Embodied Energy Versus Building Height, The "Premium" of Building Tall

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ABSTRACT

Smart and sustainable cities require a higher population density, and thus taller buildings. The general idea is that we can "invest" more into buildings, since we can "save" on transportation. But is there an optimal building height in cities? In this paper we explore the "premium" of building tall, with respect to the embodied energy of construction materials and technical systems. This paper is a first step towards understanding cities total energy consumption.

In this context a CO2 premium means: increased greenhouse gas emissions per square meter area with increasing building height. The analysis is carried out through a Life Cycle Assessment, using Simapro. The scope of the study is limited to cradle-to-gate.

The results show that there is a small premium of building tall on a per square meter basis. But there are large variations between the embodied energy of buildings, built with different construction materials. It is therefore of crucial importance to select the right construction materials in future projects, in order to move towards smart and sustainable cities.

Keywords: *life cycle assessment, building tall, embodied energy*

1. INTRODUCTION

Smart and sustainable cities require a higher population density, and thus taller buildings. The general idea is that we can "invest" more into buildings, since we can "save" on transportation. But is there an optimal building height in cities? In this paper, we explore the "premium" of building tall, with respect to the embodied energy of construction materials and technical systems. This paper is a first step towards understanding cities total energy consumption.

In this paper, a "CO_2 premium" means increased greenhouse gas (GHG) emissions per square meter area with increasing building height. Thus, this paper is investigating the following research questions:

- Is there a "CO_2 premium" of building tall?
- Is there an optimal building height?
- Is there a preferable construction material for the structural components?

1.1 Goal and scope of the study

The goal of this study is to understand how embodied and in-use GHG emissions varies with building height, and thus seek to determine an optimal building height with respect to optimise GHG emission per m^2 floor area of the buildings. A better understanding of these relationships are necessary to understand the dynamics of smart and sustainable neighbourhoods and cities for the future.

This study focusses on GHG emissions from buildings and building components. As such, it constitutes a first step towards a holistic understanding of integrated city environments, exploring the relationships between buildings components and infrastructure systems (transport, water, sewage, waste and telecom). Equally, it is a first step toward creating design criteria for the sustainable cities of the future.

Since the purpose of this study is to assess the impact of buildings on climate change, we have limited the study to investigating the relationship between embodied and in-use carbon emissions versus building height. In order to making comparison between the results possible, we present the finding on a per m^2 basis, and thus the functional unit chosen is kg CO_{2eq}/m^2 UFA. The system borders are set to cradle-to-gate.

In addition, since the focus of the study is to investigate the relationship between environmental impact and building height, all factors that are believed to be independent of building height, such as lighting systems, materials for internal surfaces and furniture are excluded from the analysis.

1.2 The building

As a basis for this study is two real buildings that are scaled up or down, and where the material need for alternative construction materials is calculated (Ytrehus, 2015; Kaspersen, 2016 and Skullerud, 2016), Table 1.

	3	7	12	21
Location	USA	USA	USA	Norway
Design wind speed	67 m/s	67 m/s	67 m/s	26 m/s
Live load	2.4 kN/m^2	2.4 kN/m^2	2.4 kN/m^2	2-3 kN/m^2
Storey height	3.66 m	3.66 m	3.66 m	3.4 m
Building height	12 m	26.5 m	44.8 m	76 m
Gross floor area	2613 m^2	6097 m^2	10542 m^2	11823 m^2

Table 1: Building specifications

An early study (Ytrehus, 2015) showed that in-situ-cast concrete was more favourable than other construction techniques with concrete. The up and downscaling off the buildings, as well as the calculation of the timber structures were done in-house, with assistance and quality check provided by a major Norwegian engineering consultancy company. The materials needed for the structural parts of the buildings are given in Table 2.

Material	**RC structures**				**Steel structures**				**Timber structures**			
Stories	*3*	*7*	*12*	*21*	*3*	*7*	*12*	*21*	*3*	*7*	*12*	*21*
Concrete C25/30 (m^3)	925	2031	3436	0	23	174	261	0	23	174	261	3
Concrete C35/45 (m^3)	0	0	0	7186	0	0	0	718	0	0	0	718
Rebar steel (t)	51	105	186	955	2	24	36	93	2	24	36	93
Construction steel (t)	0	0	0	0	197	397	684	1995	0	0	0	0
Glulam (m^3)	0	0	0	0	0	0	0	0	78	125	206	234
CLT (m^3)	0	0	0	0	0	0	0	0	513	1410	2792	4639

Table 2: Material quantity data

Kaspersen et al. (2016) investigated the CO_2 premium of the technical system (Plumbing and HVAC installations, Electrical power and elevators) for the same case buildings. Their findings showed a weak decrease of embodied emissions per m^2 with building height, up until 12 stories. At heights from 12 stories and upwards, an increase (premium) in embodied emissions from the technical systems was identified. An overview of what is included is provided in Table 3;

Technical installation	Underlying system	Production phase	Use phase
Plumbing and HVAC installation	Plumbing	+	+
	Heating	+	+
	Ventilation	+	+
	Comfort cooling	+	+
Electrical power	Low currents	÷	+
	Lighting	÷	+
Other installations	Elevator	+	+

Table 3: Overview of the technical installations included in the study

In this study, we are using the findings of Kaspersen et al. on the embodied energy in the analysis. With respect to embodied energy from façade system, there are numerous different choices. In a case study on CO_2 emissions from buildings Leung and Yip (2008) found that curtain wall façade systems ranged from approximately 8 to 250 kg CO_{2eq}/m^2 of facades installed. In this study, we have varied the embodied emissions from facade systems between 15 and 150 kg CO_{2eq}/m^2 over a 60-year lifetime of the building, and thereby including different design choices and maintenance calculation.

Since we are interested both future and existing buildings, we have modelled the in-use GHG emissions based on a very low energy demand of 50 kwh/m^2 (with some synergies based on size). And, although this is a low number by today's standards, it is higher proposed regulations for the future (EU, 2010). The reason we also include in-use emissions in this study, is to understand importance of in-use emissions versus embodied emission over a lifetime of 60 years for the building. Including in this is equally the pumping of water to height, which is found to be of a neglectable nature, less than 0,1% of total energy consumption (Aronsen et. al.,2015).

1.3 Sensitivity, best case versus worst case

The sensitivity analyses are based on 1) The best case and worst case for the production of varying construction materials, such as concrete, steel, facade and timber products, 2) The carbon intensity of the in-use energy mix, Table 4.

Material	Concrete C 25/30	Concrete C 40/45	Rebar Steel	Steel	Glulam	CLT	Technical installations	Façade systems	Electricity
Unit	kg CO_2/m^3	kg CO_2/m^3	kg CO_2/t	kg CO_2/t	kg CO_2/m^3	kg CO_2/m^3	kg CO_2/m^2	kg CO_2/m^2	kg CO_2/kwh
Worst case	349	404	2120	2400	159*	173*	45	300	350
Best Case	207	265	480	1600	91*	104*	32	30	132

* We are not applying consequential LCA, and thus a net carbon storage of approximately 600 kg per m3 timber products are not accounted for.

Table 4: Input data for best case and worst case sensitivity analysis

2. RESULTS AND DISCUSSION

The result below is shown as a shaded area between the best case and worst case (sensitivity analysis) for the various building parts; foundation, structural components, technical systems, façade systems and also for the in-use energy consumption. The functional unit for all the analysis is kg CO_{2eq}/m^2 floor area.

2.1 Embodied energy

Figure 1 shows embodied energy from the foundation work versus building height. As expected there is a premium for building tall, as taller buildings require a stronger fundament. In this analysis, we have used the same fundament across different structural materials. That this might be an overkill for timber buildings is here not taken into consideration. Given the goal and scope of the analysis, this is of minor concern.

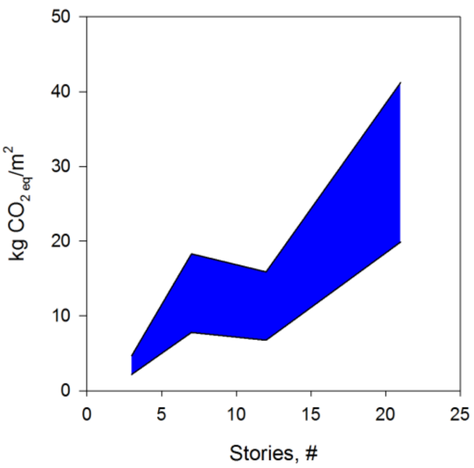

Figure 1: Embodied emissions from the foundation versus building height

The contribution of the structural components is shown in Figure 2. There is a weak negative trend in emissions up until 12 stories tall for buildings made from reinforced concrete or steel. These are cases where steel-based constructions have higher emissions than buildings of concrete. Buildings made of timber has significantly lower emissions than building made of concrete and steel. An interesting point is that the environmental impact from the timber construction is much lower than for concrete and steel buildings, although we have excluded carbon storage from this study. If carbon storage had been uncounted for, we would have negative emissions from the timber buildings of approximately 600 kg CO_2/m^2 (Skullestad, 2015).

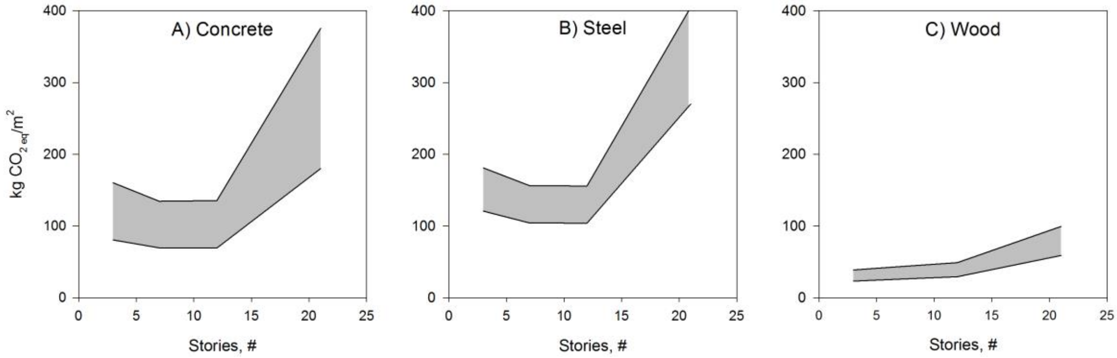

Figure 2: Embodied emissions from the structural components versus building height. A) Reinforced concrete, B) Steel and C) Timber buildings

The embodied emissions from the technical installations shows a week decrease in embodied emissions up until 12 stories, Figure 3. From 12 stories and up, there is a small increase in emissions ("premium") with building height. We believe that this "premium" will increase further with even taller buildings.

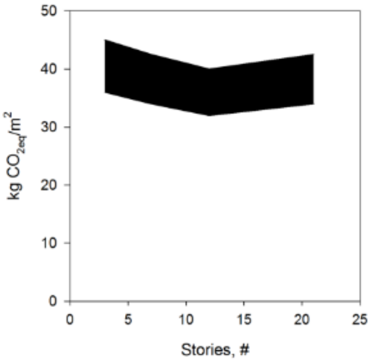

Figure 3: Embodied emissions from the technical installations versus building height

Figure 4 shows the embodied emissions from façade systems. These results are interesting for several reasons. Firstly, this reflects the great difference in embodied emissions from different façade systems per m^2 façade (including various maintenance interval schemes). There is a factor of 10 difference between the best and the worst case, Table 1.

Secondly, the U-shape of the curve suggests a decrease in emission with height up until 12 stories. After 12 stories, there is increase in emissions ("premium") with building height. We found that this behaviour can be explained by the surface (wall) to volume ratio of the building, and as such a more a design issue. This relationship will, however, always be there, and thus suggesting that there could be optimal building height with respect to embodied emissions.

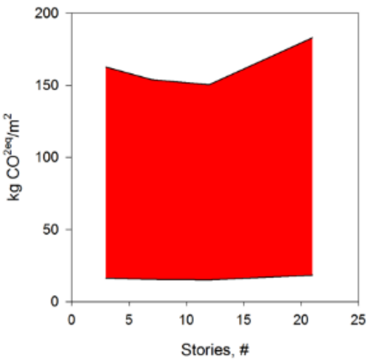

Figure 4: Embodied emissions from the facade systems versus building height

2.2 In-use-energy demand

In addition to embodied emissions from construction materials, we investigated the impact of in-use energy consumption on total emissions from the buildings over a 60-year period, Figure 5. The results clearly show that energy consumption – and the corresponding emissions – decrease with increasing building height. This change corresponds with changes in surface area to volume changes in the buildings.

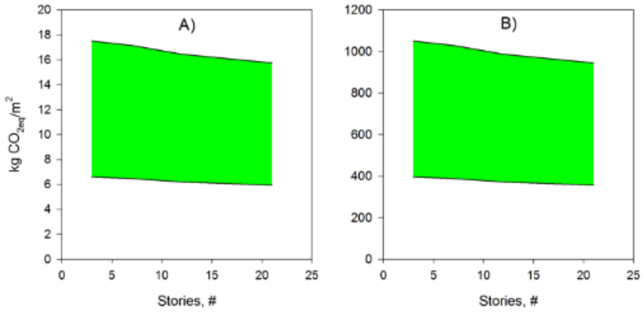

Figure 5: Emissions from the in-use energy consumption versus building height. A) Annual emissions, and B) Aggregated emissions over 60 years

The difference between the worst case and best case clearly reflects the different carbon intensities of the power grid, and are therefore outside the control of the users of the buildings. The best case reflects the expected future carbon intensity of the European grid in 2050 of 132 g CO_{2eq}/kwh, while the worst case shows todays average of 350g CO_{2eq}/kwh (Graabak and Feilberg, 2011).

2.3 Embodied and in-use GHG emissions over a 60-year service period

The total GHG emissions from the buildings over a 60-year period time period is shown in Figure 6. The results revealed some interesting relationships.

Firstly, although the expected energy consumption is very low (45 to 50 kwh/m^2), in-use energy consumption still is responsible for more than 50% of the total emissions over a 60-year period. This finding suggest that a continuous focus on the reduction of the in-use energy demand – as well as a decrease in carbon intensity of the electric grid – is of outmost importance. Thus, the reduction in energy demand from dwellings, will have a double effect. This because a lowered demand for electricity in turn will eliminate the need for the least effective (most expensive) and most polluting power plants.

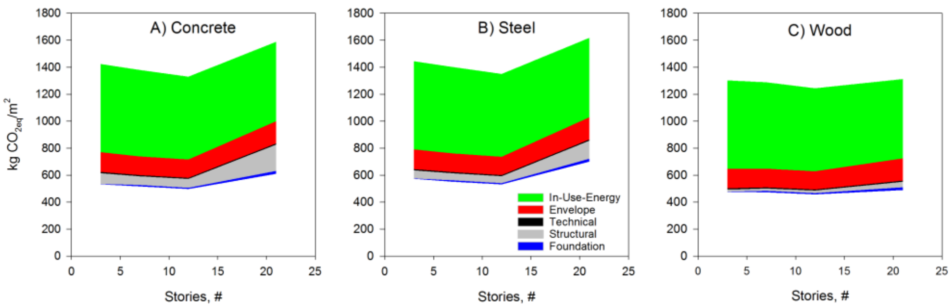

Figure 6: Total emissions from buildings versus building height over a 60 period, for A) Concrete buildings, B) Steel frame buildings and C) Timber buildings

Secondly, there is a significant opportunity for GHG emissions to be harvested by better use of construction materials. This especially concerns the increased use of wood as structural material and in the façade, which would significantly reduce GHG emission from buildings.

Lastly, the figure clearly suggests that there is an optimal building height. According to the figure, this optimum is to be found somewhere between 10 and 20 stories. This result, however, has to be verified with a larger empirical study.

3. CONCLUSION

The analysis presented in this paper indicates that there exists an optimum for building height somewhere between 10 and 20 stories regardless of construction technologies. For all the investigated building heights, wood will significantly reduce the embodied emissions from the building. Within all the scenarios presented in this paper, there is a significant discrepancy between the worst-case and the best-case CO_2 emissions. The most accessible gains stem from addressing façade and avoiding energy input to the building. Further research: the study presented in this paper does not include the potential effects of carbon storage of the building. Such effects will prominently appear in timber structures, and will potentially have significant GHG emission reduction effects.

Although the results presented in this paper indicate an optimal height of buildings (in the range between 10 - 20 stories), this can change within an analysis that include a broader scope. If, for instance, the system is expanded to include transport systems and networks, the potential seems to exist for permitting building heights of more than 20 stories. This will be explored in future papers.

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