable energy, at least in some countries, a more realistic picture may be a grid emission factor of 0.35, corresponding to the Danish grid emission factor. Countries that predominantly use hydropower, such as Sweden and Norway, obviously have much lower factors. Even with a high grid emission factor of 0.7, an embodied carbon level per m² of 0.85 tCO₂e balances with operational carbon on low consumption levels of 20 kWh/m²/year. At a lower grid emission factor of 0.35 and consumption of only 20 kWh/m²/year – i.e. what the Danish conditions will be like in 2020 – embodied carbon is in fact the largest source of emissions for all except the two lowest levels of embodied carbon, as included in Table 1.

Materials Responsible for Embodied Carbon

There appears to be an overdue need to account for embodied carbon - but which materials does it stem from? Embodied carbon, ideally, incorporates the GHG emissions from the material manufacturing, construction itself, maintenance and refurbishments, as well as the end-of-life phase, the phases represent varying shares of the climate impact. As reported in Soulti & Moncaster (2014), Gavotsis finds that transport, construction and end-of-life account for 8%, 7% and 4%, respectively, while the manufacturing of the building material is responsible for 50% of the embodied emissions, and the refurbishment for 31%. Within the refurbishment, it is the use of materials that carries the largest impact. Liljenström et al. (2015) found similar results in a Swedish perspective, as did Birgisdóttir, Mortensen, Hansen, & Aggerholm (2013) for a Danish office building.

³ A grid emission factor can of course equally be calculated for heat or gas fed into the building. It does not have to be electricity.

The degree of embodied carbon for a given building will ultimately depend on the choice of materials for construction. It is difficult to generalise on a global scale, as the conventional way of constructing a building is highly dependent on geography – traditions have developed over time depending on which resources have been abundant in the surrounding area and the prevailing weather conditions (Asif, Muneer, & Kelley, 2007). However, common traits do appear. Figures 2, 3 and 4 display the percentage split of CO₂ emissions per m² for typical houses in Spain and Sweden, and for an office building in Finland⁴. In the Spanish case, cement has the largest share, at 30%. If mortar and lime are added, as both are ingredients used to make concrete (which is the level this is aggregated in the other two cases), the share increases to 45%. Concrete, including pre-fabricated concrete, shoulders the lion’s share in the Swedish case, while the Finnish building seems to have a steel frame instead. Steel, however, is significant in all three cases. The results diverge with ceramic tiles appearing in the Swedish and Spanish

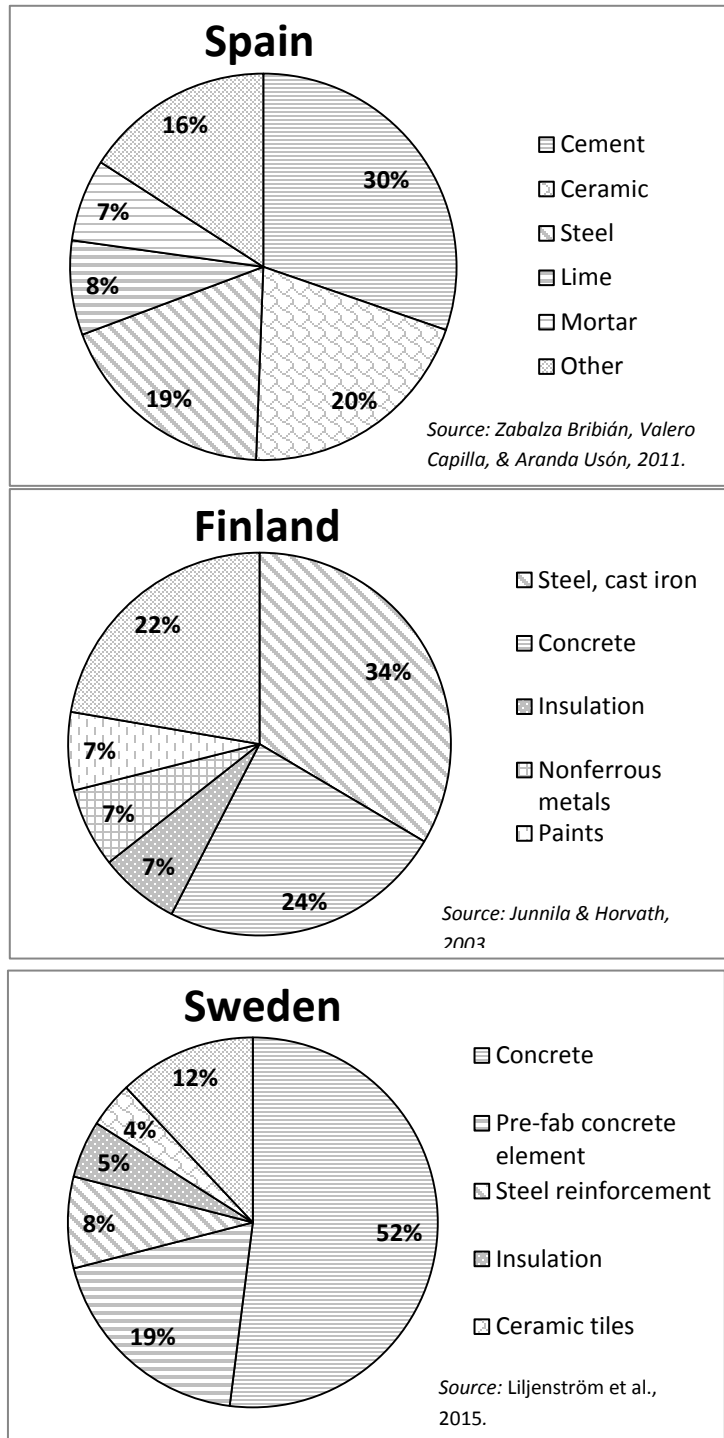


Figure 2, 3 & 4. Displaying the materials and their respective percentage splits of embodied carbon emissions for buildings in Spain, Finland, and Sweden.

⁴ Comparisons between these diagrams should be made with caution as the numbers report different aspects. The Finnish case, for example, only reports the CO₂ emissions caused while the other two studies report climate impact. Furthermore, the Finnish case includes materials used in both the initial construction as well as maintenance of the building, while the Swedish and Spanish cases report just the initial construction. The Swedish case uses concrete as one building material category, while the Spanish case breaks it down to e.g. cement, additives, and lime.

cases, and aluminium and paint in the Finnish case. Hence, concrete, cement and steel appear as the materials most significant in terms of embodied carbon.

There are several ways to address the emissions from materials manufacturing – see Fishedick et al., (2014) for a good overview – captured under three main headings for the construction industry:

- 1) to increase material efficiency (i.e. use less material),
- 2) to choose the same materials but with less embodied carbon (i.e. manufactured more efficiently or with less ‘carbon’ input),
- 3) to fully substitute one material with another.

In addition to these three options, there is the reduction of the carbon content of the energy input, which is the one factor that can have the greatest spillover impact on other sectors – unless the energy input is delivered through a captive energy production unit, i.e. the manufacturers own energy supply.

Increasing material efficiency reduces embodied carbon, as less material needs to be manufactured. The IPCC points to, for example, possibilities to reduce the use of cement by 40% by using curved moulds instead of standard ones (Fishedick et al., 2014). The European Union (EU) also suggests this as a way forward to reduce the life cycle impact of buildings in its ‘Roadmap to a Resource Efficient Europe’ (DG Environment, 2012). There are also possibilities to reduce the materials needed by changing the design of the building, e.g. by reducing the building height, which would then influence transport carbon during usage of the building’s shifting vertical transport carbon to horizontal transport carbon⁵. Additionally, the strength of materials can be increased in order to reduce the amount needed. This is relevant for both concrete (Fishedick et al., 2014, p. 759) and steel (see e.g. Jernkontoret, 2015). Reddy (2009) investigated the reduction potential of the embodied energy of a number of building materials and found that through the use of alternative low-energy materials, a reduction of embodied energy of up to 50% was possible. Therefore, there is a considerable reduction potential of carbon emissions within the material manufacturing industry.

Nevertheless, it is important to keep in mind that emissions from material manufacturing are in some cases not only attributable to heat and electricity use, but also for process emissions. These are chemical reactions inside the production process itself, especially in cement and steel production (Fishedick et

⁵ Such considerations are normally captured in ‘Transport Oriented Development’ projects (-- see e.g. the NAMA Facility supported project in Colombia (NAMA-Facility, 2014). Interestingly, vertical transport carbon (elevators and escalators) is never considered as transport, but as general power consumption together with lighting, ventilation and other ‘community power consumption’ in housing block communities.

al., 2014). For cement, ‘unavoidable’ process emissions are responsible for 50% of the emissions (Fischedick et al., 2014, p. 758)⁶.

On the whole, these two factors - the consumption of energy for the manufacturing of construction materials, and the energy consumption when the building is used - make the construction sector⁷ the largest singular source of GHG emissions, by far. However, there is close to no regulation currently in place targeting the reduction of embodied carbon in buildings.

Current Regulation of the Sector

The construction sector is accustomed to regulations. These stem from all levels of government: local, regional, national and supranational. At the supranational level, the EU has several policies in place addressing the building sector. The Energy Performance of Buildings Directive (Council Directive 2010/31/EU) and the Energy Efficiency Directive (Council Directive 2012/27/EU) are presented as key legal acts to reduce the energy consumption of buildings. While neither of these address embodied carbon, legislation currently under development is intended to do so. The EU has launched a ‘Communication on Resource Efficiency Opportunities in the Building Sector’ (Commission Communication COM(2014)445 final). As the title shows, the focus is on resource efficiency rather than embodied carbon, but the two issues are closely connected. The Communication describes how another document, the ‘Roadmap to a Resource Efficient Europe’ (Commission Communication COM (2011) 571) emphasises that policies need to look at the environmental impact from a life-cycle perspective in order to achieve the goals. New policy instruments are necessary (COM(2014) 445). It is further underscored in ‘Roadmap to a Resource Efficient Europe’ as it states that “it is not expected that significant improvements will be achieved in resource efficiency with the current policy context” (DG Environment, 2012:2). It sketches out possible policy options to be investigated, highlighting that the European Commission is in the midst of formulating policies which includes instruments directed specifically at embodied carbon.

Nationally, building codes are seen as an effective instrument to generally improve buildings’ performance (IEA, 2013). They exist throughout the world and many include standards for energy consumption. However, in many cases the codes are not compulsory (BCAP, 2009a, 2009b), as in numerous US states and in India. As these are countries, along with China where much of the future construction will happen – China will also continue constructing large quantities of new buildings, but

⁶ There are, however, ways to reduce the need to create it, or to prevent it from escaping into the atmosphere. The IPCC highlights improving material efficiency and reducing demand as the two major ways forward. There are also discussions of initiating pilot projects to install Carbon Capture and Storage technology (see e.g. Energiforsk, 2015 for a Swedish example). This applies both to steel and cement manufacturing, as both processes have considerable ‘unavoidable’ process emissions. However, the IPCC report states that numerous barriers still prevent this from commercial scale development (Fischedick et al., 2014).

⁷ This includes construction of both infrastructure and buildings.

has a mandatory building code. Lack of enforcement is often due to generic building regulations commonly being developed and issued at the national level, while enforcement is expected to happen at the local level, where interests may be more easily compromised. In places where building codes are mandatory and include requirements on energy efficiency they are believed to generate impact cost-efficiently, especially when combined with other measures (IEA, 2015).

Cities' Potential Role

Cities have a large potential influence over the construction industry. Nearly all building constructions require city government approval. This is an immensely powerful instrument, which cities commonly use prudently in order to keep a good collaborative relationship with developers and the industry, in order to support development. The two parties are obviously mutually dependent, but the cities' regulatory authority potentially puts them in a central role for reducing the construction sector's carbon footprint.

Cities have been addressing climate change for several years (Bulkeley, 2010; Rosenzweig, Solecki, Hammer, & Mehrotra, 2010) though. Some cities have joined together in organisations such as C40 (a network of the world's megacities committed to reducing GHG emissions), ICLEI (an organisation bringing more than 1,200 local governments together to work on sustainability), and Covenant of Mayors (a primarily EU initiative where local actors pledge to implement policies to help reach the EU's overall targets). The importance of cities is also highlighted in the Paris Agreement (134), and they are encouraged to scale up their efforts (135) (UNFCCC, 2015). Cities look at both mitigation and adaptation efforts, and ideas that contain elements of embodied carbon accounting have in fact been floated. Almost ten years ago, researchers from the University of California proposed the introduction of city-based carbon budgets for buildings and transport in order to mitigate GHG emissions (Salon et al., 2010). Their suggestions, however, only targeted the operational carbon for the buildings, neglecting the increasing climate impact that the embodied emissions have. Since then, ambitious city programmes have been introduced that target operational carbon through focusing on energy use and efficiency. Examples are Tokyo's Cap-and-Trade programme for buildings, or New York's Greener Greater Buildings Plan (WGBC, 2013). However, recent policy development, at the city-level, regarding embodied carbon emissions in buildings has been observed in a number of countries. A few British municipalities have moved on and already started experimenting with concepts that sensitise the construction industry to its overall carbon footprint (as an example, see Brighton & Hove, 2011). There are also a few Swedish municipalities that have taken initiatives to address the GHG of building materials. Linköping municipality, for example, a city of some 100,000 inhabitants favours buildings with wooden frames in the construction of a new city district (Linköping Municipality, 2014).

Therefore, rather than document why such an approach is not practicable, it is more interesting and beneficial to analyse *how* this just might be done. Current regulations have been effective in fostering energy efficiency in buildings. The next, and increasingly important, step would be for the city regulators to take on embodied carbon.

The Model: Carbon Budgets for Buildings

The answer is carbon budgeting that combines the two main sources of emissions from the construction sector – the operational carbon that is currently indirectly targeted by building codes, and embodied carbon that generally is not addressed. The ultimate objectives are to: 1) reduce the carbon intensity of the production bases, and 2) inspire the substitution of carbon intensive construction materials with less intensive ones. The objective is not to replace the current building code requirements on energy efficiency, but to provide a context under which the materials used to achieve a given level of energy efficiency are also considered. The first point mainly targets the energy input to manufacture, where the industry can respond to high grid emission factors, either by establishing low-emission captive power production or, more long-term, trying to influence energy policies towards greater adoption of emissions-free energy. The second point is more focused on process carbon – central products like cement and steel – which cannot be influenced easily and, therefore, currently, can only be avoided by product substitution or increased efficiency in material usage.

What is in a Budget?

The budget must cater to the building's carbon footprint, consisting of both embodied and operational carbon over a number of years, providing a reasonable balance between operational and embodied carbon. Specifically, the duration of the budget and the accounting period must roughly achieve balance between embodied and operational carbon, rather than 'importing' the industry's apparent common practice of using a period of 50-60 years as the default budget period (see e.g. Balson, Lowres, & Johnson, 2011; Cabeza et al., 2013; Liljenström et al., 2015) Balson, Lowres, & Johnson, 2011; Cabeza et al., 2013; Liljenström et al., 2015). This, obviously, will leave some long lasting materials, like cement and steel, at a disadvantage and will favour short-lived products that need to be replaced at intervals that suit the chosen carbon budget period. Such issues must be factored into the budgets.

Also, as the ultimate purpose of regulating the embodied carbon is to influence manufacturing, or choice of manufacturing bases and secondarily choice of material, the issue of treating buildings from a full-fledged LCA approach, although relevant, has less merit in this context. For the model to win ground, it cannot conjure considerable resistance from the industry. As conducting a fully fledged LCA is an onerous process, as it would be met with much resistance. Rather, an LCA perspective should be adopted at first, which provides a good idea of the distribution of climate impact. As data is collected and the knowledge of performing LCAs grows, it would be possible to gradually increase the scale of the LCA. The budget will be allocated as part of the construction approval process.. A 'carbon budget' is assigned by the city to a particular construction permit, specifying a maximum allowed amount of GHG emission. The responsibility of monitoring, reporting and verifying the GHG emission change is left to the constructor. The sector routinely predicts the energy efficiency levels of buildings, and as described above, the construction industry has also developed methods to account for the embodied carbon. . The issuing of permits will work in the same way as any other approval process in which developers are to observe general building codes and specific local regulations, for example, regarding the height of buildings or the usage in certain parts of a city (laid out for offices, industry and/or residential usage) - if the requirements are not met, no permit will be issued. It is also up to respective city to set the budget in accordance with local conditions and traditions.

It is evident that part of a building’s budget usage is already given as ‘shadow consumption’ from cohering to the building code, which prescribes a given level of energy efficiency. Therefore, the approach to policing the building code can be incorporated into the model. Energy efficiency of buildings is often assessed ex ante, i.e. the construction must comply with the standard based on the calculated operational performance of the materials employed and the designs chosen. It is, therefore, independent of the users and how many electrical appliances they choose to buy. Knowing the emission factor of energy at the location, the annual energy consumption of the building can be multiplied with the number of years for which the budget is issued in order to first calculate the operational carbon and thereafter assess how much budget remains for embodied carbon, so that, combined, they comply with the carbon budget restriction. Developers in countries with highly ambitious building codes have already moved beyond, and include own generation – typically solar PV – as part of the building design. Such captive power production allows developers to manipulate the operational carbon in order to allow more space for embodied carbon.

Calculation of carbon budgets

From a city regulator’s perspective, getting the budget right from the outset is essential. A budget too tight will hamper construction activity; too lax will miss the chance to influence the industry. Additionally, the effect on the general housing price levels would need to be considered, particularly because the carbon budgets only apply to new buildings and not existing building mass. Even though increasing prices of dwellings per square meter have a positive – from a climate change mitigation perspective – effect of decreasing the average sizes of dwellings, such trends are unlikely to be considered beneficial from a city administration and local social policy perspective.

Examples of current carbon content of buildings in Scandinavia are indicated in Table 2, indicating the balance between embodied and operational carbon. While this could serve as inspiration for benchmark setting, a geographical variability must be incorporated according to particularly climatic conditions.

Table 2. Examples of embodied carbon in buildings. Various sources.

Building Type	Division EC/OC (percentage split)	Country	Source
Residential Building	50/50	Sweden	(Liljenström et al., 2015)
Office Building A	75/25	Denmark	(Birgisdóttir, Mortensen, Hansen, & Aggerholm, 2013)
Office Building B	28/72		
Office Building C	36/64		
Office Building D	21/79		
Office Building E	41/59		
Office Building F	33/67		
Office Building G	35/65		

Note: Data availability is very limited, hence the limited geographical distribution

It is likely that technological development, as well as significant operational learning in the construction processes can help drive embodied carbon downwards. New trade-offs will evolve, for instance balancing embodied carbon in insulation materials with their emissions reduction effect over the period for which the carbon budget is allocated. Therefore, budget allocation per square meter must naturally be adjusted downwards over time to achieve the desired emissions reduction effect. The transparency of such gradual reductions is important in allowing the industry to prepare, for example, by publicizing the carbon budget allocation per square meter according to year of permit for the following 5 or 10 years – e.g. 3.5 tCO₂e/m² for buildings permitted up to 2020, 3.0 tCO₂e/m² permitted up to 2025 and 2.5 tCO₂e/m² up to 2030. This is reported to have worked well in Denmark for energy efficiency, as the relevant authorities keep multiple future versions of regulations publicly available years in advance (Bygningsreglementet.dk, 2016b; IEA, 2015). This practice also provides time for the industry to prepare for the operationalization of the system.

Allocation of Budgets

Carbon budget allocation for construction may either be grandfathered or charged for. Grandfathering means that the budget is allocated for free and this approach thus provides no income opportunity for the city, leaving the developers with only the budget challenge to comply with and not an additional cost to purchase the required carbon budget. The alternative is that the city charges a fee for the budget, which beyond the possible income generation for the city may also have developers to consider how small of a budget they can do with, potentially beating the norm. This might also inspire a desirable race to the bottom (in terms of emissions per square meter).

While there are two options for the allocation of initial budgets, there are also two optional approaches for extending them: 1) carbon budgets are set without allowing topping up – i.e. a fixed budget that is enforced through strict penalties, or 2) the city establishes a pricing policy for adding a new carbon budget to the account once the initial assigned budget is depleted. The former approach is the one this paper advocates for, thus requiring the municipality to be more technical in its assessments of available construction options, in order to get the budget right. It is the preferable option for a number of other reasons as well, the most important of which is the traditional owner/tenant conflict of interest.

Allowing topping up would encourage developers to use more carbon budget for construction, contrary to the purpose of the model, leaving future owners and tenants to take care of the topping up. Topping up would, therefore, require significant constraints to be added, which would need to be administered and monitored. Further, they only pertain to operational carbon, which is already indirectly targeted by current energy efficiency regulation. Therefore, topping up provides very little additional benefit to the model, while adding significant levels of complication. Prices would need to be at a level that unequivocally encourages prudence in the consumption of initially assigned, or purchased, budgets, but such prices could easily come under pressure. It would also require constant calculation of the operational carbon of the building with all the complications that this entails: multiple tenants, changing grid emission factors and lack of options to differentiate among different sources of consumption. Ex ante assessment of operational carbon is, consequently, much easier to administer and fundamentally aligns with current practices of applying construction standards – building codes – for grid electricity and heating.

Trading

Some may instantly think of carbon trading as a means of complying with allocated budgets. However, unless trading is kept strictly within city borders, carbon trading adds nothing to the objective, but rather subtracts from it. Intercity trading adds requirements on the fungibility of carbon budgets (a ton is a ton – or not) and comparability of conditions, e.g. climatic conditions and energy emission factors as well as cities' ambition and intended trajectory for local building's carbon footprint – i.e. how tight the budget is. Differences would challenge the exchange of carbon budgets beyond the city border. Even if kept inside city borders, trading may pose unwanted challenges in terms of market control to prevent other unintended circumventions on e.g. vintage of budgets, abandoned buildings and over-allocation that may hamper a gradual reduction of budgets over time. Intra-city trading of allocated budgets may become an option at a later stage when significant experience with such carbon budgets has accrued and budgets are tightened significantly. Only with such established experience can it reasonably be predicted how a trading option will influence the system. Therefore, in the short and medium term, trading would be an unnecessary complication of the model.

New Versus Existing Buildings

In most cities the existing building mass far outweighs the new construction. Does carbon budgeting make sense for existing buildings? The main objective of introducing carbon budgets for construction is to sensitise developers to the carbon content of the construction itself. Therefore, it has no relevance for buildings that are already constructed. If behavioural change is sought in the usage of existing buildings, including the improvement of their energy efficiency, there are more useful instruments available, like the compulsory phasing out of certain energy inefficient technologies – for instance, inefficient split A/C units. Hence, at least initially the existing building mass should not be targeted with carbon budgeting. It is possible, however, that carbon budgets for deep renovation (e.g. changing an industrial building into apartments) could benefit from a similar approach, considering the renovated building a new building with a different kind of materials and energy demand and a corresponding budget.

Although old and new buildings compete for the same buyers and/or users, the carbon budget, in practice, only introduces a new restriction on embodied carbon -- operational carbon is already addressed by building codes' energy efficiency regulation. It is not self-evident that considerations of embodied carbon automatically increase costs of construction. At the least, moderate reductions of embodied carbon have even led to cost reductions (as inter alia demonstrated in a number of projects listed by Skanska. See Skanska, 2012 for further information).

What is in it for Cities?

If the ultimate objective is to influence the production bases, what are the interests of the hosting city governments? What is in it for them?

Cities have acted on climate change for at least the past 20 years, so this, in itself, is not new. Bulkeley (2010) describes how a first wave of mainly middle-sized cities in North America and Europe started to address climate change in the 1990s. In the early 2000s, a second wave of more geographically

dispersed cities emerged, including many in developing countries. A growing number of cities address more than just adaptation, which is rapidly becoming an issue of mainstream urban planning, globally. These cities adopt ambitious emissions reduction targets, many aiming at becoming carbon neutral at a given point in time, e.g. Copenhagen by 2025 (the Carbon Neutral Cities Alliance was established in 2014 with initially 17 signing cities; see (CNCA, 2014)). Other cities establish energy efficiency programmes in public buildings, improve traffic planning, introduce electric mobility strategies or change city lights to LED, just to mention a few initiatives. Some initiatives are profitable and have other drivers; some come at a net cost and can only be seen as political positioning – or as a genuine concern for the climate and a will to act.

Bulkeley (2010) highlights certain factors that are important for a municipal action on climate change to be successful; political communication is an important factor in two aspects. First, the action has to entail an opportunity to display leadership. Carbon budgets provide such an opportunity, as there are still only a few cities and policies in place that address embodied carbon. Second, the climate action needs to be framed so that it generates additional benefits. Examples of this are actions that not only reduce GHG emissions, but also air pollution and, subsequently related health issues.

Very few cities have targeted embodied carbon within buildings (see e.g. Boverket, 2015 for an overview), but according to the above observations, the novelty of the idea is in fact a potential success factor. If a city were to introduce carbon budgeting for embodied carbon in buildings, it would spearhead a development and become a frontrunner towards taking a life cycle perspective on emissions from buildings. So how many spearheading cities can the world host? Cities compete on different parameters (green/sustainability, business environment, living conditions etc.) at different levels; megacities compete globally, while second and third tier cities compete at more local levels. Many cities compete with their neighbours. Spearheading, therefore, is not necessarily an objective that allows only a small collection of cities to join.

Moreover, carbon budgets have additional benefits as they may place the local construction material industry in a stronger position. Transport only accounts for a minor part of the embodied carbon (see Liljenström et al., 2015), so this element is quite limited. There is, however, more to it. Cities with objectives of carbon neutrality need to eventually include strategies for reducing the carbon intensity⁸ of the local economy. That would include investments in energy production, e.g. co-generation or renewable energy sources.

Essentially, cities that add to their climate change agenda by introducing a carbon budgeting model for building construction projects within the city boundaries are putting their money where their mouth is. The local industry will reap the benefits of the city's effort to become carbon neutral: local

⁸ Commonly carbon emissions per unit of GDP (at national level), but can equally be calculated for a subset of the economy like a city

manufacturing would unavoidably come closer to carbon neutrality in the process, mainly benefiting from lower emission factors, and locally manufactured construction materials with low levels of embodied carbon would obtain a ‘free’ competitive advantage. Hence, establishing carbon budgeting is not only logical, but it also creates additional benefits for climate conscious cities as they capitalize on their green strategies by, in effect, benefiting local industry. They may do so possibly without even violating any trade policies.

Another potential benefit derives from material substitution. Currently, material substitution comes quite far down the line of possible measures to reduce embodied carbon – improving production processes of conventional material and changes in building design are higher up on the list. However, as carbon budgets grow tighter, and the construction industry gets used to taking the carbon content into account, material substitution might become a more interesting option. While some of these materials exist today, such as timber, the vastness of the construction industry’s material need might provide economic incentives to innovate and develop alternative materials, or indeed find new uses for materials beyond already known practices of recycling. Cities, or city networks or others that would help pioneer innovation and development of such material solutions, may reap additional benefits.

The Industrial Response

Introducing carbon budgeting for the construction industry seems an overwhelming task – one involving a global industry, a novel approach, and a significant demand for data. Meanwhile, all of this is to be targeted and inspired by a few pioneering cities. Would the industry take it seriously and is there any chance that it would take off?

The foundation for a development towards carbon budgets for the construction industry already exists, and the industry itself has been pushing the development of standards for how to calculate and report the embodied carbon in buildings. The previously mentioned EN 15978 issued by the European Committee for Standardisation (CEN) in 2011 is central to this, building on a number of standards relevant for calculating the GHG emissions from buildings based on LCA. Prior to this, significant work had been done by the International Standards Organization (ISO) in collaboration with industry, on the ISO 14040 standard series⁹, which today include two standards that are relevant: ISO 14040:2006 laying down the principles and framework of how to conduct an LCA, and ISO 14044:2006 that introduces standardised requirements and guidelines (ISO 14040, 2006; ISO 14044, 2006). Further, ISO 21930 (2007) provides “a framework for and the basic requirements for product category rules [...] for type III Environmental Product Declarations (EPD) of building products” (ISO, 2015a). It incorporates Product Category Rules (PCR) specifying system boundaries and data requirements for an LCA for a specific product.

⁹ ISO 14040 (1997): Principles and framework, ISO 14041 (1998): Goal definition and inventory analysis, ISO 14042 (2000): Life-cycle impact assessment, and ISO 14043 (2000): Life-cycle interpretation.

Building on these tools, the industry has included considerations of embodied carbon within the green building certification schemes to spur further development (Boverket, 2015b). The most globally used certification scheme, BREEAM, has included aspects of embodied carbon for several years. For LEED, the second most used scheme that is especially prevalent in the US market, criteria regarding embodied carbon has only been introduced in the newest version four (USGBC, 2013). German DGNB bases its evaluation of the building material solely on LCA data, thus making LCA an integral part of the environmental impact assessment (Schmidt, 2012). There are also on-going discussions within the Swedish system, Miljöbyggnad, to include considerations of embodied carbon (SGBC, 2015). While these standards increase their demands, so do general building codes.

The shortcoming of the industry-led standards is, of course, that their usage and compliance with their demands is voluntary. It does not constitute regulation and, therefore, oftentimes leads to the building

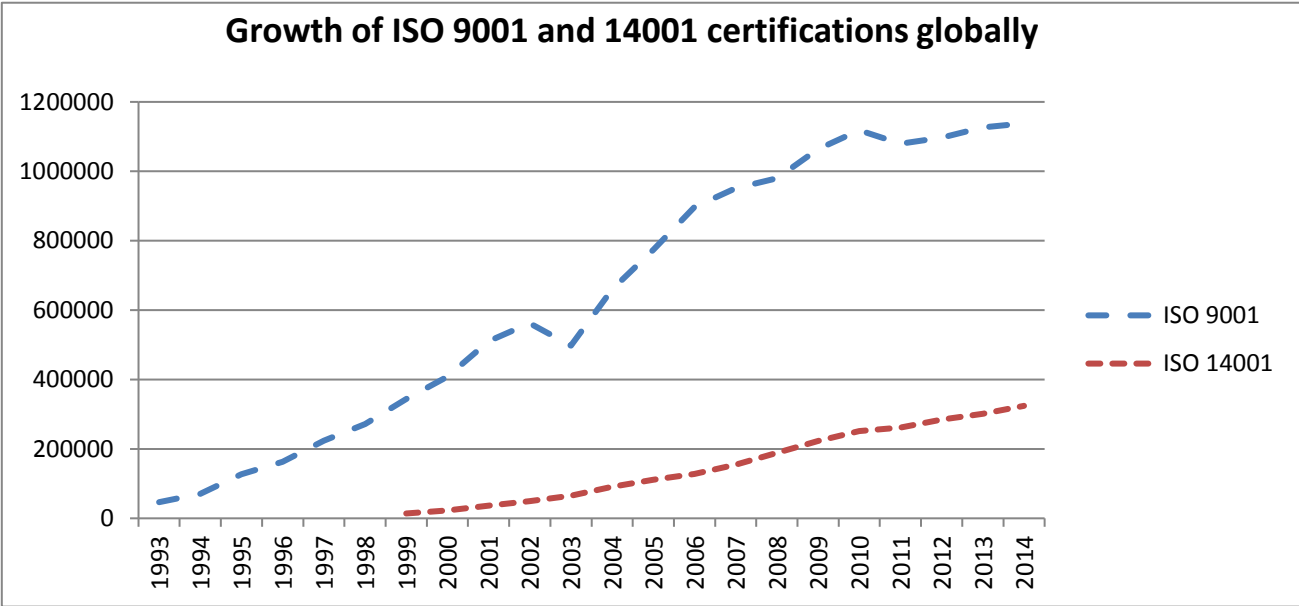


Figure 5. The growth of ISO 9001 and ISO 14001 certifications globally over time (ISO, 2015b).

of a few ‘lighthouse’ examples in a few cities, while hundreds of buildings are being built around them according to traditional building standards – and at times, not even that. Moreover, the overwhelming majority of certified buildings are commercial. Residential buildings have not been considered relevant for certification, thus far, leaving a considerable number of buildings outside the scope of these schemes. Rademaker (2014) states that the market for residential building certification is not mature. While there are certified residential buildings through BREEAM, LEED and other schemes, these only constitute a minor part. For example, less than 5% of the LEED certified buildings in the USA are multi- or single-family houses, and the numbers are similar in other countries (USGBC, 2015). Thus, the current certification schemes do not cover embodied carbon satisfactorily.

With recognized methodologies and standards available, it is entirely possible to calculate the embodied carbon of a given building. An existing challenge is data availability from the flow of materials and production processes between different companies and between countries. A construction company would have to require all the actors involved in its supply chain to provide the needed information to

perform the GHG calculations. While seemingly overwhelming at the outset, such industrial demands for provision of proof throughout the manufacturing value chains are not without parallel in history.

ISO introduced ISO 9000 for Quality Management in 1987 -- a quality assurance system documenting every step of production and defining procedures to assure a constant and consistent level of production. The system was particular in requiring a similar level of quality assurance among suppliers of components, many of which were small and medium sized, even micro sized, companies (Corbett & Kirsch, 2001). These small companies initially believed that the requirements meant certain death. The costs of introducing and maintaining such quality assurance were considered insurmountable (Frost, 2002; Lamprecht, 1992). However, a few years later no one discussed ISO 9000 anymore. Everybody had it, and was realizing the benefits of having systematized production -- even economic benefits that in many cases outweighed the cost of introducing the system. Today, the sheer extent of ISO 9000's global adoption makes it a critical 'business standard' that companies often find has become a 'qualifying criterion' in the global market. As such, companies seek certification regardless of whether they expect or believe the need for improvements in quality. In certain industries, ISO 9000 has even become a governmental requirement (Corbett and Kirsch, 2001).

After the successful introduction of the ISO 9000 standards from 1987, the ISO 14000 series of environmental management systems standards was introduced in 1996 to ensure safe handling and disposal of hazardous materials, communication with interested parties, etc. (Corbett & Kirsch, 2001). The ISO 14000 series is now following its predecessor's footsteps. Figure 2 displays the development of the number of certifications issued globally for both ISO 9001 and ISO 14001, the main standard in each series respectively. In both cases there were no data at the outset; it had to be created through ISO certification that involved advisers who could guide companies in documenting their processes. Among these were also companies, for which the processes could not ensure a uniform product quality, thereby, requiring them to shape up in order to stay in the market. This would also be the case if the calculation of the amount of embodied carbon becomes a challenge for the product in the market.

Some companies report that the ISO 9000 implementation has paved the way for an easier ISO 14000 implementation. Half of the ISO 14000 certified companies in the United States see the experience with ISO 9000 as a motivating factor for achieving ISO 14000 certification (Corbett and Kirsch, 2001). But why did companies choose to become certified?

Drivers for ISO Certification

The proportion of certified companies can vary from sector to sector, and drivers for certification vary from company to company and region to region. In the USA, both governmental requirements and export considerations have been significant drivers for certification, together with companies' aspiration to improve quality and reduce cost, while in Western Australia, for instance, external drivers such as customer requirements were regarded as more important. Companies in developed countries generally do not consider certification a central non-tariff barrier to trade, and many companies follow practices even beyond ISO 14000 standards. In highly globalized manufacturing sectors there are even concerns of being excluded from export markets if an ISO 14000 certification cannot be demonstrated -- companies such as IBM and Bristol-Myers Squibb have encouraged their suppliers worldwide to become

ISO 14000 certified. The public sector is also creating a push for certification; non-environmental regulatory bodies such as the Ministry of Economic Affairs in Taiwan and the Ministry of International Trade and Industry (MITI) in Japan encourage certification -- although mostly for export-related reasons (Corbett and Kirsch, 2001). See Figure 3 for an overview of motivations.

Generally, there seems to be a certain correlation between national environmental attitudes and ISO 14000 certifications. It may be entirely possible that a push for carbon budgets in the construction industry could ride on a growing trend among countries and companies with high environmental awareness, particularly where there are already high levels of ISO certification.

Reasons for certification	Manufacturing		Service		Construction		Total		Development of ISO 9000 certification
	(M)	(%)	(M)	(%)	(M)	(%)	(M)	(%)	
To satisfy customer demand	10	12	3	5	36	39	49	21	165
To stay in business	22	26	15	26	30	33	67	29	
To improve management	41	48	30	53	9	10	80	34	Table III. Reasons for certification (all firms)
More than one answer/others	13	15	9	16	17	18	39	17	
Totals	86	100	57	100	92	100	235	100	

Figure 6. Overview of the reasons firms in Hong Kong, China became ISO 9000 certified (Lee, 1998).

Challenges and Perspectives

From a global perspective there are a number of challenges to the idea of carbon budgeting for building constructions in cities, the most obvious being getting countries and regions on board where the construction activity is the most significant. The question then becomes, how does doing carbon budgeting in a third of Europe help when half of the world’s construction takes place in emerging countries (Global Construction Perspective, 2013)? That depends on the time perspective and the efficiency with which the supply chains will do their part – apart from the obvious chance that cities in emerging countries begin to adopt the idea as well.

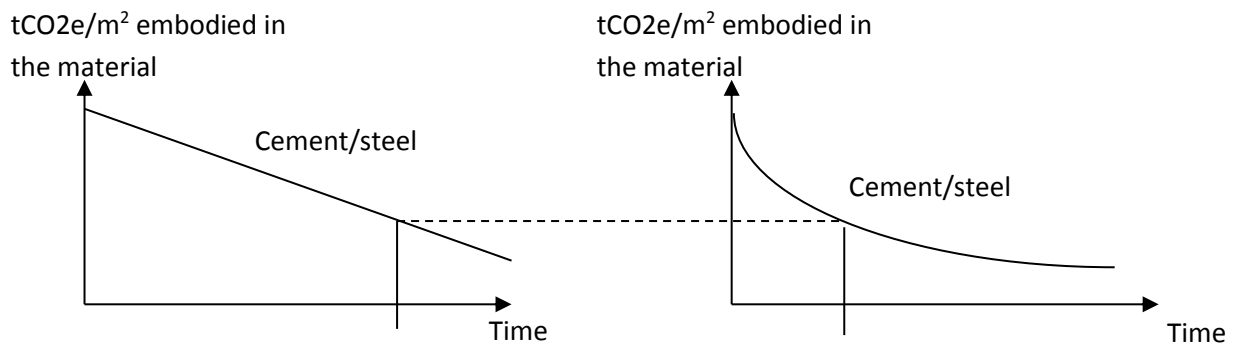


Figure 7. Illustrating how different ambition levels of cities affect the decrease of embodied carbon differently, and its effect on the time required.

The scenario may not pan out exactly like the roll-out of the ISO 9000, because the central supply chains on steel and cement are shorter. In order to come closer to an ISO 9000 scenario, other more processed products with longer and more global supply chains would have to come into focus. That, again, would depend on the ambition of the involved cities, and their strategies for tightening the budgets – the slope of the curves for future carbon budget development (see Figure 7). A linear slope may be satisfied for a relatively long period with incremental improvements in steel and cement, while an exponentially falling slope would more quickly exhaust the options in cement and steel, and move to the less significant 'carbon consumers' among the construction materials. Even that, however, would not affect the significant steel and cement consumption in emerging countries if cities there do not join in on carbon budgets.

Another challenge is the option to shift products around so that those produced with less carbon content are used in sectors under carbon budget constraints, while the more carbon intensive raw materials go to the sectors without constraints. Again, using steel as an example, if 25% of steel in Europe is used for the manufacturing of cars and another 25% for buildings, cars would be built from new steel, while buildings would use recycled steel. As nearly all steel is currently recycled, and this constitutes about 20% of European steel consumption, there is a risk that the steel flows are simply adjusted and no real effect is achieved. The challenge could of course be met if European car manufacturers would set a parallel standard for steel input to their production. Otherwise, this is an issue that particularly to steel as most other essential construction materials have their main market in construction -- cement, insulation, and tiles have little use in car manufacturing or outside buildings construction, in general.

Once budgets become tight and supply chains become affected there will be winners and losers in the manufacturing industry. Some will be punished for high carbon content in their energy supply, imposed on them through national energy systems with less emission-free power production compared to others. Nevertheless, it is unlikely this would become a trade restriction for the WTO to deal with. All suppliers are treated equally, and there is no brand preference or preferred origin. The carbon budget prescribes a certain quality of a product, and suppliers cannot insist on the right to deliver a product quality that does not meet the specified level. In addition, it is not a national regulatory entity that establishes the demand, but a local authority, and although WTO has occasionally looked at local cases (e.g. Ontario's 'local content' requirements), it is rare and the cases are weak. When Asian suppliers

realized the challenges they faced from ISO 9000, it did not become an international trade regulation issue. Instead, there is a chance for a positive spillover from companies facing a disadvantage due to the carbon footprint they 'import' from power delivered through their national electricity grids. This may either be considered emission-free captive power production, or even – if a large enough group of influential companies are affected – in the longer run possibly influence the national uptake of emission-free energy sources on the national grid.

It is imaginable that city based carbon budgeting could possibly be a challenge in the international climate change policy sphere if the effect, ultimately, would be a reduced demand for products manufactured in developing countries with high emission intensities. It could be regarded as a violation of the common view on the 'common but differentiated responsibilities' principle. If so, however, it would be a challenge that comes from a market-based change of demand. Although stemming from a political/administrative level (cities), it is at the sub-national level, which is not part of the international climate change architecture (despite the Paris Agreements' reference to non-state actors). Nevertheless, it would be difficult to imagine national legislation ruling against carbon budgeting in cities.

At the other end of the value chain, the resulting buildings may become more expensive. Price increases may result either from purchasing carbon budgets -- if allocation through grandfathering is not the chosen model -- or if constraints lead to the need to use more expensive materials. City regulators should consider the allocation model carefully as other interests may be conflicting, for instance the common desire to ensure affordable housing. While there may be market forces that would limit the extent to which increased costs can be passed on to buyers, because existing buildings are not subject to carbon budgets and compete for the same buyers, it may be a different story for rent in social housing, which is commonly regulated. However, it need not push prices upwards. Tracking embodied carbon is an efficient way to manage and reduce material use, reducing both the procurement of unnecessary materials, as well as waste generated at the building site. Skanska reports that for many projects, managing embodied carbon goes hand-in-hand with cost effectiveness, and points to resource efficiency and actors seeing it as a management tool (Skanska, 2012).

There are also other challenges that carbon budgeting may *not* have. The industry has already developed functioning standards for how to calculate and compile data to support such budgeting. Although they are applied on a voluntary basis they have been developed and are being adopted by the industry, providing ample proof of its viability. Only incentivizing their use through carbon budgets is needed.

The chosen model for combining embodied and operational carbons avoids the usual developers/owners/tenants conflicts of interests that complicate most regulatory actions on the improvement of energy efficiency of buildings. By deeming the carbon content of the future energy use through the energy standard that the building complies with *ex ante*, the actual usage of the building, including potential rebound effects and change of usage, is eliminated from the equation. Reconstruction, which commonly requires a permit from the city administration, would be allocated a new budget pertaining specifically to the construction project.

There are obviously different ways in which the city-based carbon budgeting for the construction industry can be introduced. The ideal way would be to have a few progressive cities implement the model as a test scheme in order to gain experience and observe the initial effects. This would help immensely to shed light on how the establishment of carbon footprints and carbon accounting might succeed – how it could start and penetrate the sector, including spillover effects into other sectors. It would equally help determine the critical mass of participating city regulators to make the industrial response self-sustaining. It might even help with the first indications of international trade effects. The ball is in the progressive cities' court.

Bibliography

- Adalberth, K., Almgren, A., & Holleris Petersen, E. (2001). Life-cycle assessment of four multi-family buildings. *International Journal of Low Energy and Sustainable Buildings*, 2, 1–21.
- Adriaanse, A., Bringezu, S., Hammond, A., Moriguchi, Y., Rodenburg, E., Rogich, D., & Schütz, H. (1997). *Resource Flows: The Material Base of Industrial Economies*. (World Resource Institute, Wuppertal Institute, Netherlands Ministry for Housing Spatial Planning and Environment, & Japan's National Institute for Environmental Studies, Eds.). Washington D.C.: World Resource Institute. Retrieved from http://pdf.wri.org/resourceflows_bw.pdf
- Asif, M., Muneer, T., & Kelley, R. (2007). Life cycle assessment: A case study of a dwelling home in Scotland. *Building and Environment*, 42(3), 1391–1394. <http://doi.org/10.1016/j.buildenv.2005.11.023>
- Balson, T., Lowres, F., & Johnson, K. (2011). *Operational and embodied carbon in new build housing: A reappraisal*. Retrieved from <http://www.ihsti.com/tempimg/57c152b-CIS888614800300645.pdf>
- BCAP. (2009a). Code Status: International Non-Residential. Retrieved December 3, 2015, from <http://energycodesocean.org/code-status-international-non-residential>
- BCAP. (2009b). Code Status: International Residential. Retrieved December 3, 2015, from <http://energycodesocean.org/code-status-international-residential>
- Birgisdóttir, H., Mortensen, L. H., Hansen, K., & Aggerholm, S. (2013). *SBi 2013:09: Kortlægning af bæredygtigt byggeri* (1st Editio). Copenhagen: Statens Byggeforskningsinstitut, Aalborg Universitet. Retrieved from http://www.sbi.dk/miljo-og-energi/beredygtighedsvurdering/kortlaegning-af-baeredygtigt-byggeri/sbi-2013-09/at_download/file
- Bolattu, A. (2010). Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey, 26(2006), 1301–1309. <http://doi.org/10.1016/j.applthermaleng.2005.10.019>
- Boverket. (2015a). Boverkets byggregler, BBR. Avsnitt 9 Energihushållning. Karlskrona: Boverket. Retrieved from <http://www.boverket.se/globalassets/vagledning/kunskapsbanken/bbr/bbr-22/bbr-avsnitt-9>
- Boverket. (2015b). *Byggnaders klimatpåverkan utifrån ett livscykelperspektiv*. Karlskrona.
- Bulkeley, H. (2010). Cities and the Governing of Climate Change. *Annual Review of Environment and Resources*, 35(1), 229–253. <http://doi.org/10.1146/annurev-environ-072809-101747>
- Bygningsreglementet.dk. (2016a). Bygningsreglementet. Energiramme for boliger, kollegier, hoteller o.lign. i bygningsklasse 2020. Retrieved January 8, 2016, from http://bygningsreglementet.dk/br15_00_id161/0/42
- Bygningsreglementet.dk. (2016b). Bygningsreglementet. Energirammen for boliger, kollegier, hoteller m.m. Retrieved January 8, 2016, from http://bygningsreglementet.dk/br15_00_id108/0/42
- Cabeza, L. F., Barreneche, C., Miró, L., Morera, J. M., Bartolí, E., & Inés Fernández, A. (2013). Low carbon and low embodied energy materials in buildings: A review. *Renewable and Sustainable Energy Reviews*, 23, 536–542. <http://doi.org/10.1016/j.rser.2013.03.017>

- CEN - TC. (2011). Building level Standards - EN 15978. European Committee for Standardisation - Technical Committee. Retrieved from http://portailgroupe.afnor.fr/public_espacenormalisation/CENTC350/building_level.html
- Circular Ecology. (2015). Embodied energy and carbon - The ICE database. Retrieved October 20, 2015, from <http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#.Vksv6narRpg>
- CNCA. (2014). *Framework for Deep Carbon Reduction Planning*. Retrieved from <http://usdn.org/uploads/cms/documents/cnca-framework-12-16-15.pdf>
- Corbett, C. J., & Kirsch, D. a. (2001). International diffusion of ISO 14000 certification. *Production and Operations Management*, 10(3), 327–342. <http://doi.org/10.1111/j.1937-5956.2001.tb00378.x>
- Commission Communication (2011) 571 final Communication on a Roadmap to a Resource Efficient Europe.
- Commission Communication (2014) 445 final. Communication on resource efficiency opportunities in the building sector.
- Council Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. OJ L 153, 18.6.2010, p. 13–35
- Council Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. OJ L 315, 14.11.2012, p. 1–56
- DG Environment (2012) Roadmap: Communication on sustainable buildings. Brussels: Directorate General Environment.
- Embodied Carbon Industry Task Force. (2014). *Embodied Carbon Industry Task Force Recommendations*. London. Retrieved from http://www.asbp.org.uk/uploads/documents/resources/Embodied Carbon Industry Task Force Proposals_June 2014_Final%5B1%5D.pdf
- Energiforsk. (2015). *Processindustrin och nollvisionen*. Stockholm. Retrieved from http://www.energiforsk.se/SiteAssets/Agenda_processindustrin_webb.pdf
- Fischedick, M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J., Ceron, J.-P., ... Tanaka, K. (2014). Industry. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, J. C. Minx, E. Farahani, S. Kadner, ... T. Zwickel (Eds.), *Climate Change 2014 Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 671–738). Cambridge, United Kingdom: Cambridge University Press.
- Frost, R. (2002). Editorial: Creativity and management systems. *ISO Management Systems*, 2(2).
- Global Construction Perspective. (2013). *Global Construction 2025*. Retrieved from <http://www.globalconstruction2025.com/uk/>
- IEA. (2013). *Modernising Building Energy Codes to secure our Global Energy Future: Policy Pathway*. Paris.
- IEA. (2015). *Energy efficiency. Market Report 2015*. Paris.

- ISO. (2015a). ISO 21930. Retrieved August 24, 2015, from http://www.iso.org/iso/catalogue_detail?csnumber=40435
- ISO. (2015b). ISO Survey. Geneva: International Organization for Standardization. Retrieved from <http://www.iso.org/iso/iso-survey>
- ISO 14040. (1997). Environmental management -- Life cycle assessment -- Principles and framework. Geneva: International Organization for Standardization.
- ISO 14040. (2006). Environmental management -- Life cycle assessment -- Principles and framework. Geneva: International Organization for Standardization.
- ISO 14041. (1998). Goal definition and inventory analysis. Geneva: International Organization for Standardization.
- ISO 14042. (2000). Life-cycle impact assessment. Geneva: International Organization for Standardization.
- ISO 14043. (2000). Life-cycle interpretation. Geneva: International Organization for Standardization.
- ISO 14044. (2006). Environmental management -- Life cycle assessment -- Requirements and guidelines. Geneva: International Organization for Standardization.
- ISO 21930. (2007). Sustainability in building construction -- Environmental declaration of building products. Geneva: International Organization for Standardization.
- Junnila, S., & Horvath, A. (2003). Life-Cycle Environmental Effects of an Office Building. *Journal of Infrastructure Systems*, 9(4), 157–166. [http://doi.org/10.1061/\(ASCE\)1076-0342\(2003\)9:4\(157\)](http://doi.org/10.1061/(ASCE)1076-0342(2003)9:4(157))
- Khasreen, M. M., Banfill, P. F. G., & Menzies, G. F. (2009). Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability*, 1(3), 674–701. <http://doi.org/10.3390/su1030674>
- Lamprecht, J. L. (1992). *ISO 9000: Preparing for Registration*. New York: Marc Dekker Inc.
- Lee, T. Y. (1998). The development of ISO 9000 certification and the future of quality management. *International Journal of Quality & Reliability Management*, 15(2), 162–177. <http://doi.org/10.1108/02656719810204766>
- Liljenström, C., Malmqvist, T., Erlandsson, M., Fredén, J., Adolfsson, I., Larsson, G., & Brogren, M. (2015). *Byggandets klimatpåverkan*. Stockholm. Retrieved from http://www.ivl.se/download/18.41ba7c1514a956c967dcb5/1423832085017/B2217_ME.pdf
- Lockie, S., & Berebecki, P. (2012). *Methodology to calculate embodied carbon of materials*. London. Retrieved from http://www.rics.org/Documents/Methodology_embodied_carbon_final.pdf
- Lucon, O., Ürge-Vorsatz, D., Ahmed, A. Z., Akbari, H., Bertoldi, P., Cabeza, L. F., ... Vilariño, M. V. (2014). Buildings. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... J. C. Minx (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom.
- NAMA-Facility. (2014). Colombia Transit-oriented Development (TOD) NAMA. Retrieved March 3, 2016, from <http://www.nama-facility.org/projects/colombia-i.html>

- Rademaekers, K. (2014). *Market study for a voluntary common European Union certification scheme for the energy performance of non-residential buildings*. Rotterdam. Retrieved from [https://ec.europa.eu/energy/sites/ener/files/documents/Final report - Building Certification Schemes - FINAL 26112014.pdf](https://ec.europa.eu/energy/sites/ener/files/documents/Final_report_-_Building_Certification_Schemes_-_FINAL_26112014.pdf)
- Rosenzweig, C., Solecki, W., Hammer, S. a, & Mehrotra, S. (2010). Cities lead the way in climate-change action. *Nature*, *467*(7318), 909–911. <http://doi.org/10.1038/467909a>
- Salon, D., Sperling, D., Meier, A., Murphy, S., Gorham, R., & Barrett, J. (2010). City carbon budgets: A proposal to align incentives for climate-friendly communities. *Energy Policy*, *38*(4), 2032–2041. <http://doi.org/10.1016/j.enpol.2009.12.005>
- Schmidt, A. (2012). *Analysis of five approaches to environmental assessment of building components in a whole building context*. Brøndby. Retrieved from http://www.eurima.org/uploads/ModuleXtender/Publications/97/Force_Study_Building_certification_systems_May_2012.pdf
- SGBC. (2015). Aktuellt i Miljöbyggnad. Retrieved September 1, 2015, from <https://www.sgbc.se/aktuellt-i-miljoebyggnad>
- Skanska. (2012). Skanska & Carbon Footprinting in 2011. Retrieved April 15, 2015, from http://skanska-sustainability-case-studies.com/index.php/latest-case-studies/item/download/192_41ade13ae200b0d9f0968462f4258fab
- Soulti, E., & Moncaster, A. M. (2014). *UK experience of the use of timber as a low embodied carbon structural material*. Barcelona. Retrieved from http://wsb14barcelona.org/programme/pdf_poster/P-189.pdf
- UNEP. (2014). *The Emissions Gap Report 2014*. Nairobi.
- UNFCCC. (2015). Adoption of the Paris Agreement. Paris: United Nations Framework Convention on Climate Change. Retrieved from <https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf>
- USGBC. (2013). LEED v4 for Building Desing & Construction. Retrieved August 18, 2015, from <http://www.usgbc.org/resources/summary-changes-leed-2009-leed-v4-bdc>
- WGBC. (2013). *The Business Case for Green Building. A Review of the Costs and Benefits for Developers, Investors and Occupants*. Retrieved from http://www.worldgbc.org/files/1513/6608/0674/Business_Case_For_Green_Building_Report_WEB_2013-04-11.pdf
- Zabalza Bribián, I., Valero Capilla, A., & Aranda Usón, A. (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment*, *46*(5), 1133–1140. <http://doi.org/10.1016/j.buildenv.2010.12.002>