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Exploring the CO_2-Impact for Building Height; *A Study on Technical Building Installations*

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Abstract

Building tall typically requires a different operational energy demand and additional material. The purpose of this article is to analyze the adaption of technical systems to increased building height with particular interest to CO_2 emissions. The analysis is carried out through a Life Cycle Assessment, using Simapro. This study covers only commercial buildings ranging from 4 to 21 floors. The scope of the study is limited to cradle-to-gate. The calculation model is based on the material quantities of the different components in the technical systems and corresponding material emission factors. The results show that plumbing, HVAC and elevators in total cause a minimal increase of greenhouse gas emissions per square meter area with increased building height. The greenhouse gas emission trend up to 12 floors varies slightly and is highly dependent upon the technical system solution. From 12 to 21 floors there is a small increase in GHG emissions. As the change in greenhouse gas emissions per square meter appears to be minimal, it has been concluded in this study that the change in GHG emissions caused by technical installations is negligible.

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Keywords: Life *Cycle Assessment; Technical installations; Building Height; Greenhouse gases; Climate change*

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1. Introduction

The world is facing major environmental concerns, especially in the form of global warming [1,2]. Over the last years, environmental impacts caused by buildings have gained more attention. The Intergovernmental Panel on Climate Change (IPCC) stated in 2010 that the building sector was accountable for 32 percent of the global energy use and 19 percent of energy-related greenhouse gas (GHG) emissions [4]. In the literature, the conclusion is consistent: operational energy (OE) constitutes the largest share of the overall life cycle energy use for conventional buildings [2,3,7,8]. Hence, focusing on reducing the OE in the use phase ought to be greatly emphasized with regards to mitigations of climate change [9,10]. In an effort to reduce the OE, the emergence of more energy-efficient buildings, such as low energy buildings and passive houses, has increased. Reducing energy in the operational phase, as a mitigation measure, causes the production phase to grow in importance; this is mainly due to the need for additional materials for insulation and improvement of technical solutions, as described by [11]. Consequently, additional materials will require increased energy use and GHG emissions in the production phase [5,11,12]. [5] stipulated a connection between OE and embodied energy (EE) for conventional, low energy and self-sufficient buildings; buildings with lower OE have higher EE and vice versa.

Moreover, the work of [6] concluded that during the lifetime of the building, the structural systems, followed by the HVAC systems and electrical systems, contributed the most to the overall GHG emissions. Further, [14] concluded that in the production phase, building services, including transport and HVAC systems, represented the second largest contribution to the embodied energy, after building structure and building envelope.

In 2014, more than half of the global population lived in urban areas [13]. Further, [13] predicts that by 2050, as much as 66 percent of the global population will live in urban areas. The growing global population and urbanization will in the near future entail an increasing demand on the building industry to build taller. Ultimately, studying building height enables us to ascertain how tall it is preferable to build from an environmental perspective; by identifying where the significant GHG emissions occur when building taller.

Combining the growing urbanization and the GHG emissions caused by the building sector, GHG emissions in conjugation with building height are of great interest. This is particularly true when considering the importance of technical systems in regards to GHG emissions attributed to both the production and use phase.

1.1. Aim and structure of the article

The aim of this study is to investigate the relationship between technical building installations and material GHG emissions attributed to materials used in technical systems. In this study the following general research question will be investigated: "*Will increased building height affect the technical systems in form of additional materials, leading to increased embodied energy and embodied carbon?"* In light of this, the following questions need to be answered:

- Do the GHG emissions from technical installations change for increased building height?
- How do the GHG emissions vary with building height?

The scope of the study is limited to cradle-to gate, only including GHG emissions from the production stage. The LCA approach is attributional and the software program used to calculate the material emission factors is Simapro. The impact category examined is climate change. Two case studies are conducted. In the first case study, the building is a 21-story passive-house hotel located in Trondheim, Norway. This building is scaled down to 17, 13, 9 and 5 floors. The second building is a 4-story office and health care building in Minnesota, US. This building is scaled up to 8 and 12 floors.

Nomenclature

BIM	Building Information Modelling
CED	Cumulative energy demand
EC	Embodied carbon
EE	Embodied energy

EPD	Environmental product declaration
GFA	Gross floor area
GHG	Greenhouse gas
GWP	Global warming potential
HVAC	Heating, ventilation and air conditioning
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
NRA	Net rentable area
OE	Operational energy

2. Theoretical framework

2.1. Technical installations in buildings

Technical installations are categorized under non-structural building elements [29]. This study has divided the technical installations into four categories, adapted from NS 3451:2009. These are the following: plumbing & HVAC, electrical power, telecommunication & automation and other installations. Each of these categories is further divided into underlying technical systems. This is depicted in Table 1.

Table. 1. Overview of the technical systems from NS 3451:2009

3. Plumbing and HVAC installations	4. Electrical power	5. Telecommunication and automation	6. Other installations
3.1 Plumbing	4.1 Basic installations	5.1 Basic installations	6.1 Prefabricated rooms
3.2 Heating	4.2 High voltage power supply	5.2 Integrated communications	6.2 Elevators
3.3 Fire protection	4.3 Low currents	5.3 Telephony and paging	6.3 Transport facilities for goods
3.4 Gas and pressure air	4.4 Lighting	5.4 Alarm and signal system	6.4 Stage equipment
3.5 Process cooling	4.5 Electrical heat	5.5 Audio-visual system	6.5 Central vacuum system and waste disposal
3.6 Ventilation	4.6 Reserve power	5.6 Automations	6.6 Fixed outfitted for business
3.7 Comfort cooling (AC)	4.7 Other electrical power installations.		6.7 Loose outfitted for business
3.8 water treatment			6.8 Complementary installations
3.9 Other related installations			

2.2. LCA of buildings

When assessing GHG emissions related to buildings, they are commonly put in context with the life cycle of the building. From a life cycle perspective, the total environmental impact of a building described by [16], with reference to EN 15978 and EN 15804, includes the following stages: production, construction, use and demolition. Consequently, the total environmental impacts are the sum of these stages. Table 2 illustrates the different life cycle stages with the corresponding underlying processes, called modules.

Table. 2. Life cycle stages of a building

Production stage (P)	Construction process stage (C)	Use stage (U)	End of life stage (E)
A1: Raw Materials Supply	A4: Construction-installation process	B1: Use	C1: Deconstruction, demolition
A2: Transport	A5: Transport	B2: Manufacturing	C2: Transport
A3: Manufacturing		B3: Repair	C3: Waste process for reuse
		B4: Replacement	C4: Disposal
		B5: Refurbishment	
		B6: Operational energy use	
		B7: Operational water use	

2.3. Terminology

The division and terms used for the different life cycle stages differs in literature. [17] defines four life cycle stages. However, the use of three life cycle stages is also practiced; this is done by incorporating the production stage and the construction process stage into one stage, often called before-use stage or pre-use stage. [19] is an example in this regard, adapting the three life cycle stage division, expressed as the production phase. [26] refers to the incorporated stages as the before-use stage. Regardless of the inconsistent use of terms and classification concerning the different life cycle stages, the environmental impacts of buildings are calculated on the basis of direct and indirect impacts.

The allocation of direct and indirect environmental impacts differs based on how far upstream or downstream the boundaries are set. Hence, different boundaries implicate different calculation models when calculating the indirect environmental impacts. [20] includes material extraction, production, maintenance, transport and demolition in the indirect environmental impacts calculations, whilst the direct environmental impacts constitutes the energy consumption in the use phase. [17] sets the boundary further upstream, only accounting for the processes from the material extraction and production of building materials in the indirect environmental impact calculations. [18] includes all emissions from the processes in the production- and construction process stages, in the indirect environmental impact calculations of the CO_2 emissions. In this study, the embodied impacts (indirect environmental impacts) are calculated based on all processes in the production stage (A1-A3). Only initial impacts from material production are included, no recurring impacts.

In literature, different expressions are used for the coefficient used to calculate the embodied carbon. [23] uses the term embodied CO_2 eq. intensity in order to calculate the embodied carbon. [28] uses the term global warming potential (GWP) intensity express through monetary unit, CO_2 eq./\$. [27] uses the term carbon coefficient in order to calculate the embodied carbon, whilst [24] uses the term embodied carbon emissions. In this study, the term material emission factor (ε) is adopted, expressed as kg CO_2 eq./kg. This factor is used to calculate the embodied carbon expressed as the material GHG emissions.

2.4. Literature review

Studies examining environmental performance of buildings are many. The environmental performances of buildings are often presented in terms of life cycle energy use and GHG emissions. This subsection accounts for some of the existing background literature regarding the research question of this study.

Numerous publications have evaluated the climate change impacts of buildings of varying height. [22] did a hybrid LCA of cumulative energy demand (CED) and global warming potential (GWP) for low, mid and high-rise dwellings. The calculation model included operational energy for heating and cooling of the building, manufacturing of HVAC equipment, building material production and construction processes. The findings showed that both the CED and

GWP increased with increased building height. The GHG emissions included emissions from both structural and non-structural building components such as material for exterior walls and frame, and HVAC equipment. [28] performed a hybrid LCA in order to evaluate environmental performance in form of CED and climate change impact of dwellings ranging from 3 to 21 floors. The results showed that the CED and CO_2 eq. increased on a per square meter basis with increased building height. The study included material extraction and production for both structural and non-structural components, construction and operation of the heating and cooling systems of the dwelling for 50 years. An allocation of the different impact contributions in [22] and [28] would be of interest in order to assign the contribution of the GHG emissions to the different building components. In order to do so, a limitation of the scopes is necessary. If the scopes had been disaggregated to look at individual contributions from the structural and non-structural components, the result of these studies and the conclusions would have been more transparent.

[21] studied the GHG emissions attributed to the load-bearing system for buildings of varying height. The result showed that the structural system resulted in a non-existing CO_2-premium for buildings up to 12 floors. In this context, a CO_2-premium means: increased GHG emissions per square meter area with increased building height. Above 30 floors, the premium was highly dependent upon the material choice and structural system solution. With the best practice material choice and best structural solution, the premium was very small, almost negligible for buildings ranging from 12 to 70 floors.

[25] evaluated the CO_2 emissions for a residential building, with floors ranging from 1 to 60. The scope included material CO_2 emissions from the envelope, foundation and frame, and operational CO_2 emissions from the heating and cooling of the buildings. The optimal building height was concluded to be approximately four stories, as this height resulted in the lowest material- and operational CO_2 emissions per square meter. The operational CO_2 emissions from heating and cooling increased with increased building height, the same result applied for the material CO_2 emissions. This indicates that the GHG emissions increase with increased building height for the operation of the heating and cooling systemd. The effect of the material GHG emissions associated with heating and cooling equipment were, however, not accounted for.

[6] assessed an office building during its lifetime of 50 years. The results revealed that the structural system, closely followed by the HVAC system and electrical system, constituted the major contributions to the climate change over the entire life cycle of the building. This stresses the importance of including technical systems when assessing the climate change impacts during the life cycle of the building.

The discussion above demonstrates that literature addressing environmental performance related to varying building height exists. However, so far the environmental performance has encompassed structural components, or an aggregation of structural- and non-structural components and activities such as transportation. The discussion above suggests that there is a gap of knowledge regarding GHG emissions from non-structural building components, such as technical systems, and especially in conjugation with increased building height.

3. Method

The LCA approach applied in this study is attributional LCA and is conducted according to ISO 14040/44. The software used in this LCA study is Simapro and the life cycle impact assessment method used is ReCiPe 2008. The goal of this study is to calculate the GHG emissions from the material production of the technical systems, in order to study the GHG emission trend for increased building height. Consequently, the environmental impact category studied is climate change, and the functional unit is GHG emissions per square meter for increased building height, CO_2 eq./m^2.

3.1. System boundary

The system boundary is limited to cradle-to-gate, only including the impacts from the production stage, module A1-A3 (see Table 2). The reason for not expanding the boundary to include the construction process stage is due to the poor access to data [31]. Additionally, as described by [30], in the pre-user stage (the production- and construction process stages), the material manufacturing is the dominant stage in regards to EE.

In this study, the categories plumbing & HVAC and other installations are included from Table 1. Furthermore, only parts of the underlying technical systems within plumbing & HVAC and other installations are included. These are listed in Table 3. The reason for excluding electrical power and telecommunication & automation is due to lack of relevant data.

Table. 3. Overview of the technical systems included in the study

Technical installation	Underlying technical system
3. Plumbing and HVAC installations	3.1 Plumbing
	3.2 Heating
	3.6 Ventilation
	3.7 Comfort cooling (AC)
6. Other installations	6.2 Elevators

3.2. Calculation model

The calculation model is mainly based upon two sets of variables. The first set is the inventory of the technical parts within the technical systems in Table 3, expressed either as material quantities or products, such as valves and supply air terminals. The second set is the corresponding material emission factors. When the LCI was established, the material quantities of the different materials and amount of the different products within the technical systems were multiplied with the corresponding material emission factors. This is illustrated in Eq. (1).

$$MGHG = \sum_i Q_i \times \varepsilon_i \tag{1}$$

MGHG is the material GHG emissions, Q_i is the amount of material or product i from the LCI, either expressed as mass (kg) or piece (p). ε_i is the material emission factor for material or product i, either expressed as kg CO_2 eq. per kg or p.

3.3. Material emission factors

Several studies have stressed the influence of material emission factors on the environmental impacts of buildings. The study by [28], presented in the literature section, is an example of this. [28] demonstrated the uncertainties associated with steel emission factors for building LCA.

For the material emission factors, a reference scenario was used. This scenario reflects the average production conditions and utilized technology for the production of the materials mainly in Europe. All the material emission factors were calculated by using the LCA software Simapro or by using EPDs provided by the industry. When available, EPDs were used for the complex products.

4. Case studies

Two case studies have been conducted in order to study the GHG emission trend from the adaption of the technical systems with increased building height. Each case study consists of one building, which was scaled up or down in order to make fair comparisons of the GHG emissions attributed to the technical systems with increased building height. In this regard, fair comparison means that comparing technical systems for different types of buildings is not possible as different system solutions, strategies and building standards are used. In case study A, a 21-story hotel building located in Trondheim was examined. This building was scaled down to 17, 13, 9 and 5 floors. In case study

B, a 4-story office and health care building in Minnesota was studied. This building was scaled up to 8 and 12 floors. The details of the two case studies are described in Table 4.

Table. 4. Description of the case studies

	Case study A: **Scandic Hotel Lerkendal**	**Case study B:** **Office and health care building**
Location	Trondheim, Norway	Minnesota, USA
No. of floors	21 floors	4 floors
Scaled	Down to 17,13,9 and 5 floors	Up to 8 and 12 floors
Building code	Passive house	n/a
Ventilation	Mechanical ventilation Decentralized (21-17-13-9-story buildings) Centralized (5-story building)	Mechanical ventilation Centralized (4-8-12 story buildings)
Data collection	BIM model	Technical drawings
Elevators	Yes (for all buildings)	Yes (for all buildings)

4.1. Data collection

The material quantity data for the HVAC and plumbing systems for the Scandic Hotel Lerkendal building was collected from the BIM model. The material quantities for the HVAC and plumbing systems for the office and health care building in Minnesota were collected from technical drawings. The pipes and ducts were manually measured to calculate the material quantities.

For the elevator systems, the LCI was collected based upon an LCA conducted by [32]. This was an 8-passenger elevator system ranging up to five floors. Additional materials were estimated for the elevator system with more stops, which was the case for the buildings ranging above 5 floors in both case studies. Materials for landing doors, hoist and motor were adjusted according to the number of stops in the elevator system. Estimation of the required number of elevator systems was done by using a calculation model complied by [33].

Tables 5 and 6 show the technical parts included in each of the technical systems.

Table. 5. Material list for case study A

HVAC	**Plumbing**	**Elevator system**
Ducts	Cast iron drains	Aluminum
Steel pipes	PP pipes	Cast iron
Insulations	Copper pipes	Stainless steel
Supply and exhaust air terminals	Valves	Steel (uncoated)
Silencers	Sprinkler heads	Steel (zinc coated)
VAV regulators		Plastic
Air handling units		Rubber
		Glass
		Electronics and components

Table. 6. Material list for case study B

HVAC	Plumbing	Elevator system
Ducts	Cast iron drains	Aluminum
Steel pipes	PP pipes	Cast iron
PEX pipes	Copper pipes	Stainless steel
Insulations	PEX pipes	Steel (uncoated)
Supply and exhaust air terminals		Steel (zinc coated)
		Plastic
Silencer		Rubber
VAV-regulators		Glass
Air handling units		Electronics and components

5. Results

In this section, the results from the case studies are presented in two graphs. Figures 1A and 1B illustrate the material GHG emissions per gross floor area (GFA) for each of the individual technical systems and the sum of these systems. Figure 1A is attributed case study A (Scandic Hotel Lerkendal) and Figure 1B is the results from case study B (office and health care building in Minnesota).

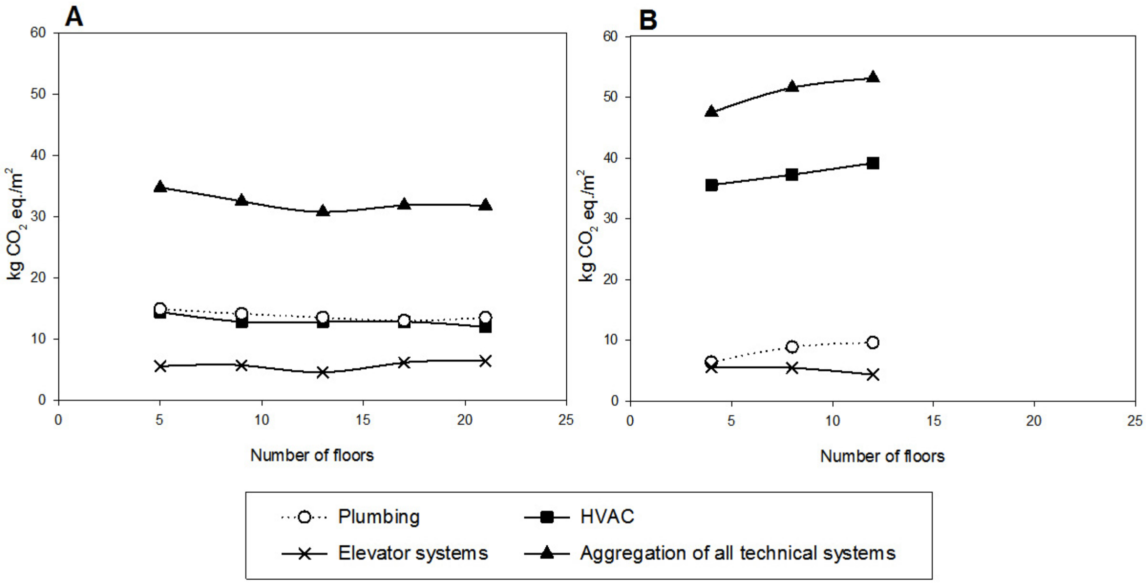

Figure. 1. Material GHG emissions for the two case studies

For case study A (Figure 1A), there is a minimal decrease in the GHG emissions for the aggregated technical systems from 5 to 13 floors, which corresponds to 4 kg CO_2 eq./m^2, which is equivalent to 12 percent. From 13 to 21 floors there is a small increase of 7.4 percent, corresponding to 2.30 kg CO_2 eq./m^2. This increase is however less than the decrease between 5 and 13 floors. When assessing all building heights from 5 to 21 floors, the overall GHG emission trend is decreasing for increased building height. This decrease corresponds to 1.7 kg CO_2 eq./m^2, which is approximately a decrease of 5 percent from 5 to 21 floors. When studying the individual technical systems, the material

GHG emissions from both the HVAC and plumbing systems slightly decrease between 5 and 21 floors. The material GHG emissions from the elevator systems decrease between 9 and 13 floors, and increase above 13 floors.

For case study B (Figure 1B) there is an increase for the aggregated technical systems. The increase between 4 and 8 floors is approximately 8.0 percent, equivalent to 4.09 kg CO_2 eq./m^2. Between 8 and 12 floors the increase corresponds to 3.0 percent, equivalent to an increase of 1.6 kg CO_2 eq./m^2. Looking at the individual technical systems one can see that there is an increase in the GHG emissions caused by the HVAC and plumbing systems. For the elevator system there is a decrease in the GHG emissions from 4 to 12 floors.

6. Discussion

In this paper, we studied the GHG emissions for increased building height caused by technical installations and how the GHG emissions vary with building height. Based on the findings in the above sections, we can now assess these questions within the context of the two cases examined.

6.1. Material GHG emissions

For the HVAC and plumbing systems, the GHG emissions were nearly constant in case study A, whilst in case study B there was a small increase. In case study A, a centralized HVAC system solution was chosen for the 5-story building, while a decentralized HVAC system solution was chosen for the other buildings ranging from 9-21 floors. In case study B, a centralized HVAC system solution was chosen for all buildings.

The materials in the elevator system that are affected by increased building height are materials for the hoist, landing door and the motor. The increased quantities of these materials due to increased building height will not result in significant material GHG emissions. Since the material GHG emissions are divided by the total GFA, the material GHG emissions per GFA caused by one elevator system will decrease for increased building height. Examples of this are the decreased GHG emissions from 9 to 13 floors in case study A, and from 4 to 12 in case study B. Building taller will require more elevator systems, this is one of the contributors to the increase in GHG emissions from 13 to 21 floors in case study A, even though the increase is small.

For the overall GHG emissions, the case studies insinuate a small increase for buildings between 12 and 21 floors. The GHG emission trends for lower buildings are dependent on technical system solutions. In case A, the GHG emissions were decreasing, while in case B the GHG emissions were increasing. The overall results show that the GHG emission trend for all building heights is very small, seemingly negligible.

This study only included a limited number of technical systems. Other non-structural elements, such as the building envelope, alongside structural building elements were excluded. Nevertheless, it is important to stress that these elements may entail potential material GHG emissions.

6.2. The CO_2-premium for building height

Both [22] and [28] acknowledge an increase in GHG emissions with increased building height. These studies have encompassed either structural components or a combination of structural and non-structural components. A comparison of these results and the findings in this article is therefore difficult. In order to make a comparison, a disaggregation of the scope in [22] and [28] is necessary.

[21], as mentioned in the literature subsection, concluded that the CO_2-premium from the structural system was non–existent up to 12 floors and between 20-30 floors. Above 30 floors, the premium was dependent on the structural solution and material choice. When choosing the best practice material and structural solution, the premium was small, seemingly negligible for buildings between 12 and 70 floors. When the latter result is put in context with the results in this study, it can be suggested that buildings up to 20 floors will not cause additional material GHG emissions.

When arguing whether building taller is better for the environment than building low, the GHG emissions for all building elements have to be aggregated. This means that all of the GHG emissions for the structural and non-structural elements of the building have to be summarized, as some of the elements will lead to increased GHG emissions per square meter area for increased building height, whilst others will not. This again has to be considered together with the interaction between transportation and the height of buildings. By doing so, a conclusion can be drawn regarding the environmental performance of building taller and more compact.

6.3. The method

This study has only accounted for the GHG emissions from the production stage, module A1-A3, seen in Table 2. To what extent the remaining life cycle stages potentially would alter the results is uncertain. As stated by several authors, including [3] and [7], the OE constitutes the largest share of emissions. Additionally, [25] acknowledges an increase in GHG emissions from operation of the heating and cooling systems. OE should therefore be included when drawing a conclusion towards the GHG emissions from technical systems when building taller.

The system boundaries are limited to buildings ranging from 4 to 21 floors. Buildings above 21 floors may potentially result in a greater increase in GHG emissions, and should be studied in order to draw a broader conclusion regarding building taller.

Moreover, it is also important to note that a comparison on a net rentable area (NRA) basis would be more accurate than using GFA. GFA accounts for external walls, which is not included when dimensioning the different technical systems. GFA constitutes for a bigger area than NRA; consequently, the material GHG emissions per square meter based on NRA would increase slightly.

6.4. Uncertainties

Several uncertainties are associated with this study and should be considered when evaluating the results and its credibility. Some of these are:

- *Excluded technical parts*. In both case studies, some technical parts were excluded such as pumps, boilers, and different types of valves and radiators. These technical parts were excluded due to lack of data.
- *Material calculations*. In case study B, there were some uncertainties in regards to the data collection. This included manual measurement of the pipes and ducts from drawings and the scaling factors. Approximations were made in order to scale the measured lengths.
- *Simplifications of the elevator systems.* Data regarding how the materials used in electronics and components increase with increased building height were not easy to access and were therefore not accounted for.

7. Conclusion

This study has examined the material GHG emissions caused by technical systems for increased building height. The study has revealed that the GHG emissions caused by technical systems are small and close to negligible.

In order to make a broader generalization of the results presented in this article, more quantitative case studies are required. Nonetheless, the results conclude that the change in GHG emissions per square meter area for increased building height is small. Thus, we argue that the GHG emissions caused by technical installations are negligible for buildings up to 21 floors. When contextualizing this conclusion with regards to the increased urbanization and mitigation measure of building taller and more compact, the material GHG emissions of technical systems will support the measure of building taller, as it will cause negligible additional material GHG emissions per square meter for increased building height.

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