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The Environmental Impact of Ventilation Systems in a Norwegian Office Building from a Life Cycle Perspective

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Preface

This is the master thesis in the 5-year Master of Science degree at the Norwegian University of Science and Technology, Department of Energy and Process Engineering.

Several people have been essential for the the successful completion of this thesis. First of all, I would like to thank my supervisors Helge Brattebø and Christian Solli for always pushing me to be goal-oriented and detailed with my work, while also steering me towards the relevant topics for the thesis. Jens Tønnesen and Thorildur Kirstjandottir were helpful with providing the main inventory dataset for ventilation components, and giving me important background information.

I would also like to thank Erik Langøren and the rest of the team at NCC for providing me with the BIM files for Abels Hus, and giving me important input in the start phase of the project.

Also, thanks to Anne Sigrid Nordby for helpful discussions concerning the subject matter and the rest of Asplan Viak AS for a good working environment at their office. Finally I am grateful for the generous work of Thomas Haaland, Astrid Hovde and Jakob Boye Hansen, for invaluable comments and proofreading.

The cover photo is a concept photo of the office building Abels Hus in Trondheim, which has been assessed in this study. Photo: Narud Stokke Wiig.

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MASTER THESIS

for

Student
Alexander Borg

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The Environmental Impact of Technical Installations in Office Buildings from a Life Cycle Perspective

Miljøpåvirkning av tekniske installasjoner ved et Kontorbygg i Trondheim sett fra et livssyklusperspektiv.

Background and objective

Energy use in buildings has a considerable contribution to the global energy demand and thereby to the emission of stressors to the environment. Technical installations, like ventilation, heating and cooling systems constitute a considerable amount of energy use in office buildings, and well-timed investments in technical installations in the building's construction period can help reduce energy use throughout the lifetime. However, user behavior has a large impact on the energy use in buildings and one must consider potential diminishing returns from solely focusing on technical solutions for energy conservation. Furthermore, the embodied energy and embodied emissions in the installations have a contribution to total life cycle energy demand and the environmental profile of the building.

There is a knowledge gap on the life cycle environmental impact of technical installations in Norwegian office buildings. To fill this gap, Building Information Modeling (BIM) can be used to extract information about the physical and functional characteristics of a facility. From BIM documentation life cycle inventories can be generated and the environmental impact of the installations can be calculated by use of LCA software. An increased awareness of climate change has led to a focus on the environmental impact of Greenhouse Gases in many environmental impact assessments. However, the production of technical installations comes with other stressors to the environment like resource depletion of rare metals, toxic impacts in the supply chains and waste treatment. Therefore, other impact categories should also be considered when assessing the overall performance of these systems.

The objective of the master thesis is to perform a Life Cycle Assessment (LCA) of technical installations in an office building in Trondheim. BIM data provided by NCC AS will be examined, and an LCA methodology applied, to determine the environmental impact from a cradle-to-grave-perspective.

The following tasks are to be considered:

1. Carry out a literature study on life cycle assessment relevant to the objective of this work, covering LCA methodology and findings related to buildings and technical installations in buildings.
2. Provide a description of your case study, and give a definition of the system according to LCA methodology, including a functional unit, goal and scope, system boundaries, as well as relevant data inputs and assumptions.
3. Define relevant impact indicators and metrics for documenting the environmental impact of the system.
4. Extract data from the BIM model into Simapro for inventory calculation and analysis.
5. Perform a Life Cycle Impact Assessment (LCIA), and report results in a clear and consistent manner.
6. Discuss sensitivities and uncertainties regarding the results of the LCIA.
7. Discuss the overall findings of the study, its agreement with literature, strengths and weaknesses of the methods, and its implications for the assessment of technical installations in office buildings.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14. January 2016

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Summary

The main topic of this thesis has been a study of the environmental impacts of the ventilation system in Abels Hus, an office building in Trondheim, from a life cycle perspective. The objective of the study has been to develop a methodology for easier Life Cycle Assessment (LCA) of buildings based on Building Information Models (BIM) and the scope has been a cradle-to-grave analysis.

The background for the study is the increased complexity of technical installations in buildings leading to a need for reassessment of the share of impacts that belong to embodied emissions, while also taking into consideration more impact categories than just climate change. Additionally, the conventional LCA methodology does not sufficiently reflect the time-dependent impact of greenhouse gases when considering systems with such a long lifetime as a building. Thus, a dynamic methodology is applied to better encompass the long lifetime of buildings.

A literature study on Life Cycle Assessments of buildings revealed that the use phase constitutes the majority of impacts throughout the buildings lifetime. To explore these findings a BIM model has been used to find inventory data on a ventilation system. A supplied dataset, combined with environmental product declarations and component data sheets was used to create the inventory for the embodied impacts in the building components, and energy simulations gave the energy use throughout the use phase of the building. To model impacts to climate change for construction and demolition services, input output analysis was applied with the use of modified input-output tables for construction.

Scenario analyses were performed through variations in the electricity supply mix. Four supply mixes were analysed: The Norwegian Mix, Nordic, EU very optimistic, and EU realistic-optimistic. Recycled content of the steel in the ventilation system was also varied. Uncertainties of the embodied impacts were assessed through Monte Carlo simulation.

The results show that energy use constitutes the majority of the impacts for most impact categories, but embodied impacts have a larger share of emissions than previously shown in literature, although total impacts coincide with literature data. The dynamic LCA gives a 33% lower result in climate change impacts than the conventional LCA, and it better shows when in the life cycle the impacts occur, while also keeping consistent with the given time horizon. The ventilation impacts from energy consumptions in the use phase constitute 22%-33% of total emissions from energy consumption.

Policy makers should consider a reduction in embodied impacts of ventilation systems, through increased recycled content of materials, and alternative ventilation methods like hybrid natural ventilation. Without a standardization of BIM models, LCA through BIM is very time consuming, but with the recent developments in BIM standards, these could prove a viable tool for environmental assessments in the early design stages.

Global Warming Potential, kg CO_2 eq/m^2							
Supply mix	Norwegian Mix		NORDEL		EU	Very Opt.	Realistic Opt.
LCA Method	Conv.	Dyn.	Conv.	Dyn.	Conv.	Dyn.	Dyn.
Total Ventilation	131.63	88.32	239.59	118.69	610.87	271.59	394.86

Sammendrag

Hovedformålet med denne oppgaven har vært å studere miljøpåvirkninger av ventilasjonssystemet til Abels Hus, et kontorbygg i Trondheim, fra et livssyklusperspektiv. Målet med studiet har vært å utvikle en metodologi for å enkler utføre livssyklusanalyser (LCA) av bygg basert på 3D-modeller (BIM), og omfanget av studiet har vært en vugge-til-grav analyse.

Bakgrunnen for oppgaven er den økende komplekisteten av teksniske installasjoner i bygninger, noe som har skapt et behov for å revurdere andelen miljøpåvirkninger som angår bundne utslipp, samtidig som det er viktig å ta i betraktning andre mijøpåvirkninger enn global oppvarming. Fen konvensjonelle LCA metodologien gir ikke et presist nok bilde av klimagassutslipp for et system med så lang levetid som et bygg. Derfor er en dynamisk LCA metode inkludert for sammenligning.

Et litteraturstudie på LCA i bygg viste at energibruk i bruksfasen utgjør den største miljøpåvirkningen gjennom byggets levetid. For å undersøke dette, ble en bygningsmodell brukt for å finne invantardata til ventilasjonssystemet. Et datasett for ventilasjonskomponenter, kombinert med byggvaredeklarasjoner og datablader for komponenter ble brukt å kartlegge de bundne materialutslippene til ventilasjonssystemet, mens energisimuleringer gav energibruk i byggets bruksfase. For å modellere utslipp knyttet til bygningsarbeider ble kryssløpsanalyse brukt med modifiserte krysløpstabeller for konstruksjonssektoren.

Senarioanalyser ble gjennomført ved å variere elektrisitetsmiksen brukt i systemet. Fire elmikser ble brukt: Norsk, nordisk og europeisk veldig optimistisk og realistisk-optimistisk. Samtidig ble andelen resirkulert stål i ventilasjonskomponentene variert. Usikkherheter av materialutslipp ble analysert ved hjelp av Monte Carlo simuleringer.

Resultatene viser at energibruk i bruksfasen har størst miljøpåvirkning, men bundne utslipp utgjør en større andel av utslipp enn det litteraturdata viser, selv om totale utslipp er sammenlignbare. Den dynamiske LCA metoden gir 33% lavere klimagssutslipp enn den konvensjonelle metoden og den viser bedre hvor i livssyklusen den faktiske miljøpåvirkningen skjer, samtidig som den er konsekvent med den gitte tidshorisonten. Klimagassutslipp fra energibruk i bruksfasen for ventilasjonsanlegg utgjør 22%-33% av totale klimagassutslipp fra energibruk for bygget.

Beslutningstagere burde vurdere å redusere budne utslipp gjennom større andel resirkulert materiale og alternativ ventilasjonsteknologi som hybrid naturlig ventilasjon, dog kun hvis løsningen tilfredstiller krav for inneklima og komfort. Uten en standardisering av BIM, er LCA med denne metoden veldig tidkrevende, men med nylige utviklinger i BIM standarder, kan slike løsninger være et nyttig redskap for å utføre grundige miljøanalyser tidlig i prosjektfasen av et bygg.

Global Warming Potential, kg CO_2 eq/m^2							
Elektrisitetsmiks	Norsk Mix		NORDEL		EU	Veldig Opt.	Realistisk Opt.
LCA Metode	Konv.	Dyn.	Konv.	Dyn.	Konv.	Dyn.	Dyn.
Total Ventilasjon	131.63	88.32	239.59	118.69	610.87	271.59	394.86

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Abbreviations

AHU Air Handling Unit

BIM Building Information Model

UFA Heated Floor Area

BREEAM Building Research Establishment Environmental Assessment Method

DCF Dynamic Characterization Factor

EEIO Environmentally Extended Input-Output

EPBD the Energy Performance of Buildings Directive

EPD Environmental Product Declaration

GHG Greenhouse Gases

GWP Global Warming Potential

HVAC Heating Ventilation and Air Conditioning

IFC Industry Foundation Classes

LCA Life Cycle Assessment

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

LEED Leadership in Energy and Environmental Design

PHS Plumbing Heating and Sanitation

1 Introduction

The building sector accounts for 40% of primary energy use and 36% of the energy related CO_2 emissions in the industrialized countries [1]. This percentage mostly represents energy use in the use phase of buildings, as production of building materials such as steel and concrete are considered to come from the industry sector. These activities also emit a considerable amount of Greenhouse Gases (GHG) and other pollutants to the environment. When considering Western Europe specifically, building material production accounts for as much as 8-12% of total CO_2 emissions[2]. Additionally, transport of building materials and activities linked to the construction of the building itself must be considered when assessing the environmental performance of buildings.

Like other industries, the construction sector is affected by the trend of sustainable production and eco-green strategies. The importance of revealing the environmental impact of buildings is broadly recognized, and a tool like Life Cycle Assessment (LCA) can be used to achieve sustainable building practices.

The increased complexity of technical installations, therein ventilation systems, requires a re-assessment of the economical and ecological feasibility of these solutions, as there is a trade-off between the decrease in specific energy consumption in buildings and the increased embodied emissions in the construction of ventilation components. This, combined with an electricity mix based on renewable energy, could shift the focus from energy emissions in the use phase to embodied emissions in construction. With this shift in focus one must consider problem shifting to other environmental impacts when reducing impacts from climate change like depletion of rare metals and impacts to human toxicity.

The long lifetime of a building (typically 50-70 years), lends the need for a different methodology than conventional LCA practice which assumes an instantaneous emission of all environmental stressors at time zero, instead of throughout the life cycle of the building. A dynamic LCA method, that considers the actual time the emissions occur can be applied to yield a more representative result of the environmental impacts to climate change.

Building Information Model (BIM) can be utilized to extract information about the physical properties of a building, and thus provide a resolution down to the component level of the system inventory. In this study, a mechanical ventilation system in an office building in Trondheim is assessed through the use of BIM and LCA. A literature study on life cycle assessments of buildings has been conducted and two methodologies, a conventional and a dynamic LCA have been applied in the calculations. From this, the goal and scope of the system has been defined to answer the following research questions:

- What are the environmental impacts throughout the life cycle of a mechanical ventilation system in the Abels Hus in Trondheim, assessing different impact categories?
- In terms of sensitivity, how robust are the results to differences in LCA methodologies and scenario analyses?
- What are the implications of this in terms of future environmental assessment and policy for technical installations, as well as office buildings as a whole?

2 Background

This section presents the background of the study. First the embodied energy and emissions in the construction sector are outlined. Then the development of ventilation systems in Norway is presented. Then building information models and green building certifications and their connection to LCA is shown. The difference between consequential and attributional LCA and its importance to electricity mixes and the global steel production is given. Finally an introduction to LCA methodology is shown.

2.1 A Recognition of the Environmental Impact of Embodied Energy and Emissions

For a long time, the analysis of operational energy and the emissions contained therein, has dominated the discussion on issues of environmental impact and resource conservation. A literature survey on buildings' life cycle energy use in residential and non-residential buildings revealed a relationship between operating and embodied energy use through a buildings' lifetime[3]. Figure 1 shows that operational energy conventionally comprises about 90-95% of total primary energy demand. For newer buildings, however, the operating energy is consistently smaller, thus making embodied energy have a larger contribution to energy demand. While modern energy efficient buildings use only a fraction of the use phase energy of old buildings, the production energy use is in the same level or even higher. [4] Indeed, embodied energy can be larger for modern buildings, as a consequence of more material use for insulation as well as an increase in technical installations.

Additionally, when considering environmental impact instead of embodied energy use, the environmental impact due to operation will be relatively smaller compared to energy use. Operational energy use mostly consists of electricity which, considering the Norwegian electricity mix, has a smaller impact per kWh than the more fossil-fuel heavy energy that goes into production of buildings [5]. A concept analysis of a zero emission office building shows embodied emissions to be 66% of total CO_2 emissions during the buildings lifetime [6].

2.2 The Increased Complexity of Ventilation in Buildings

Official regulations have a strong influence on Norwegian building ventilation practices. With the implementation of the the Energy Performance of Buildings Directive (EPBD), as relevant to the European Economic Area Agreement, stricter regulations for low energy use and indoor air quality in residential and non-residential buildings are enforced. New regulations implement a recommended safety factor of 1.3 both to ensure sufficient ventilation, and to accommodate flexibility regarding future change in the use of the premises. Additionally the building standard TEK 10 [8] proposes to avoid unnecessary cooling in new buildings. This has led to the more efficient ventilation cooling replacing local water-borne cooling. Thus, ventilation systems might have to provide higher airflows than the minimum ventilation requirements.

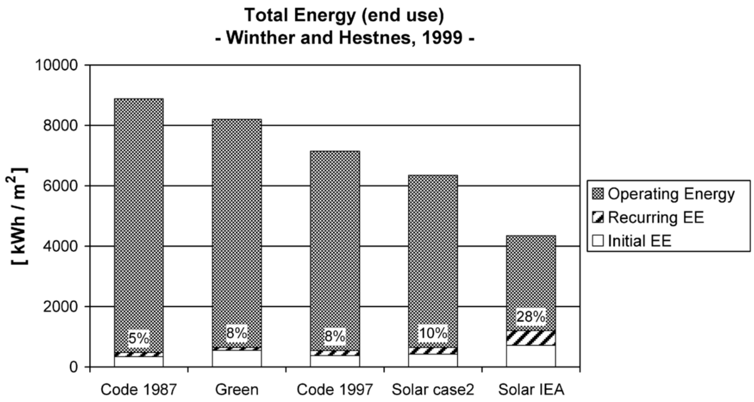


Figure 1: Life cycle energy of five buildings from Winther and Hestnes [7]. "Solar case 2" and "Solar IEA" are low-energy buildings, all the others are conventional.

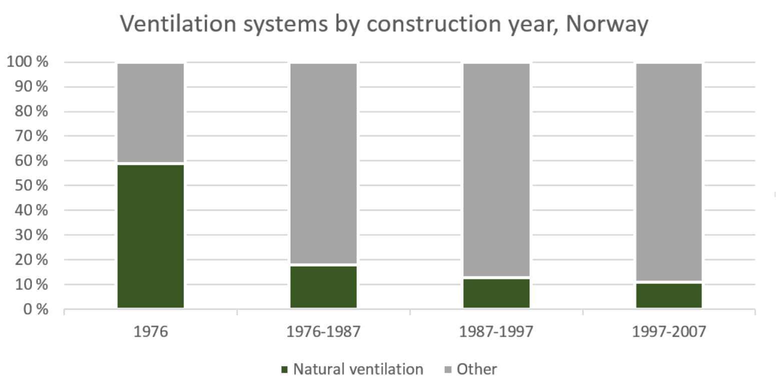


Figure 2: Distribution of ventilation systems in Norwegian houses by construction year. [9]

In practice, these factors make modern energy efficient ventilation compulsory in all types of buildings, which was not the case until now. Figure 2 shows the increasing trend of technical ventilation systems in Norwegian homes [9], with the category "other" mostly consisting of mechanical ventilation.

While the increased focus on indoor air quality and sufficient ventilation volume is definitely beneficial for the inhabitants of the building, the increased complexity and material use calls for a re-evaluation of the environmental impact of these installations both when considering impacts to climate change and other impact categories.

2.3 Intergrating Building Information Models and LCA in Sustainable Building Design

A Building Information Model (BIM), is a powerful tool for providing three-dimensional representations of buildings and building components. A BIM is applied in the architecture and engineering field to represent the building before its actual construction. Individual building objects like doors, windows or ventilation components are modelled, and meta-data on their dimensions, material make-up, cost etc. are held in BIM databases. The data structure in BIM software like Revit or AutoCAD, allows for communication with other programs and data export to perform cost, energy or environmental assessments.

Industry Foundation Classes (IFC) is a file format that works between different BIM software. Norwegian authorities are pushing for a standardization in the industry through the implementation of IFC as a standard file format and standardization of component types and classes. Recently, this has been done through the implementation of Norwegian Standard NS 8360:2015 - BIM objects[10], which recommends IFC as a industry standard. Although there is no mandatory standard format at the moment, standardization of BIM could prove to make environmental assessment of buildings in the early design stage an easier and more precise task.

2.4 Green Building Certifications

LCA methodology combined with a streamlined, BIM based inventory has the potential to aid decision-making in construction projects. With the increased focus on sustainability in building design, several green building certification schemes have been created. These certifications serve as a guidance tool for construction, comparison between buildings as well as a documentation of the strategies and solutions implemented in the building. Examples of these certification methodologies are the Building Research Establishment Environmental Assessment Method (BREEAM) in Europe, and the Leadership in Energy and Environmental Design (LEED) in the United States. Figure 3, shows the procedure for BREAAM certification. Assessment credits for different issue categories are aggregated, weighted, and a single BREEAM score is given. A rating is then produced based on the score ranging from not passed (¡30%) to outstanding (¿85%). As is evident from the issue categories, BREEAM certifications may easily benefit from the advantages of life cycle assessment. Since BREEAM certification starts already in the design stage of the building, it is essential to apply methods to easily assess the environmental performance early in the project stage.

2.5 Attributional and Consequential LCA and Implications for the Choice of Supply Mix

Energy use plays an important role in the life cycle of a building, as such a large amount of energy, specifically electricity, is consumed during the use phase of the building. Thus, the electricity supply mix, meaning the energy sources used to produce the electricity, will be highly relevant

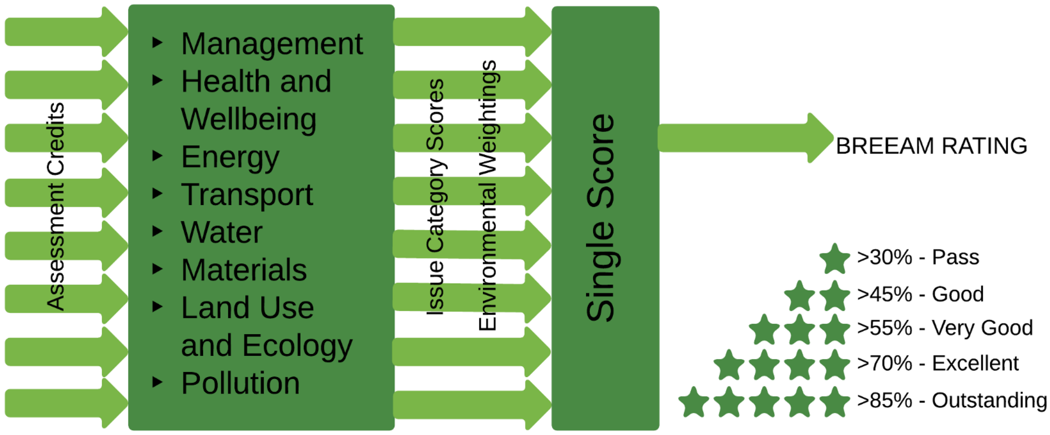


Figure 3: Illustration of the procedure for BREEAM certification. Assessment credits are given for each environmental issue category, the credits are weighted, then aggregated into a single BREEAM rating. Figure based on BREEAM UK briefing paper. [11].

to the total environmental impacts of the study. Clearly, a supply mix based on fossil fuels will have a different environmental profile than a supply mix based on renewable energy.

In the context of LCA the electricity mix will be dependent on the scope set for the assessment. Countries are usually judged on the use of natural resources and emissions occurring in their territories, i.e. the producer principle. Using the producer principle, an LCA of a system in Norway would use the Norwegian electricity mix, with relatively low environmental impacts based mostly on hydropower. This would imply an aim to reduce the environmental impacts within Norwegian borders. When choosing the supply mix applied in an LCA a distinction between attributional and consequential methodology must be made.

In methodological terms, an attributional LCA describes the model "as is" with a static technosphere and combines product specific data with average or generic data for products served by a market with many producers using different technologies.[12]

Consequential LCA however, looks at the consequences a change in the analysed system has on the surrounding technosphere. To exemplify this, one can look at the consequences of the electricity consumed in a building. Applying a marginal approach, a marginal change in electricity use in Norway could replace, or increase production of, electricity in other countries through exports or imports. These electricity mixes could have a much higher environmental impact. In this context it is interesting to study the impact of other electricity mixes, like the Nordic grid mix known as NORDEL, or the entire European mix, if consequential thinking is applied one step further. The development of future energy mixes will also be of relevance when discussing life cycle emissions over such a long time span as the life cycle of buildings.

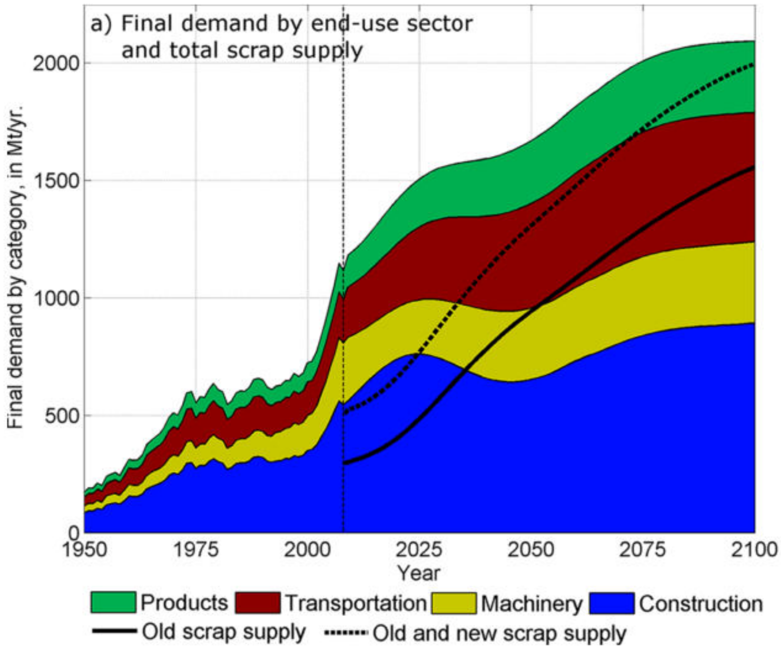


Figure 4: Global final steel demand and total scrap supply by end use sector as calculated by Pauliuk et al. [14]

2.6 Supply and Demand of Steel Scrap in the 21st Century

Since steel is the main material in ventilation systems, scenarios for the steel market will be relevant to analyse when considering environmental impacts. In 2010, steel production accounted for 25% of industrial and 9% of anthropogenic energy and process-related greenhouse gas emissions[13]. Developing forecasting models of global steel production and consumption is crucial for decision-making concerning reduction in carbon emissions. One can also argue that since steel-containing products provide service over a long life time, in-use stock of steel rather than extrapolation of the consumption flow is a more adequate parameter for forecast modelling of steel flows. To estimate future steel final demand, Pauliuk et al. [14] used a stock driven model based on assumptions on future steel stock development and product lifetime on a global scale. Global steel demand was around 1400 Mt/yr as of 2012 and around 75% of this steel demand goes into the construction sector. The estimated current and future global demand of steel scrap and primary steel is shown in figure 2.6.

Material quality requirements and lifetime will vary greatly between the different sectors and products, like buidlings, cars, machines, laptops, etc. Construction is a sector which generally has a high tolerance for the amount of steel scrap in consumed steel. Therefore, if one assumes that most of the secondary steel goes into the construction sector, figure 4 shows final demand exceeding new and old scrap supply until 2025, and only old scrap supply until around 2040. From a consequential perspective, since the global supply of secondary steel is saturated, a marginal increase in steel scrap final demand, will marginally increase global primary steel production, even if steel scrap is consumed. This scenario will be further analysed in the study.

2.7 Life Cycle Assessment as a Tool for Environmental Analysis

Life Cycle Assessment (LCA) is a standardized method used to account for all stressors to the environment that occur in the life cycle of products or systems, including raw material production, manufacture, distribution, use and end-of-life disposal, as well as all transportation occurring in these steps. All induced use of materials, energy and services have to be detected and accounted for when conducting an LCA.

The frameworks and rules for the performance of an LCA are given by ISO 14040 "Environmental management - Life Cycle Assessment, Principles and framework" [15] and ISO 14044 "Environmental management - Life Cycle Assessment. An LCA study consists of four phases which are Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and the interpretation phase.

2.7.1 Goal and Scope

In this phase of the LCA, the purpose of the assessment is presented and the system boundaries are set. The goal of the LCA will decide the methodology to be used. An example of a goal might be to identify the unit process of a product or system with the greatest environmental impact in order to efficiently reduce the total impact of the system. Another goal could be to compare two systems or products that serve the same purpose, in order to find the alternative with the lowest environmental impact.

Additionally, the functional unit is decided in this phase. A product or system may have many functions and it is important to define the specific function that is to be analysed in the assessment. The functional unit characterizes the system and serves as a reference to which the inputs and outputs of the system are normalized. Therefore the functional unit must be clearly defined and measurable. This is of special importance when comparing two systems, as to ensure both that they indeed serve the same purpose, and that a fair comparison between the two is made.

The system boundaries define the cut-off criteria and the level of detail of the model describing the relevant system. The cut-off criteria must be consistent with the goal of the study. A preliminary LCA in the planning phase of a project will often have a higher amount of uncertainty and lower level of detail than an LCA analysing an existing system or product. The model consists of unit processes - materials, products or processes that are needed to deliver the functional unit. To better describe the system and the system boundaries it can be helpful to construct a process flow diagram showing the unit processes of the system and their inter-relationships.

Finally, in this phase one decides the impact categories, time horizons of impacts, category indicators and characterization models that are to be included in the study.

2.7.2 Life Cycle Inventory

After the goal and scope of the study has been defined, the life cycle inventory phase of an LCA can be conducted. In the Life Cycle Inventory (LCI) phase all relevant inputs and outputs of the unit processes within the system boundaries are found and quantified. This includes the input of energy and materials to all processes, outputs of products, co-products, as well as waste and stressors to air, water and soil.

Data can be obtained from different sources, like suppliers, product declarations, existing literature or statistical data. Another alternative is to use established LCI databases. Ecoinvent, is a database that is commonly used in Europe and Frischknecht et al. have described its methodology in great detail [16].

Conventionally, all emissions and other stressors are assumed to occur simultaneously, even if they in reality occur at different times. Therefore, the LCI results is a list of all occurring stressors associated with the life cycle of the functional unit. This list is further analysed in the LCIA phase.

2.7.3 Life Cycle Impact Assessment

In the LCIA phase, the stressors found in the the Life Cycle Inventory are translated into environmental impacts. The LCIA phase is divided into four parts.

- **Selection of impact categories and characterisation models:** Different impact categories highlight different environmental concerns like climate change or terrestrial acidification. The impact categories included should be related to the goal and scope of the study.
- **Classification:** The stressors from the LCI phase are classified and assigned to different impact indicators. A stressor can contribute to more than one impact category.
- **Characterisation:** Based on physical characteristics and mathematical models, the impact from each stressor is quantified with the use of characterization factors. The factors describe the contribution each stressor has to the impact category relative to a reference stressor.
- **Normalization, weighting and grouping (optional):** In this last optional step, the impacts are normalised and the magnitude of the impacts relative to a reference is calculated. The impact categories can also be grouped and weighted according to some end-goal to give a final score of the assessment.

2.7.4 Interpretation

The main interpretation is done at this stage where the results are evaluated in relation to the defined goal and scope. Limitations of the study are discussed and a sensitivity analysis should also be included. It is important to note that the interpretation phase is not necessarily a phase in itself, as interpretation should be applied through all the other stages of the assessment.

2.8 Dynamic LCA

The conventional LCA does not fully describe the environmental impacts related to climate change of a system with a long lifetime, like for instance a building. The selection of a time horizon is a critical aspect of the carbon accounting process. Conventionally, a time horizon of 20, 100 or 500 years is chosen for climate change, with 100 years being the most common time horizon. Since many GHGs are prevalent in the atmosphere a long time after their release, the choice of a time horizon acts as a cut-off criterion, which means that impacts occurring after the given time horizon are not considered in the analysis. Conventional LCA aggregates all emissions as occurring at time 0, not considering the time at which the emissions occur. Thus, there is an inconsistency between the time horizon chosen for the analysis in a given LCA study, and the time period covered by the results. This is true especially for long lasting projects like the life cycle of a building.

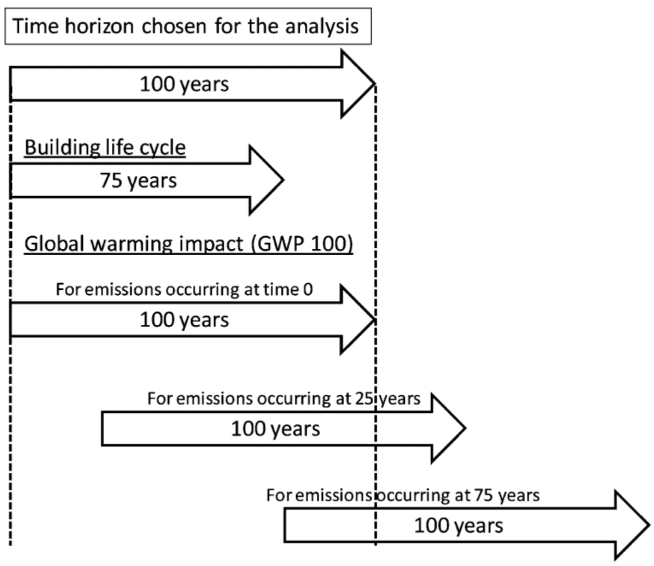


Figure 5: Illustration of the inconsistency in time frames for global warming LCIA with the example of a 75-year lifetime building. [17]

Levasseur et al.[17] exemplify this inconsistency by using a life cycle of a building with a 75-year lifetime. A building will have emissions throughout its life cycle, from the construction phase, use and demolition phase. A conventional impact assessment method that uses GWP with a time horizon of 100 years should consider the global warming impacts over 100 years. This is not the case with the current methodology. Figure5 shows the different time frames actually calculated in a conventional LCA. It is apparent that impacts that occur 25 years after construction will be considered from year 25 to year 125, and emissions happening at the end-of-life of the building, 75 years after construction, will be considered to year 175, far extending the initial time horizon of the study. The authors propose an alternative methodology for dynamic life cycle assessment which has been used in this study, and is thoroughly outlined in section 4.2.2.

3 Literature Review

This section presents a literature study on LCA of buildings. First, embodied emissions in the construction sector as a whole are presented. Then, LCA methodologies and challenges specific to building LCA are outlined as found in literature. Finally, earlier studies on building LCAs, specifically Heating Ventilation and Air Conditioning (HVAC) and ventilation systems are given, as well as literature on the combination of BIM and LCA.

3.1 Assessing Embodied Emissions in the Construction Sector

To assess embodied energy and emissions, two approaches may be used. A bottom-up approach, represented by process-based LCA, and a top-down approach represented by an Environmentally Extended Input-Output (EEIO). There is a difference between calculated energy use in the production phase according to these two approaches, with EEIO consistently reporting a larger energy use as shown by Nassen et al[5]. The paper compares direct and indirect energy use and carbon emissions in the production phase of buildings and uses input-output tables compiled by the National Accounts at Statistics Sweden. Total energy use and emissions per unit of final consumption are calculated using transactions between sectors and factors of direct energy and emissions in each sector for the monetary amount spent. The method shows the emissions from consumption based on the production of an unlimited number of upstream sectors. The construction sector is split into into six sub-sectors.

- New Construction of:
  - Detached residential buildings
  - Multi-dwelling buildings
  - Service buildings
  - Industrial buildings
- Reconstruction/refurbishment of buildings
- Roads/infrastructure

The data is split using data on materials use from the Swedish Environmental Protection Agency and a database on costs for production of various house types divided into groups of building components, materials and labour.

The input-output analysis results divide CO_2 emissions into mobile, stationary and process emissions. Mobile emissions include emissions from petrol, diesel, marine bunker and jet fuels for transport and operation of mobile machinery. Stationary emissions are all other energy related emissions, and process emissions originate from chemical processes such as the calcification of limestone in cement production and the use of coke as a reducing agent in iron and steel production.

The study defines an emissions factor (CO_2/primary energy) and the results are shown in table 1. Total emissions factor for building production is given as 15.9 tC/TJ. This can be compared to 7.6 tC/TJ for the Swedish economy as a whole. The emissions from total emissions attributed to building construction, 938 ktonC, correspond to about 6% of the total emissions within Sweden in 2000, although this is a low figure compared to an average in the period 1950-2000. The input-output analysis also reveals a larger share of total emissions than previously assumed to be attributed to embodied emissions and the construction phase, from the previous 15% to 25% of total life cycle emissions. It is worth noting that the study uses the amount of carbon and not the amount of CO_2 released when assessing emissions. This must be taken into consideration when comparing the study with other studies.

A similar study done in Norway evaluates the entire construction sector as a whole, considering nine types of main air emissions: Greenhouse gases(GHGs), acidification precursors (NO_X, SO_X, and NH_3), ozone precursors (e.g. NO_X, CO and CH_4), and PM10.

In the Norwegian case, results show that the embodied air emissions in the Norwegian construction sector and its contribution to total national emissions increased between 2003 and 2007. However, the intensities of the embodied emissions decreased during this time period, which implies an improvement in environmental efficiency in the construction sector. The authors suggest the largest potential for emission reduction in the Norwegian construction sector relies on up-stream suppliers, and emission reduction could be achieved by introducing policies to drive stakeholder to select low emissions materials and material suppliers with low embodied energy.

Sector	Primary energy (TJ)	CO2 mobile (kton C)	CO2 stationary (kton C)	CO2 process (kton C)	CO2 total (kton C)	Cumulative share of CO2(%)
Concrete and cement	5416	2	126	139	267	28.5
Construction	11003	157	62	0	219	51.8
Siron and steel production	4414	4	59	46	109	63.4
Freight transport by road	3003	61	0	0	61	69.9
Other non-metal mineral products	1284	1	30	2	32	73.3
Petroleum refining etc.	1262	0	26	0	26	76.1
Air Transport	999	20	0	0	20	78.1
Steam and hot water supply	2079	0	18	0	18	80.1
Non-ferrous metal industry	564	0	9	9	18	82
First processing of iron and steel	714	0	11	5	15	83.7
Mining of fossil fuels	692	1	14	0	15	85.3
Water transport	1160	13	0	0	13	86.7
Mining of non-metal minerals	565	2	11	0	12	88
Electricity production	15755	0	12	0	12	89.3
Glass and glass products	401	0	8	2	10	90.4
Wholesale and retail trade	496	9	1	0	10	91.4
Chemicals nand paint	139	0	8	0	8	92.2
Wood and wood products	2108	2	5	0	7	93
Structural metal prducts etc	359	2	5	0	7	93.8
Agriculture	344	5	2	0	7	94.5
Paper and paper products	1027	0	4	0	4	94.9
Ceramics	234	0	4	0	4	95.4
Other sectors	4652	25	19	0	43	100
Total	28970	304	431	203	938	

Table 1: Primary energy and CO2 emissions linked to activities in the Swedish building sector in year 2000 taken from a study by Nässen et al.[5].

3.2 Life Cycle Assessment of Buildings

Although LCA has been widely used in the building sector since the 1990s, it is less developed than other industries like the engineering and infrastructure sector. This is not to say that it is not an important field within LCA practice. A review of practices and methodologies of LCA's of buildings reveals several factors that combine to make the building sector especially complex in terms of Life Cycle Assessement [18] [19].

- Buildings have a long lifetime, a lifetime of 50-70 years is typically assumed. This results in considerable uncertainties in the LCA findings and assumptions need to be made on the building operations, and maintenance during the use phase [20], making it difficult to predict the whole life-cycle from cradle-to-grave. This problem can be somewhat mitigated by applying uncertainty analysis to the LCA.

- A building might undergo significant changes to its form and function during its life span. These changes can significantly change the environmental profile of the building, and they are only partly a function of the original design.

- As mentioned in section 2.1, traditionally, up to 80% to 90% of the life cycle energy use occurs in the use phase. Nevertheless, it is clear that proper design and material selection play a significant role in reducing life cycle emissions of the building.

- Site specific impacts need to be specifically considered such as the buildings effect on the surrounding environment, rain and storm water flows as well as neighbourhood security [20].

Goal and scope definitions will vary, depending on the available realistic data and the purpose of the assessment. In some cases unavailability of national specific data can drive the study in the wrong direction or change its goal and scope.

The functional unit in a building will vary from study to study, although there have been many attempts for standardization [21]. Typical functional units are m^2, m^2 internal space, m^3, and number of occupants. Some studies consider ton of material as the unit when the study is related to a material environmental burden [18]. The most used functional unit seems to be square meter floor area (m^2) or living floor area in the case of dwellings. It is important to remember that even though different projects might have a similar functional unit, a comparison between them is not valid unless the scope is also similar.

Often included life cycle stages in the scope of the study is the embodied energy of materials and building component combinations, the transport of materials and building components to the site, the energy use of the building, maintenance and replacement, demolition of the building, and transport of waste to the treatment side. Usually omitted is the construction phase at the site and waste [22].

Several different approaches have been applied to completely encompass the complexity of LCA of buildings. Although most studies follow a traditional approach, other approaches have been applied. Erlandsson and Borg [23] propose an alternative method to work around the aforementioned challenges. Instead of a simple, linear, static approach with the usual phases of construction, operation and end-of-life, they treat buildings as dynamic service providers and

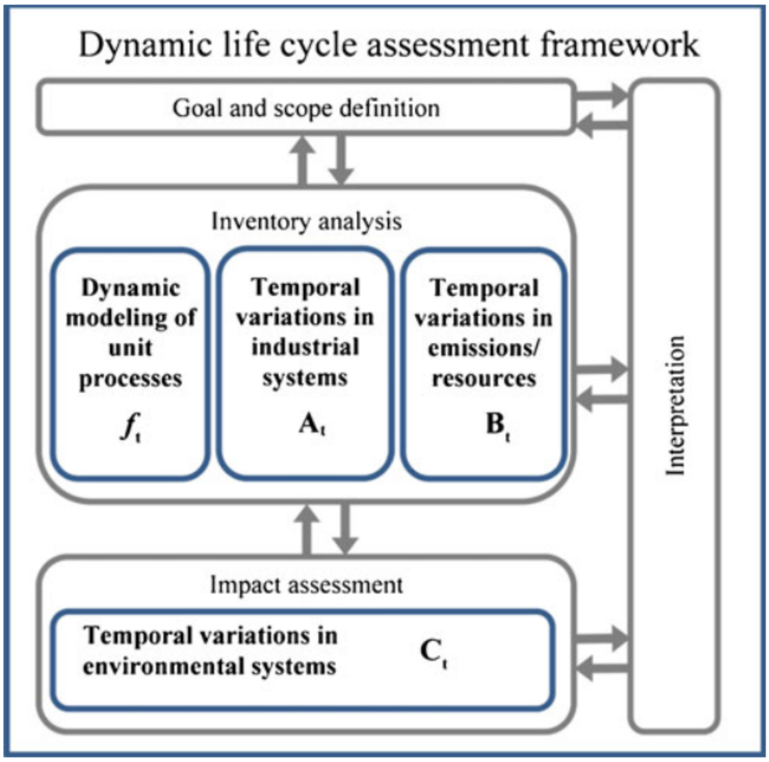


Figure 6: The conceptual framework of a dynamic LCA as presented by Collinge et al.[24]

include the possibility for a building to be modified. Since both the building and its utilisation will change over time, a flexible LCA model is presented that allows user choices.

The concept of a dynamic LCA is defined by Collinge et. al [24] as "an approach to LCA which explicitly incorporates dynamic process modelling in the context of temporal and spatial variations in the surrounding industrial and environmental systems". The implications of the concept of a dynamic LCA on LCA framework is shown in figure 6. The authors apply the model on an institutional building and show that the environmental impacts of a building vary significantly from what would be predicted if temporal changes were not taken into account. The results highlight the importance of changes in building use, energy sources, and environmental regulations in calculating the overall environmental impacts of the building and advocate a more dynamic focus when assessing the environmental profile of a building.

To address the uncertainties inherent in LCA methodology, especially when considering the long time horizon of building LCA's, Huijbregts et al. [25] identify three types of uncertainties and make a distinction between parameter, scenario, and model uncertainties. Parameter uncertainty is introduced by measurement errors in input data. Scenario uncertainty reflects the uncertainties inherent in the choices in the modelling procedure e.g., concerning the relevant time horizon or geographical scale. Model uncertainty is associated with the discrepancy with the theoretical LCA structure and relevant aspects in the real world. The authors developed a methodology to holistically assess the uncertainty in the study by using Monte Carlo simulation to quantify parameter uncertainty and various decision settings to quantify model and scenario uncertainty.

Additionally, several authors stress the need to assess other impact categories apart from climate change. As well as addressing the lack of attention to occupant well-being in LCA practices, Hellweg et. al [26] show conflicting results to previous building LCAs that stress the significance of energy use over other environmental impacts. The authors conclude that other environmental impacts like use-phase human health effects must be considered in order to avoid "burden shifting from environment to workers' health."

It is clear that energy use in the use phase is not the only phase that must be considered in order to avoid burden shifting, and that conventional LCA practices like a static LCA cannot always give a balanced picture of the environmental profile of the life cycle of a building. The choice of methodology will obviously have a large impact on the results and must be chosen to best reflect reality.

3.2.1 Life Cycle Impact of Buildings

Several studies have been conducted on the environmental impact of non-residential buildings. Junnila and Horvarth [27] studied significant environmental aspects of a high-end office buildings with a life span of over 50 year. The results show the majority of the impacts being associated with electricity use and building materials manufacturing. The authors highlight electricity used in lightning and HVAC systems and manufacture and maintenance of steel, concrete and paint as some of the most significant aspects. The total GHG emissions were estimated to be 48 000 ton CO_2 eq/m^2 per 50 years.

Ramesh et al.[28] conducted a review of Life Cycle Assessments of buildings. The cases included studies from all around the world, and found that life cycle primary energy varied between 250-550 kWh/m^2a for office buildings, as indicated by figure 7. According to the authors 80-90% stemmed from building operation, while 10-20% stemmed from embodied energy, although some studies state embodied energy to be up to 30% of total primary energy demand. Optis and Wild [29], identify a range for embodied energy of between 2-51%.

Ramesh et al.[28] explain the wide variation in embodied energy found within building types to differences in building location, climatic conditions and the local energy mix. In addition, Optis and Wild [29] include other factors to explain the range in values like building lifespan, insulation levels, material replacement schedules and occupancy levels.

Sartori and Hestnes [3], conclude in their review on life cycle energy use in low energy buildings that energy use during the operational phase is the most important area to address. They do however suggest that evidence in the literature implies the potential for reducing embodied energy through recycling. They also conclude that waste management is not emphasized in LCAs of buildings.

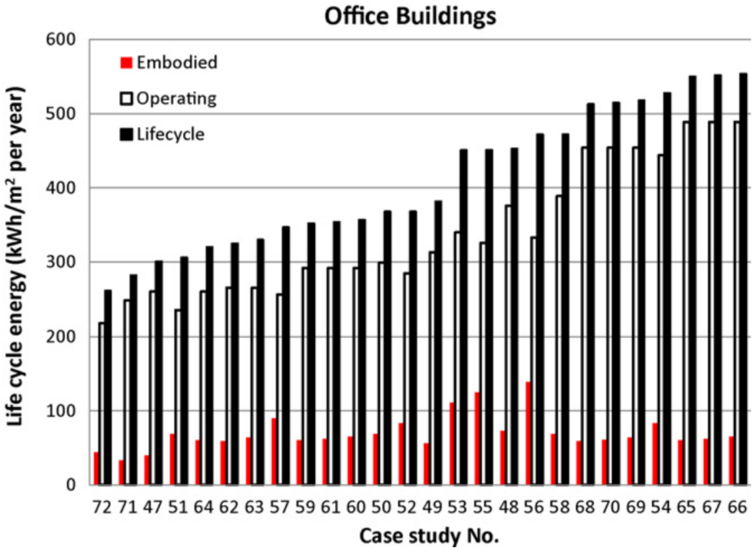


Figure 7: Normalized life cycle energy for conventional office buildings (primary) [28].

3.2.2 The Knowledge Gap on the Environmental Impact of Technical Installations in Buildings

Although some studies have examined technical installations in buildings, few encompass the same scope as this thesis. Shah et al. [30] preformed a life cycle assessment of residential heating and cooling systems in four US regions. Though they did not assess ventilation systems, many common factors can be taken away from the study. They found that operational energy consumption is the dominant phase over the entire study period, and that the HVAC equipment will have different environmental impact based on the regional climate and energy source. In particular, the study found that electric heat pumps in areas with an electricity mix consisting of mostly hydro-electric power, will have lower emissions than a furnace and air-conditioner combination or a boiler and air-conditioner system. The electricity mix will have a large impact on the environmental profile of technical installations.

A comprehensive study on HVAC equipment in North American buildings has been conducted using an Input-Output methodology and found life cycle CO_2 emissions from a range of building types across different climate zones in the United States [31]. It is important to note that the electricity mix from four regions of the U.S. was used, with emission rates varying from 0.64 to 0.97 kg CO_2-eq/kWh. This is a lot higher than the emission factor for the Norwegian supply mix which is around 0.05 kg CO_2 eq/kWh. It is however comparable to the European average supply mix of 0.46 kg CO_2 eq/kWh. The results show a large variation in GHG emissions per square meter over different climate zones as shown in figure 8 and table 2.

Nyman and Simonson [32] preformed an LCA of residential ventilation units in Finland, evaluating two different ventilation units, both of which include air-to-air energy exchangers. The ventilation units were equipped in typical three bedroom house of 120-150 m^2. The lifetime of the building is set to 50 years. Figure 9 shows the total emissions from the production of

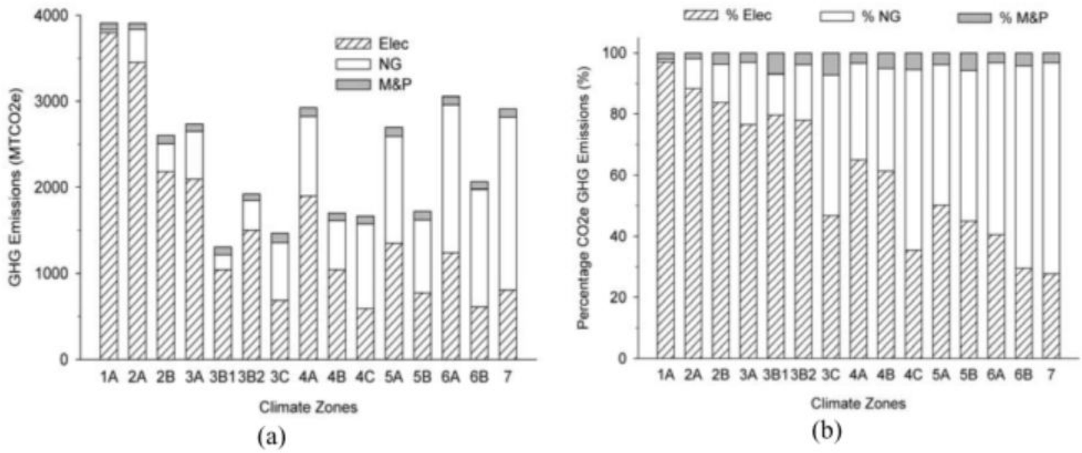


Figure 8: (a) CO_2 eq GHG emissions of medium offices for all climate zones in the American study by Tan et al., and **(b)** percentage CO_2 eq GHG emissions of medium office for all climate zones. NG is natural gas, while M and P are embodied emissions from materials and production [31].

	CLIMATE ZONE														
Building type	1A	2A	2B	3A	3B1	3B2	3C	4A	4B	4C	5A	5B	6A	6B	7
Medium office	0.78	0.78	0.52	0.55	0.26	0.39	0.29	0.59	0.34	0.33	0.54	0.35	0.61	0.41	0.58

Table 2: MT CO_2 eq GHG emissions per square meter of conditioned floor area for each climate zone in the U.S. [31].

materials and the ventilation units over the 50 year life cyce [32].

The authors attribute a large amount of avoided emissions from the thermal energy recycled in the heat exchanger. This is however not relevant in the context of this thesis, since the case study is of a building already being constructed with a decided technology for ventilation and heating. The results are however not expected to coincide with the results from this thesis, both because of the difference in building types, as well as the difference in scope. Nyman and Simonson do not consider ventilation ductwork, and neither the heating of the ventilation air.

Few studies in Norwegian climate have been preformed, but Dokka et al. [6] analyse a zero emissions concept analysis of an office building, including the ventilation system in the process. Although the building concept varies in many aspects from a traditional office building, because of elements like PV-solar panels producing on-site electricity equal to total demand, the technical systems in the model are based on traditional design and material use of a Norwegian office building. Therefore the results could be comparable to the results from this thesis.

The model was based on a concept building of a four storey high office building plus a basement, with the total Heated Floor Area (UFA) being 1980 m^2. The ventilation system was a balanced, demand controlled ventilation system with variable air volume based on CO_2 levels, temperature, and presence sensors. The Air Handling Unit (AHU), situated in the unheated basement, was a high efficiency rotary wheel exchanger. To reduce the pressure loss, a combined coil for both heating and cooling in the AHU was used. Additionally, heating was provided by a more conventional hydronic radiator system.

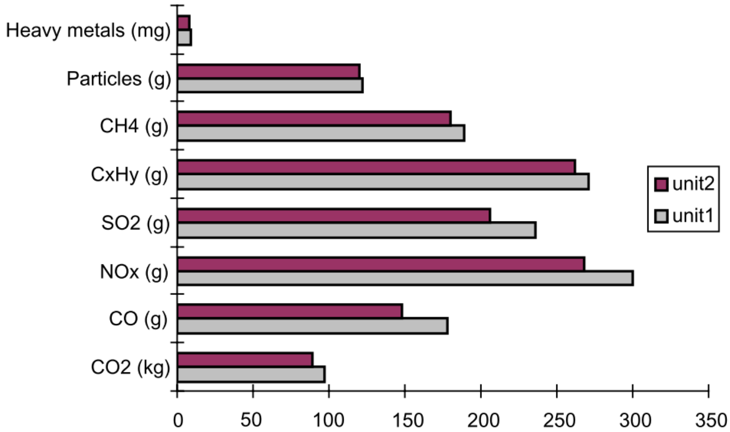


Figure 9: Total emissions from the production of materials and the ventilation units over the 50 year life cycle of the swedish study on ventilation units.[32]

Phase	kg CO_2 eq/m^2	kg CO_2 eq/m^2 per year
Initial material use	384.0	6.4
Replacements	126.0	2.1
Total	510.0	8.5

Table 3: Total embodied GHG emissions from material use for the ZEB-concept.[6]

To calculate the embodied emissions, the author set the system boundaries to the extraction of raw materials and the manufacturing of the main products and materials needed, as well as replacement of the materials over the expected lifetime of the building, which is 60 years.

The material inputs are generated from a BIM model created in Revit, and are structured after the table of building elements, NS 3451. The authors highlight a relevant issue which is that the level of detail in the assessment is only as accurate as the level of detail in the BIM model. Since the project is in a pilot phase, only estimates on metals used in ventilation system, duct air handling units, etc. are implemented. These are based on experiences from pilot buildings and literature. The impact categories chosen are cumulative energy demand (CED), and the IPCC Global warming potential method from 2007 with a 100 year time horizon.

The results are divided into embodied emissions and emissions for energy use. Table 3 shows total CO_2 emissions over the lifetime of the building. Ventilation constitutes around 0.4 kg CO_2 eq/m^2 per year or roughly 5% of total embodied emissions as shown in figure 10. Note that in this case Solar Cell materials sum up to 25% of total embodied emissions.

Energy use emissions are given in table 11, although ventilation does not show as a separate post in this case. Operation of pumps is shown to be very small, thus heat and pumps are mostly energy use for ventilation. Additionally, part of the cooling demand will come from the ventilation cooling. The study find operational emissions to constitute 34% of total emissions, and embodied emissions to be 66%. This is mainly thanks to the minor operational emissions from the PV system. Emissions from end-of-life are not considered in this study.

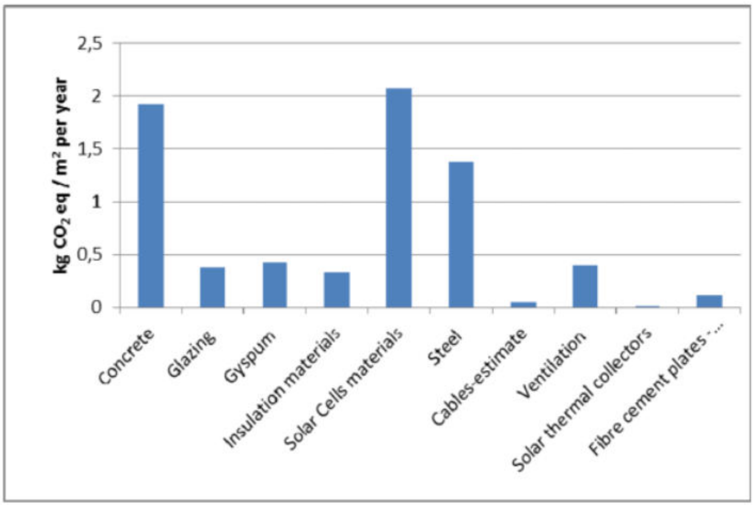


Figure 10: Greenhouse gas emissions for the main materials and technical installations in the ZEB-concept [6]

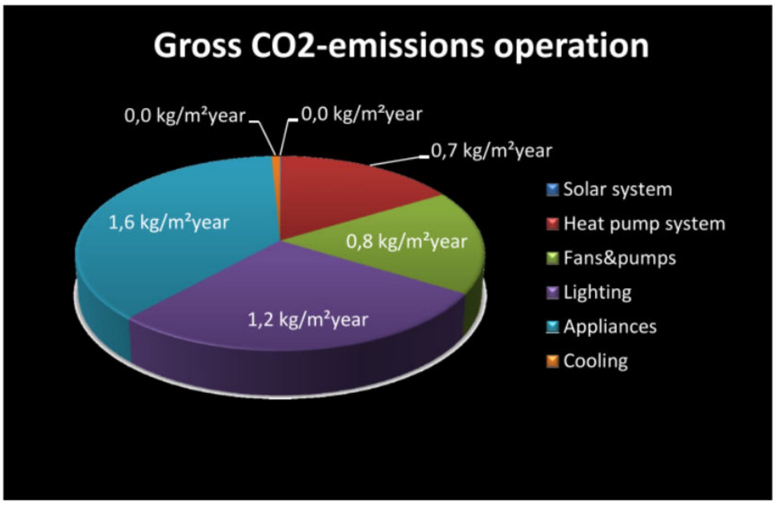


Figure 11: Greenhouse gas emissions for the operational energy use in the ZEB. [6]

3.3 BIM Modelling as a Tool for LCA Analysis

Antón and Díaz [33], recognize the potential for an integration of Life Cycle assessment in a BIM environment and propose an approach to easier implement sustainability in building design. They state that as quality and availability of data is one of the main drawbacks of LCA in the building design process, BIM modelling can be used to provide inventory data, and in turn improve the environmental performance of the building. The two approaches proposed are:

- Direct access to the BIM model information to calculate the LCA performance.
- Environmental properties included in the BIM objects.

The first method is deemed more accurate as it would include more stages of the building in the process. The authors also advocate the IFC data format as a standard file-sharing format.

Stadel et. al[34], cites experience from working with LCA plug-ins in BIM programs like Revit and conclude that these are not precise enough compared to results from dedicated Life Cycle Assessment tools like SimaPro. One of the main challenges the authors cite in using BIM for LCA, is that the material takeoff tool requires that composite materials be manually disaggregated in order to achieve the individual material estimates. As an example a concrete wall with wooden studs will only be presented as a compact wall and not its separate concrete and wooden component.

Figure 12: Concept of the office building Abels hus, Image: Narud Stokke Wiig .

4 Methodology

In this section the methodology of the study is presented, starting with a description of Abels Hus, the building under study. Then the mathematical background of conventional LCA calculations is shown, an essential basis for Environmentally Extended Input-Output Analysis and the modified Dynamic LCA, methods which are then outlined. Choices for the three main phases of the LCA, Goal and Scope, Life Cycle Inventory and Life Cycle Impact Assessment, are then presented finishing with the assumptions, scenarios and sensitivity analyses applied to the study.

4.1 Description of Abels Hus

The building which has been analyzed is Abels Hus, located in Abels gate in Trondheim. The building is a six story office building with high flexibility in the floor designs, meaning there are many possible layouts of cell-offices, team-offices and open office environments. The useful floor area is close to 15000 m^2 for the office with a garage of 3100 m^2, the useful floor area per story is shown in table 4. The expected time of completion is spring, 2017.

The project is to be certified as "Excellent" according to the current version of the BREEAM-NOR manual. A pre-analysis of the project has been conducted, showing that this grade will indeed be achieved for the project. Additionally, the energy performance of the building must comply with an energy certificate of grade A. This means that the energy consumption of the building must be low. The calculated energy consumption is given at 93.6 kWh/m^2a which is adequate and very low compared to a required energy consumption of 150 kWh/m^2a for the Norwegian standard TEK-10. The low energy consumption is achieved through high insulation in the external walls and efficient technical installations and lighting.

The plumbing, heating and santiation installations are dimensioned according to governmental regulations and BREEAM specifications. The building is equipped with water-borne heating

Area per floor of Abels Hus	
Level	Area [m^2]
1	2921
2	2450
3	2451
4	2271
5	2040
6	1409
7a	80
7b	85
7c	16
U1 - a	577
U1 - b	666
U1 - Parking	3100
Total w/o Parking	14966
Total with Parking	18066

Table 4: Useful floor area as given in the planning documents for Abels Hus.

with an air-to-water heat pump and district heating. A balanced ventilation system ventilates the building with air mixing applied as the ventilation concept. Variable Air Ventilation will be used provided by the system Wise by Swegon. The ventilation will be demand controlled through CO_2, temperature and motion sensors. Ventilation cooling is supplied by a heat pump.

Sets	Pro		Processes
	Str		Stressors
	Imp		Impact categories
Matrices and Variables	A	pro × pro	Matrix of inter process requirements
	y	pro × 1	Vector of external demand of processes
	x	pro × 1	Vector of outputs for a given external demand
	L	pro × pro	The Leontief inverse, Matrix of outputs per unit of external demand
	S	str × pro	Matrix of stressors intensities per unit output
	e	str × 1	Vector of stressors generated for a given external demand
	C	imp × str	Characterization matrix
	d	imp × 1	Vector of impacts generated for a given external demand
	D	imp × pro	Total impacts by process

Table 5: Sets, Vectors and Matrices used in LCA [35].

4.2 Mathematical Methodology

4.2.1 Mathematical Basics of LCA

The interdependency between processes in LCA is modelled as a linear system, and the Open Leontief Model is used, with linear algebra as the mathematical basis. The inter-process requirements matrix, A, gives the amount of product i necessary to produce one unit of product j. This is represented as a_{ij} in the matrix. The matrices and variables used in LCA calculations are given in table 5.

First, the x vector is calculated, which gives the production output of the system. This is equal to the intermediate demand, plus final demand.

$$x = Ax + y \quad \Leftrightarrow \quad (I - A) = y \quad \Leftrightarrow \quad x = (I - a)^{-1}y \tag{1}$$

Where

$$L = (I - A)^{-1} \quad \Rightarrow \quad x = Ly \tag{2}$$

L is the Leontief inverse, the coefficients in L (l_{ij}) show the amount of output for a process i, required per unit final demand of process j.

The stressor matrix, S, gives the stressors or emissions associated with one unit of output of a given process. The e matrix, the total stressors associated with an external demand, is found simply by multiplying the stressor matrix with the output x.

$$e = SLy = Sx \tag{3}$$

The emissions are then aggregated into impact categories using the characterization matrix C, which gives the contribution each stressor has to an impact category, relative to a reference stressor. The final impact in equivalent units, for instance kg CO_2 equivalents, is then found by the following equation:

$$d = Ce \tag{4}$$

This methodology forms the basis for the calculation of Life Cycle Impacts, but when assessing for example emissions related to building construction services, economical input-output tables are used for the analysis. Here, Environmentally Extended Input-Output Analysis (EEIOA) is applied. The calculation is similar to the outlined procedure, but the inter-process requirements matrix A is replaced by inter-industry requirements,

$$A = Z \times \hat{x}_{ind}^{-1} \tag{5}$$

where $\hat{x}_{ind}$ is the vector x_{ind} diagonalized into a matrix. The Z matrix represents the inter-industry flows within an economy given in economical input-output tables. The vector x_{ind}, must not be confused with the previously given output vector, but is the total output of each industry in the economy. The remaining calculation is done in a similar way except that the previously given stressor matrix S is replaced with the industry specific stressor matrix F,

$$F = M \times \hat{x}_{ind}^{-1} \tag{6}$$

Where M is the total industry specific stressors occuring in the economy, which can be taken from industry statistics or national emissions inventories.

Resource use and emissions, E associated with a specific final demand can then be calculated in the same manner as for standard LCA,

$$E = F(I - A)^{-1}y \tag{7}$$

Environmental impacts can then be aggregated into impact categories analogously to equation 4.

4.2.2 Dynamic LCA

As we have seen, standard LCA practice is to add all emissions of a single pollutant throughout the life cycle to a single aggregate emission. Then, the environmental impact from the pollutant is characterized in the environmental impact assessment method to link the selected pollutant to an environmental problem. As described in section 4.2.1, each of these LCIA methods provide characterization factors to give a linear relationship between the pollutant and its effect on the selected impact category.

Since the inventory results traditionally are aggregated and said to be occurring in time zero, this will not reflect reality as releasing a big amount of a pollutant instantaneously will generally

	20 years	100 years	500 years
CO_2	1	1	1
CH_4	72	25	7.6
N_2O	289	298	153

Table 6: GWP Values for CO_2,CH_4 and N_2O for time horizons of 20, 100, and 500 years as published by the IPCC in the fourth assessment report [17]

not have the same impact as releasing the same amount of pollutant at a small rate over several years. Thus, conventional LCA will have a decreased accuracy when analysing systems over a long time period, because of the inconsistencies in methodology outlined in section 2.8.

To understand the importance of temporal information for calculation of the Global Warming Potential (GWP) one must understand how the GWP is calculated for different time horizons and for different greenhouse gases. The mathematical expression for GWP of gas i is given by

$$GWP_i^{TH} = \frac{\int_0^{TH} a_i[C_i(t)\mathrm{d}t]}{\int_0^{TH} a_r[C_r(t)\mathrm{d}t]} \tag{8}$$

Where,

TH - The chosen time horizon for the analysis.

a - The instantaneous radiative forcing per unit mass increase in the atmosphere. [W/m^{2}kg]

$C(t)$ - Time dependent atmospheric load of the released gas. [kg]

i - The released gas.

r - Reference gas, carbon dioxide.

Radiative forcing expresses the change in energy in the atmosphere due to a GHG emission. Figure 13 shows the radiative forcing of a unit mass pulse emission at time zero for carbon dioxide to illustrate the atmospheric effect of different gases over different time horizons. From equation 8 it is evident that carbon dioxide will have a GWP of 1 for a given time horizon, while other greenhouse gases will have a GWP relative to carbon dioxide. This is shown in table 6. To calculate the global warming impact in "kg CO_2 equivalent" the LCI results for each greenhouse gas are multiplied by their respective GWP. In the case of methane, which has a short lifetime in the atmosphere of about 12 years, its total greenhouse effect will occur during the first years after its emission. Considering methane, one can see from figure 13, that when the time horizon changes from 100 to 500 years, the numerator in equation 8, represented by the area under the graph, remains constant while the denominator increases significantly. This is why GWP values for methane increase considerably with a decreasing time horizon.

The use of a time horizon in LCIA has a large effect on the results of the analysis. Therefore one must be consistent with the chosen time horizon.

Levasseur et al. [17] propose a dynamic LCA model which is used in this study to deal with

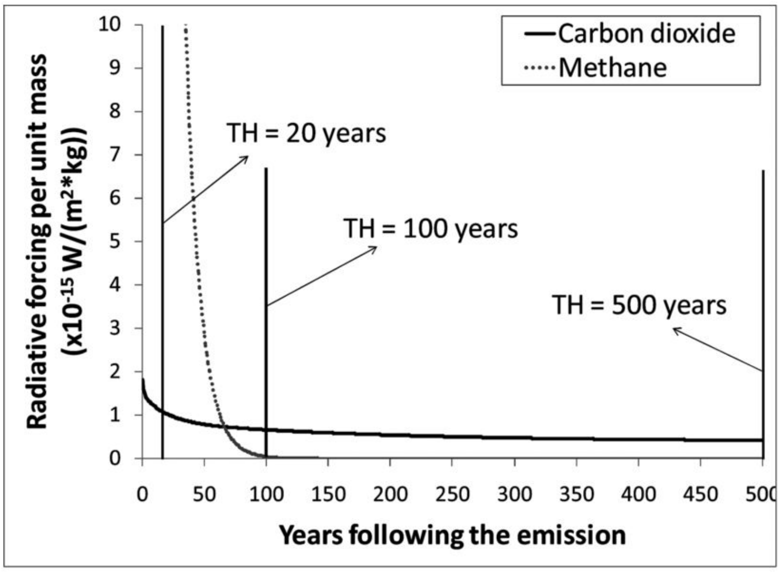


Figure 13: Radiative forcing of a unit mass pulse emission at time zero for carbon dioxide and methane with the three time horizons proposed by IPCC[17].

the methodological inconsistencies with GWP presented earlier. Since the methods for characterization factors are based on scientific models, they only need to be adjusted to a temporal perspective to be applicable to the model. The Dynamic Characterization Factor (DCF) represents the cumulative radiative forcing per unit mass of GHG released in the atmosphere since the emission as shown in figure 14a. To obtain the instantaneous value of a DCF for any year following the emission, shown in figure 14b, the model divides into one-year time periods, and integrates for every time step.

$$DCF_i(t)_{instantaneous} = \int_{t-1}^{t} a_i[C_i(t)\mathrm{d}t] \tag{9}$$

It is then possible to compute the time-dependent impact on global warming (GWI) for a specific dynamic life cycle inventory with yearly emissions of GHGs.

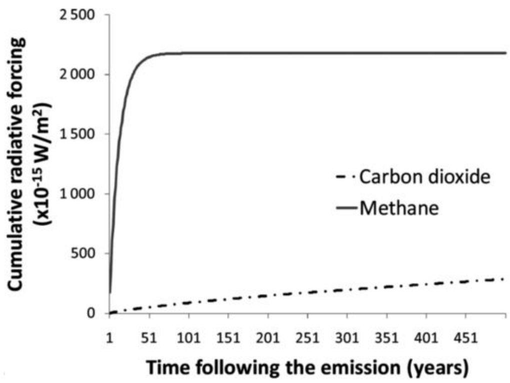
$$GWI(t) = \sum_i \sum_{j=0}^{t} [g_i]_j * [DCF_i]_{t-j} \tag{10}$$

g - inventory result

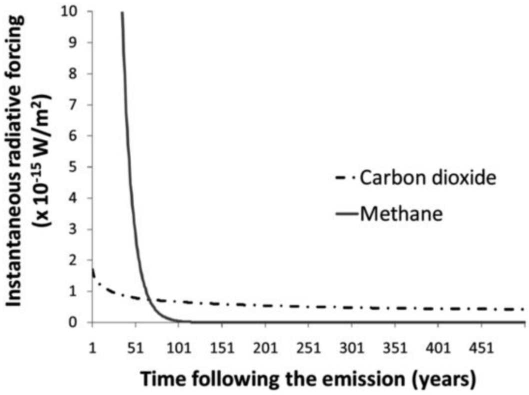
DCF - The instantaneous dynamic characterization factor

i - every GHG present in the inventory.

This model provides the cumulative increase in radiative forcing at time t caused by every discrete GHG emission over the course of all the life cycle processes since the beginning of the life cycle.



(a) Cumulative radiative forcing.



(b) Instantaneous radiative forcing

Figure 14: Time-dependent, cumulative radiative forcing **(a)** and instantaneous radiative forcing **(b)** of a unit mass pulse emissions at time zero for carbon dioxide and methane [17].

	Pre-use stage		
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: Maintenance	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	

Table 7: The different stages of LCA for construction products as given in NS-EN 15804:2012+A12013.[36]

4.3 Goal and scope

The scope of this study is a cradle-to-grave analysis. The modules considered are the production stage (P), construction stage use stage (U) and End-of-Life stage (E). Available data allowed for analysis of the Production and Construction stage as a whole, while the use stage includes modules B1-B4 and B6 as given in table 7. The End-of-Life stage includes module C1 demolition, but the products do not get any environmental benefit for materials recycling as the benefit of recycled content is already given for the use of secondary steel in the production of ventilation components. This is done according to the recycled content method of end-of-life considerations [37]. Transport of ventilation is included in all stages except from the ventilation factory to the construction site and transport at end-of-life, due to lack of data. Furthermore, if one assumes a 100 km transport distance for both stages, the impacts are found to be negligible.

The goal of the LCA is to estimate the life cycle environmental impact associated with the ventilation and conditioning of air to one m^2 of the office building Abels Hus. To achieve this two methodologies are used, a conventional LCA method as well as a dynamic LCA.

4.3.1 Functional Unit

The functional unit is the ventilation of 1 m^2 of heated floor area (HFA) in the office building over an estimated lifetime for the building of 60 years. The function of the ventilation system is to ventilate and condition the air in the office building, thus give a good indoor air quality to the occupants of the building. When considering the actual use of the ventilation system, it is difficult to separate the fan work from the ventilation heating which is provided to the system. If one considers thermal comfort in the use phase, a ventilation system without heated air would cause cold gusts of wind and be uncomfortable for the office workers. Therefore one must consider both the fan work and the conditioning of the air to fully capture the purpose of the ventilation system.

4.3.2 Boundaries

The boundaries of the study are from extraction of raw materials and the manufacturing of the main products and materials needed for the technical installations. The replacement of new materials over the lifetime is included.

The precision of the study will only be as good as the inventory data provided. Since the IFC file for ventilation is limited to the ductwork and the air handing units, the electrical components, like wiring and control systems are not inside the scope of the study. The BIM-models are separated into different disciplines, (architecture, plumbing, ventilation, electrical etc.) and the wiring and control systems will be in the electrical part of the BIM-models, and it would be time consuming to separate it from the rest of the electronics.

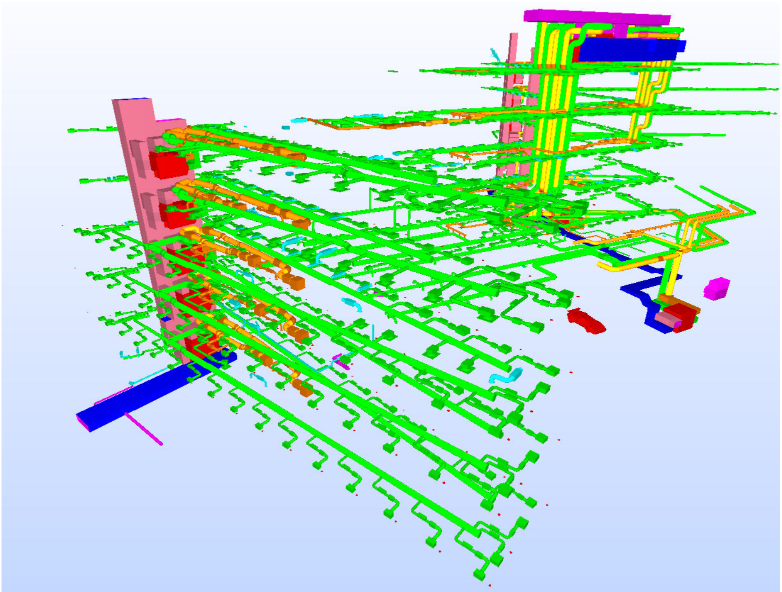


Figure 15: The BIM model for the ventilation system as viewed through Solibri Model Viever, a visualization program for BIM files.

4.4 Life Cycle Inventory

When assessing the Life Cycle Inventory (LCI) for each of the phases, the material and energy use must be calculated. As a first step, an inventory of the ventilation components were mapped as given by the scope of the system, and the lifetime of the components was incorporated to find the total amount of materials consumed during the lifetime of the building. To find emissions during the use phase, energy simulations for the ventilation systems were used to give the annual energy consumption, and cost estimates combined with input-output tables were used to estimate the impacts associated with construction, replacement and demolition of the ventilation system.

4.4.1 Gathering of Material Data

To find the materials needed for the building a BIM-model of the office building was used. The model was developed by NCC and is the basis for the construction of the building, thus it is deemed to be fairly accurate. When the model is opened in Revit, a material take-off table can be extracted to a CSV file. The table can then be manipulated in Excel using Pivot tables to create an inventory of the amount and type of all components in the model. Afterwards these components were linked to LCI data of background processes from earlier studies and existing Ecoinvent processes.

Earlier work on inventory analysis for ventilation components in office buildings was used as a basis for collection of inventory data. Preliminary work was done by Jens Tønnesen, and

Thorildur Gudmundsdottir, which again was based on a Master Thesis by Marie Schau [38]. This data was combined with Environmental Product Declaration (EPD) and data sheets from the manufacturer to as closely as possible estimate the embodied impacts of material use in the ventilation system. The EPDs and data sheets for different components are provided in Digital Appendix C.

4.4.2 Background Processes

The description of the background processes applied to the system is presented in this chapter.

Steel: This is the dominating material in the ventilation system, used in most of the components. The steel consumed is based on a mix between primary and secondary steel. The European recycling rate is 40/60[39], meaning that 40% of the steel comes from secondary production. A European average process from Ecoinvent is used for both the primary and secondary steel production. The recycling rate in these processes in the base scenario is set to 36% scrap steel and 64% primary steel.

Aluminium: A small amount of the ventilation components contain aluminium. Since the amount is so small, a Ecoinvent process with no modifications is used to model aluminium use.

EPDM rubber: Many of the ventilation components contain EPDM rubber between the joints, to model this process an Ecoinvent model for synthetic rubber was used, a European average.

Insulation: Insulation is used in some of the ventilation ducts and components for sound-proofing and to avoid condensation. Both glass fibre, glass wool and cellular rubber is used. For calculation of glass wool and cellular rubber respectively, the density was set 40 kg/m^3 and 140 kg/m^3, while the amount of glass fibre is given from earlier studies, and can be found in the data sheet in Digital Appendix D.

Welding: This process represents the arc welding in meters required for some components. The welding amount is dependent on the geometrical shape of the component, in most cases its circumference.

Ventilation components factory: The ventilation component factory is an infrastructure module which represents the infrastructure required of a company that produces metal parts and components for ventilation systems. The amount required per component is based on calculations for ducts and silencers already provided in Simapro.

Sheet rolling: Sheet rolling is based on a process in Ecoinvent, and all steel and aluminium in the system is assumed sheet rolled before it is galvanized.

Galvanizing: Galvanizing is preformed on most of the steel components to prevent rust, and the amount is taken from the inventory provided for ventilation ducts, which sets the amount of galvanizing at 2.75 g/m^2 (two sided). The galvanizing process itself is taken from Ecoinvent.

Powder Coating: Some of the components are powder coated with white finish to be more visually appealing.

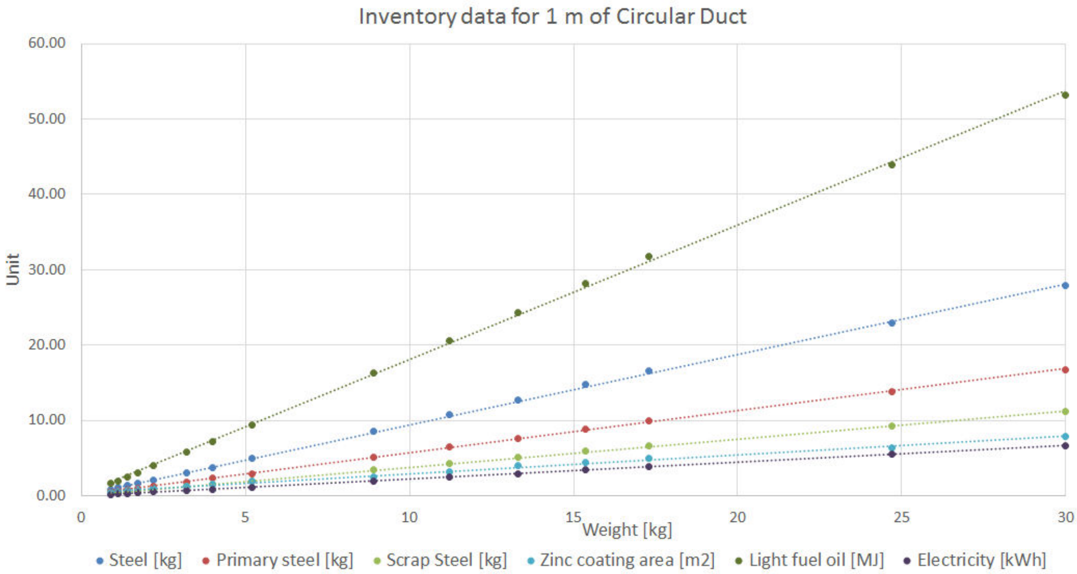


Figure 16: Inventory data for circular ducts interpolated with respect to duct weight, which is taken as a proxy for duct size.

Electrictiy, medium voltage: The electricity required to produce the ventilation components is based on existing processes in Simapro. The electricity was modelled with different supply mixes as described in section 4.6.1.

Natural gas and light fuel oil: These processes represent the fossil fuel energy needed to construct the ventilation components. The amount is based on existing processes in Simapro.

Electronic components: Some of the technical components, like aggregates and flow dampers contain electronic components, which are modelled as printed circuit boards.

4.4.3 Description of Ventilation Components

Earlier work on LCI of ventilation components by Marie Schau [38] and continued by Jens Tønnesen was used as a basis for the calculation. Where applicable, inventory data was used directly on a component basis. In some cases component specific sizes did not match, the given data was interpolated to give the required inventory data. All the interpolated figures are given in digital appendix D with the original data set, and an example for interpolation data for circular ducts is given in figure 16. The component weights were taken from data sheets provided by the manufacturer or from EPDs of the specific component. All data sheets and EPDs are supplied in Digital Appendix C.

Circular Ducts: Data on circular ducts with diameters between 63 mm and 1250 mm was provided by Jens Tønnesen Larsen.

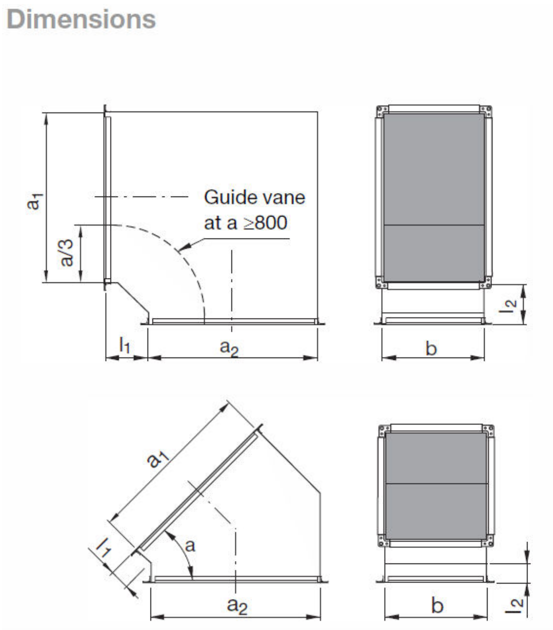


Figure 17: Dimensions for the rectangular bends taken from data sheets [40], where a and b equals the width and height of the channel, while l_1=l_2=125mm.

Rectangular Ducts: No specific inventory data for rectangular ductwork was found. The data sheet for rectangular ducts is given in Digital Appendix C. From these weights, an extrapolation from circular ducts was performed.

Duct fittings

Circular Bend: The Revit BIM model makes ventilation bends for any angle, in order to fit the needed space. In reality, only specific angles are manufactured, this being angles of 15, 30, 45, 60 and 90 degrees. These ducts are later cut to shape on site to fit the specified space. Therefore all angles supplied by the BIM model are rounded up to the standard angles. Data on 90° circular bends were provided by Jens Tønnesen Larsen. The remaining circular bends were interpolated according to the weight given on the data sheet for each specific bend.

Rectangular Bend: These are modelled similarly to rectangular ducts, but approximated with length equal to the width of the duct plus 250 mm (two times 125 mm), as indicated from the dimensions in figure 17. The 45°angle bends are approximated to half of the 90°angle bends.

Connection Piece: Instead of T-bends, connection pieces are used to make a 90° branch connection. All data on the connection pieces were provided in the dataset shown in Digital Appendix D.

Plug: The plugs are end pieces for square and circular ducts, the material amount for the plugs were given from data sheets for circular plugs and interpolated for rectangular plugs.

Reduction: Reductions are connection pieces between two ducts of different diameter. An

Component group	Amount	Unit
Extract Air Devices	205	p
Supply Air Devices	539	p
Circular Bends	1877	p
Rectangular Bends	76	p
Circular Ducts	3562	m
Rectangular Ducts	354	m
Outlets	793	p
Plugs	157	p
Reductions	464	p
Fire Dampers	23	p
Flow Dampers	542	p
Silencers	553	p
Air Handling Units	12	p

Table 8: The amount of each ventilation component extracted from the BIM file. The units are pieces for all components, except the ventilation ducts which are given in meters.

interpolation from ducts based on weight was used to get material amounts for these components.

Air Terminals

Supply and Extract Air Device: These devices are used to supply or extract air out of the room or to the outside environment. Supply and extract devices are often interchangeable, but come in many different sizes and models. Most models were based on data sheets and EPDs, and are supplied in Digital Appendix C. Not all models given in the material take-off were found, and a mass-based interpolation was preformed to find these figures.

Other Components

Fire Damper: Fire dampers consist of a duct piece equipped with a mechanical spring release mechanism that is activated in the case of a fire to prevent air circulation and fire spreading through the ducts. Material amounts were based on EPDs for different

Flow Damper: Flow dampers regulate the air stream to the correct airflow based on pre-set minimum and maximum flows. The components were based on the Swegon AS, ADAPT Damper, provided in the appendix data sheets.

Silencer: The silencer is a square sound attenuator with circular end spigots, used in a circular ventilation system. Mineral wool is used as sound insulation. The dataset in Digital Appendix D shows all inventory data for the silencers used in the study.

Air Handling Unit: The air handling units for the system is the Gold RX system which is an aggregate with a rotating heat exchanger supplied by Swegon AS. The inventory for the air handling units were based on a previous EPD provided by Asplan Viak, and supplied in digital D.

Table 8 shows a breakdown of the components extracted from the BIM-model divided into subcategories. The complete inventory can be found in Digital Appendix D.

	Space heating	DHW	Ventilation heating	Ventilation cooling	Local cooling	El. Specific
District Heating	30%	50%	30%	-	-	-
Electricity	-	-	-	-	-	100%
Heat pump	70%	50%	70%	100%	100%	-

Table 9: Energy supply for different areas of energy use utilized in the office building.

4.4.4 Estimating Insulation Amount

The following components are listed in the material list of the IFC file as to having an external insulation.

- Rectangular ducts
- Circular ducts
- Circular bends
- Rectangular bends
- Plugs

The components have insulation of either 25 mm or 100 mm mineral wool, or 13 mm cellular rubber. The amount of insulation for each of the components was estimated for a simplified geometrical shape e.g. Insulation for circular bends was modelled as a part of a hollow torus.

4.4.5 Use Phase

To model the energy use throughout the use phase of the building, an energy simulation report provided by NCC has be used. An energy simulation conducted in SIMIEN shows the expected energy use revised to Norwegian building standard TEK-10 [41]. The calculated yearly energy consumption is given for different parts of the building and shown in table 10. To estimate the required energy use from the ventilation system, the combined energy use from ventilation heating, fans and ventilation cooling was used, corresponding to 1b, 3a and 6b in table 10. The table also shows the distribution of energy consumption for different energy carriers, as given in the planning documents and shown in table 9. This constitutes a net energy consumption for the ventilation system of 27.2 kWh/m^{2}a or 446445.2 kWh/a, distributed over electricity, district heating and heat pumps as shown table 10.

The processes used to model the energy consumption from heat pumps and district heating were pre-made processes in Simapro. The efficiency of the heat pump is set to 2.5 which means that it produces 2.5 more thermal energy than the electric energy that is consumed. The district heating process is based on Trondheim district heating with economic allocation between the waste products that are disposed and the ones that are burned for heat. The complete inventories for energy carriers can be found in Digital Appendix A.

Table 10: Expected net energy consumption, split on different areas of consumption and energy sources. The first two columns are translated from the SIMIEN report documenting fulfilment of building standards. The remaining columns are calculated based on table 9. HP means heat pump, while DH means district heating.

Expected energy use (§ 14-4, total net energy requirement) (kWh/m^2)				
Description	Total	El.	HP	DH
1a Space heating	5.8	-	4.1	1.7
1b Ventilation heating (heating batteries)	7.2	-	5.0	2.2
2 Hot water (tap water)	5.0	-	2.5	2.5
3a Fans	12.7	12.7	-	-
3b Pumps	1.1	1.1	-	-
4 Lighting	20.0	20.0	-	-
5 Technical equipment	34.5	34.5	-	-
6a Space cooling	-	-	-	-
6b Ventilation cooling, (cooling batteries)	7.3	-	-	7.3
Total calculated energy consumption, sum 1-6	93.6	68.3	11.6	13.7
Regulation requirements for TEK-10	150.0			

4.4.6 Lifetime of Components

When modelling the life cycle inventory of the ventilation components, their expected lifetime must be considered to encompass total material use throughout the time scope of the of the study. To achieve this, the required materials are multiplied by a lifetime factor, F, which is given by,

$$F = \frac{\tau_{study}}{\tau_{comp}} \tag{11}$$

Where,

τ_{study} - Time horizon of the study

τ_{comp} - Expected lifetime of the component

The expected lifetime of ventilation components from an economical perspective is given in "NS-EN 15459:2007 Energy performance of buildings - Economic evaluation procedure for energy systems in buildings" [42]. Where data was not available from the standard, the expected lifetime was taken from data sheets of the manufacturer. The standardized values are deemed more reliable, as data from the manufacturer might have a bias and therefore overestimate the expected lifetime. Relevant lifetime data is given in table 11.

Component Category	Expected Lifetime (years)
Dampers with control motors	15
Duct systems	30
Air grills	20
Diffusers	20
Fire dampers	15
Silencers	30
Aggregates	25

Table 11: Expected lifetime of the ventilation components as given by the Norwegian Standard [42].

	Sanitary	Heating	Fire Extinguishing	Ventilation Services	Comfort Cooling
Price (NOK/m^2)	215	563	385	837	365

Table 12: Distribution of costs for PHS services in a 15000 m^2 Norwegian office building with a garage, taken from the Norwegian pricing book. [43]

4.4.7 Labour Activities

The impacts related to labour activities were modelled for construction and demolition both at the beginning and end of the life cycle, as well as for material replacements. To model the labour and auxiliary activities associated with the building, Environmentally Extended Input-Output analysis was used, combined with estimated costs for the respective services in the life cycle.

Analysis of the construction sector in the input-output table allowed to distinguish the processes that were not connected with material use, but provision of services like labour and related activities. The basis for the input-output table was the Norwegian construction sector in 2007, and the sectors related to material use were removed from the table. The modified table was scaled back to the original total output per 1 NOK input, and the complete modified table is given in the Digital Appendix G. The input-output tables only had emissions related to climate change, thus only this impact category has been included in the analysis of labour impacts. Other impact categories are discussed quanlitatively in the section 6.5.

The monetary values, where available, were taken from the Norwegian pricing book for construction services [43]. For the construction and demolition costs, only aggregated costs for Plumbing Heating and Sanitation (PHS) equipment were found. The costs were then allocated to different PHS services according to total PHS costs divided by PHS services, given in the Norwegian pricing book for an office building of 15000 m^2 with a garage, and shown in figure 12. Figure 13 shows the chosen monetary values used for labour in the different phases of the life cycle. Since the construction and demolition costs were given for the construction and demolition of the entire system, when assessing construction and demolition in component replacement, this was scaled with respect to the amount of material being replaced.

	Service	Value	Unit
Constuction	Construction Services	64.8	NOK/m^2
Demolition	Demolition of ventilation components	23.0	NOK/m^2

Table 13: Cost values used in the estimation of impacts from labour and construction activities not related to material embodied emissions.

4.5 Life Cycle Impact Assessment

The method used in the impact assessment is ReCiPe midpoint method from a hierarchical perspective [44]. Selected impact categories were: Climate change with a 100 year time horizon, terrestrial acidification, metal depletion and fossil fuel depletion.

Two impact assessment methodologies were done as outlined in section 4.2. The conventional assessment with all four impact categories included, and a dynamic impact assessment. Recent developments in LCA methodology have led to an increased understanding of how some impact categories change when a temporal perspective is added. Traditional LCA calculates the impact of all emissions as if they occurred at time zero. We know for a fact that this is not the case for a building over a 60 year time horizon. Emissions will occur every year both from maintenance, and energy consumption of the ventilation system. When assessing the CO_2 emissions over the lifetime of the building a dynamic CO_2 approach has been applied.

4.6 Scenario and Uncertainty Analysis

To explore the sensitivity of the results, different scenarios have been applied to the assessment. Different electricity mixes have been modelled and applied to both the conventional and dynamic LCA methods and the effect of the steel recycling rate on the environmental impacts from the ventilation components has been calculated.

4.6.1 Scenario Modelling for Recycled Content and Supply Mix

From the life cycle inventory one can gather that steel production will have a large share of the total environmental impacts. As presented in section 2.6 a shortage in global secondary steel supply, from a consequential perspective, could give secondary steel consumers the environmental burden of primary steel production. To explore this scenario, the system is analysed with an industry average of 64% primary steel and 36% secondary steel, as well as only primary steel being used in the ventilation components.

Additionally, one can explore how sensitive results are to the change in supply mix used throughout the life cycle, both for materials production and for energy consumption in the use phase. Four different electricity mixes were applied to the assessment. The supply mixes chosen were Norwegian, the Nordic mix known as NORDEL, and two forecasts of European mixes. When considering the temporal aspect of the environmental impact of greenhouse gases in the dynamic LCA, a forecast scenario is used for the electricity mixes. In contrast, the conventional assessment uses the current electricity mixes throughout the life cycle of the building.

For the dynamic LCA, the Norwegian mix was kept static, with the assumption that its carbon footprint is not expected to change substantially before 2050. When assessing the future NORDEL mix, a relatively optimistic approach was applied. Future energy and climate policies from Nordic countries by 2050 were used to estimate the change in energy mix while moving towards a low carbon society. The countries involved in the Nordic energy mix are Finland, Sweden, Norway and Denmark.

The future Finnish supply mix will be based on the principle of increased self-sufficiency as well as meeting long term energy and climate objectives set by the EU [45]. The long term goal is a carbon neutral society, but to meet the criterion for self-sufficiency, some coal production is expected to remain by 2050. Denmark has proposed a policy with a complete phase out of fossil fuels before 2050 [46]. this is taken into consideration when assessing the Danish mix in 2050. The Swedish mix is based on a Swedish Energy Scenario made by WWF Sweden, and is considered the most optimistic case for the four countries [47].

For the European grid mix in 2050, two technology scenarios are applied, one realistic-optimistic and one very optimistic. Both these scenarios are based on the NEEDS project which seeks to make life cycle inventories of the European supply mix by 2050 [48].

To reconcile the current and the future supply mixes, a linear interpolation was preformed from 2016 to 2050. The chosen electricity mixes are shown in table 14, and graphically in figures 19 and 18. The complete breakdown of all electricity supply mixes can be found in Digital Appendix A.

		Fossil	Nuclear	Hydro	NRW	Imports
2016	Norway	2.24 %	0.00 %	90.19 %	0.85 %	6.61 %
	NORDEL	13.57 %	20.24 %	51.36 %	10.76 %	4.07 %
	European	49.84 %	26.86 %	10.77 %	10.23 %	2.31 %
2050	NORDEL	2.27 %	22.22 %	56.63 %	16.68 %	2.20 %
	EU VO	19.70 %	0.00 %	23.30 %	56.10 %	0.90 %
	EU RO	47.60 %	24.40 %	14.50 %	12.80 %	0.70 %

Table 14: The electricity supply mixes used in the dynamic scenario analysis. EU VO is the very optimistic supply mix forecast, while RO is the realistic optimistic forecast given by the NEEDS project. NRW stands for New Renewables and Waste.

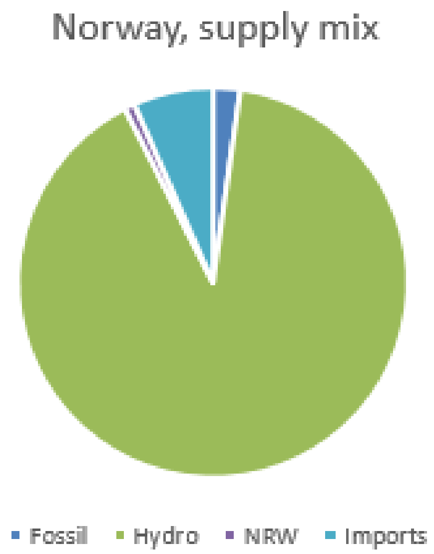
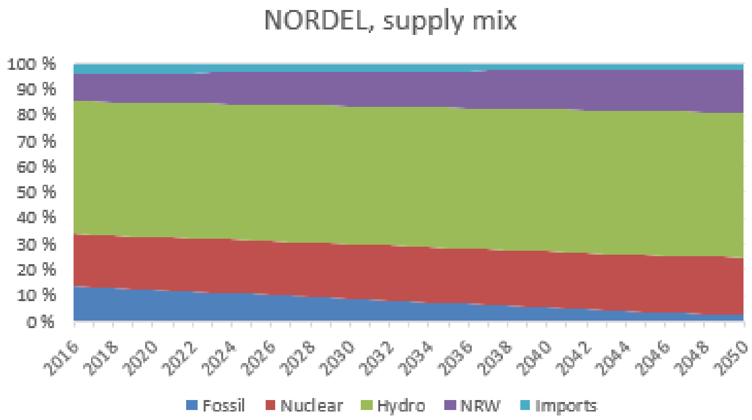
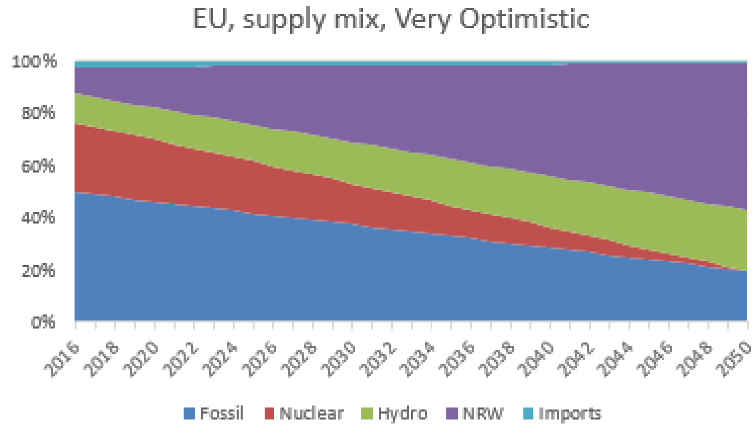


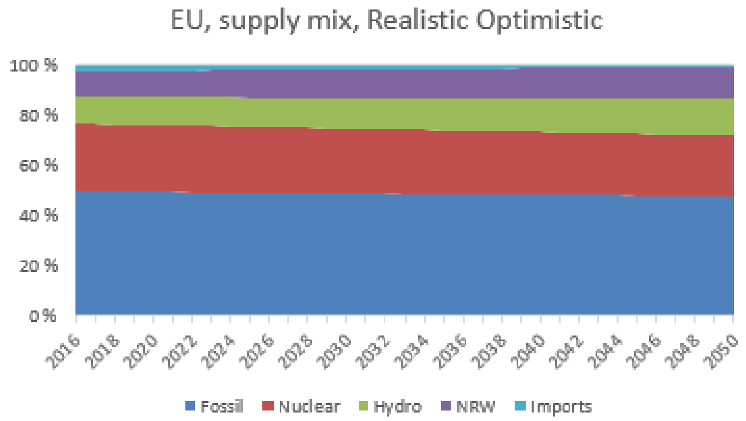
Figure 18: The electricity supply mix for Norway is kept static throughout the analysis.



(a) NORDEL



(b) European Mix Very Optimistic



(c) European Mix Realistic Optimistic

Figure 19: Electricity supply mixes used in the dynamic analysis for **(a)** NORDEL, **(b)** Europe - Very Optimistic and **(c)** Europe - Realistic Optimistic.

4.6.2 Monte Carlo Simulation

To model the uncertainty of the material use in the ventilation components, uncertainties were applied to the amount of all system processes used in the inventory of the embodied emissions. Simapro has a built-in methodology for modelling of uncertainties in the form of a pedigree matrix. The pedigree matrix has a predefined uncertainty based on the collection method of the data, an this method has been applied to all components in the inventory. Simapro then has the possibility to preform a Monte-Carlo simulation to give the resulting uncertainty of the environmental impacts, based on the uncertainty for the system processes. The uncertainties given for the components can be found in Digital Appendix D.

4.7 Assumptions

The main assumption in this analysis is the constant technosphere throughout the time horizon of the study. This implies that the technology used in the construction of the ventilation components does not change during the lifetime of the building. The energy efficiency of the system is also not expected to change and the energy consumption is kept constant throughout the assessment. A fairly static use of the building throughout its lifetime is also assumed. It is not possible to predict large-scale changes to the building functionality. Additionally, the system will only be an average representation for its building type, like for instance the lifetime of the ventilation components. These assumptions are all consistent with conventional LCA practice, that study the system "as is" with a constant technosphere. An exception to this are the dynamic electricity mixes used in the dynamic LCA assessment.

When assessing the life cycle inventory of the ventilation system, some of the components, like circular ducts, did not have a perfectly linear relationship between duct weight and the amount required of the different processes. This is explained by the fact that sheet thickness changes slightly as the diameter of the duct increases. The differences are however considered negligible and a linear fitting is deemed acceptable for the scope of the study. Additional assumptions for the ventilation system are the use of connection pieces instead of T-bends for all junctions in the ventilation system. This has to do with the way the building model has been created and is deemed acceptable due to the total mass of the system being roughly equivalent.

For the embodied emissions, transport of materials is also assumed embedded in the background material processes for the ventilation component production. As mentioned earlier, transport from the ventilation component factory to the construction site and transport to the waste disposal facility is neglected due to lack of data.

Small parts of the ventilation system were assumed negligible, either due to lack of data or due to inadequate description of the components. Some components also showed up as a duplicate in the material take-off file and had to be removed. The complete list of removed components can be found in Digital Appendix D.

5 Results

This section presents the results from the Life Cycle Impact Assessment. First, the life cycle impacts from a conventional LCA for four impact categories are shown in section 5.1. Different electricity mixes and recycling rates are applied to model the sensitivity of the results to these parameters. The contribution from the different phases as well as when in the life cycle of the building the impacts occur is shown. Additionally, a sensitivity analysis of the embodied emissions in the ventilation components is presented.

The dynamic LCIA of the impact to climate change is presented in section 5.2, along with the impacts per kWh from the electricity scenarios presented in the methodology section.

Finally, in section 5.3.1, the impacts from GHG emissions in the conventional LCA and the dynamic LCA are compared, and the differences for the methodologies in the relationship between embodied emissions and emissions from energy use are presented. The energy use for the ventilation system is also compared to the total energy use of the building to explore the significance of the ventilation system when compared to the rest of the building.

All results are presented for the entire lifetime of 60 years and per m^2 floor area, unless stated otherwise, meaning the area of the office building without the garage, which equals to 14966 m^2.

5.1 Conventional LCA

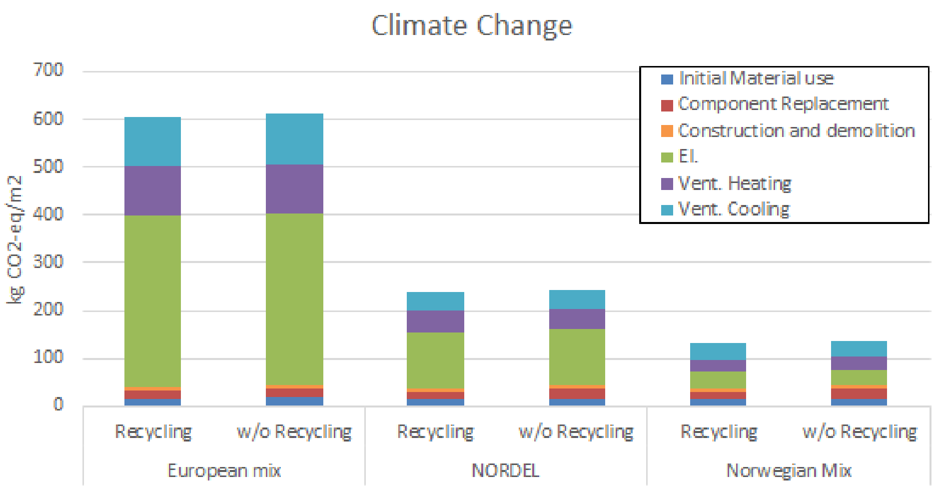
5.1.1 Total Results

The total life cycle results using conventional LCA methods throughout the 60 year lifetime of the building are given in this section. The results are given for three electricity mixes with a standard recycling rate (36% secondary and 64% primary steel) as well as only primary steel being utilized. The Global Warming Potential of the life cycle of the ventilation system is shown in table 15. The remaining result tables for the other impact categories are given in Appendix A. All total results for all impact categories are shown graphically in figure 20. The environmental impacts separated between embodied material impacts and energy use for all impact categories are given in figures 21 and 22. Total impacts for different electricity mixes are shown in table 18, section 5.3.1.

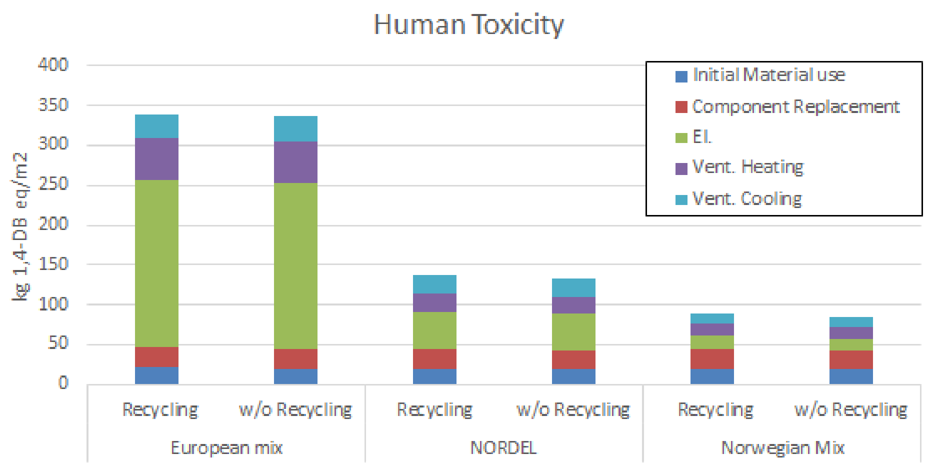
The results show the electricity mixes having the largest impact on all impact categories, except for metal depletion, where the embodied impacts from the production of the ventilation components has the largest effect. The electricity consumed by the ventilation system is from the fans driving the ventilation. These results are discussed in section 6.1.

Climate Change	Norwegian Mix		NORDEL		European mix	
(kg CO_2 eq/m^2)	Rec.	w/o Rec.	Rec.	w/o Rec.	Rec.	w/o Rec.
Initial material use	13.92	16.35	14.25	16.62	15.21	17.40
Component replacement	16.35	19.08	16.72	19.39	17.81	20.29
Constr. and demolition	6.86	6.86	6.86	6.86	6.86	6.86
Electricity	33.50	33.50	116.81	116.81	358.71	358.71
Vent. heating	27.47	27.47	44.06	44.06	103.62	103.62
Vent. cooling	33.53	33.53	40.89	40.89	104.00	104.00
Total	131.63	136.79	239.59	244.62	606.21	610.87

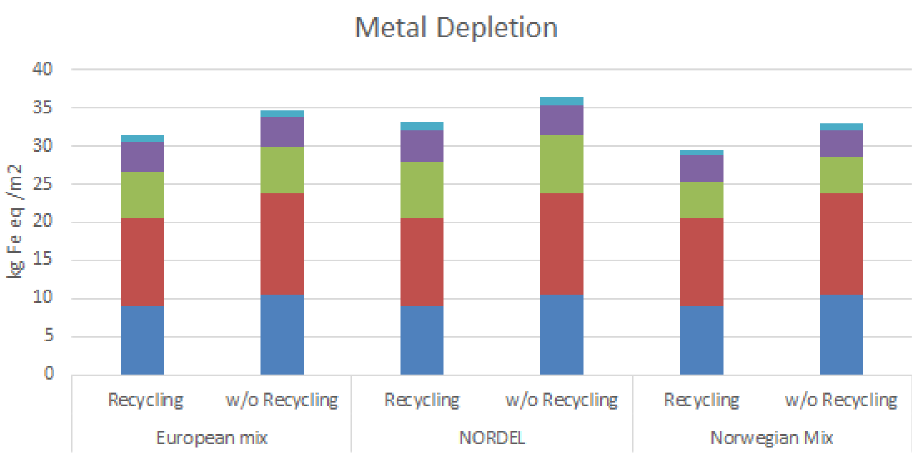
Table 15: Environmental impacts to climate change for all scenarios, divided upon embodied emissions and energy use.



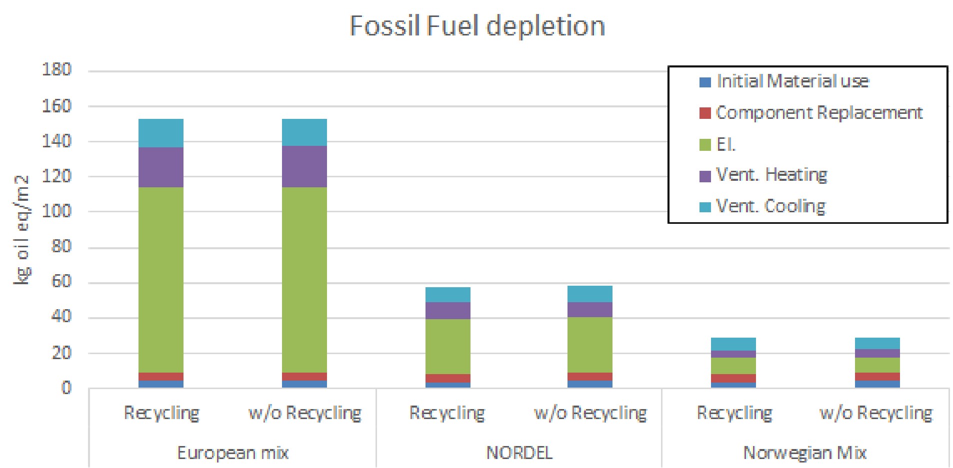
(a) Climate Change



(b) Human Toxicity

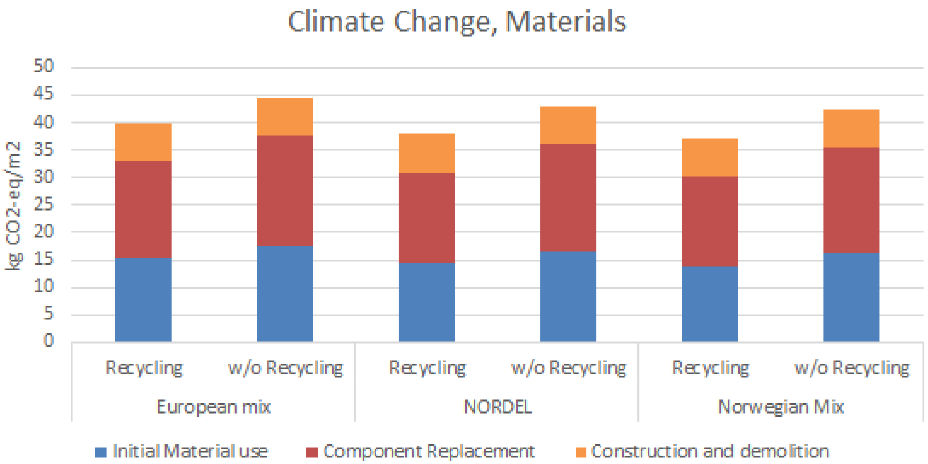


(c) Metal Depletion

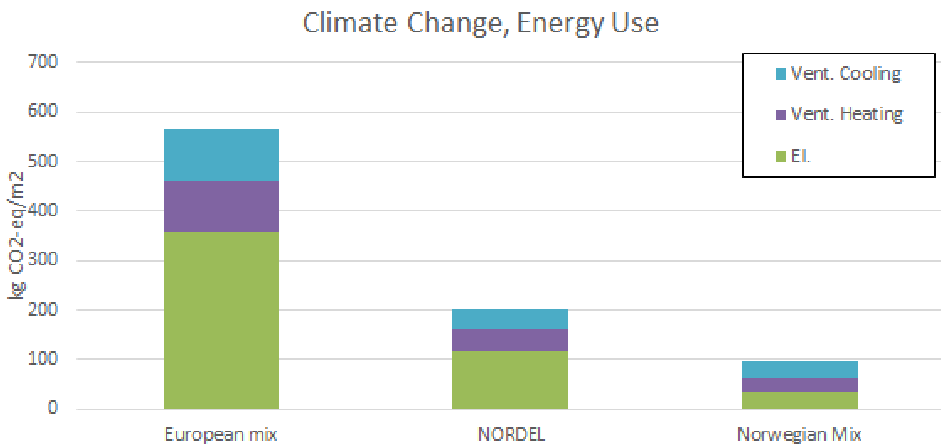


(d) Fossil Fuel Depletion

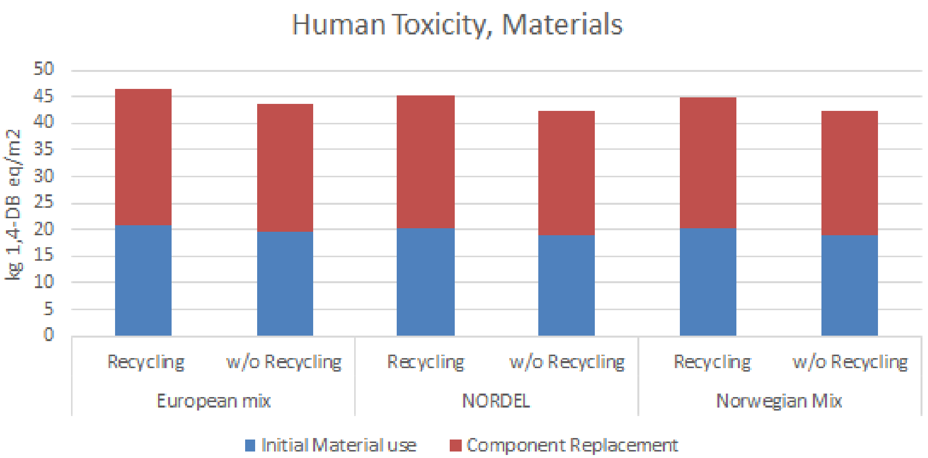
Figure 20: Total impacts per square meter floor area for the building life cycle for **(a)** climate change, **(b)** human toxicity, **(c)** metal depletion and **(d)** fossil fuel depletion.



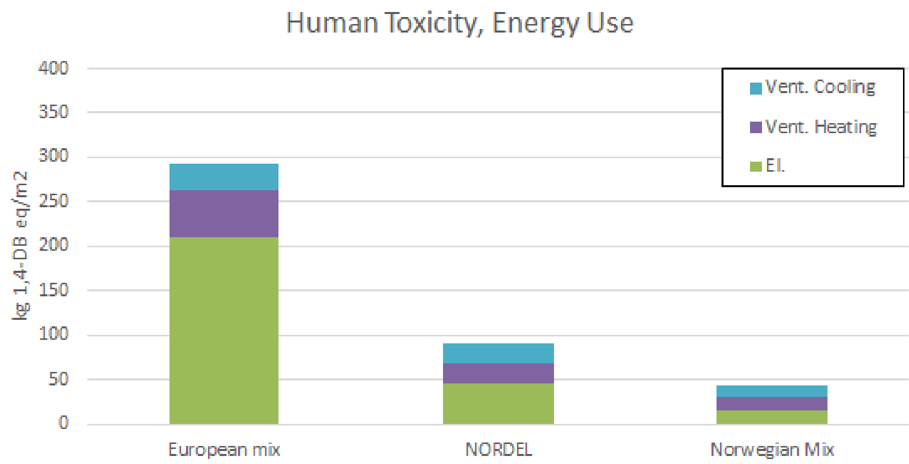
(a) Climate change, materials.



(b) Climate change, energy use.

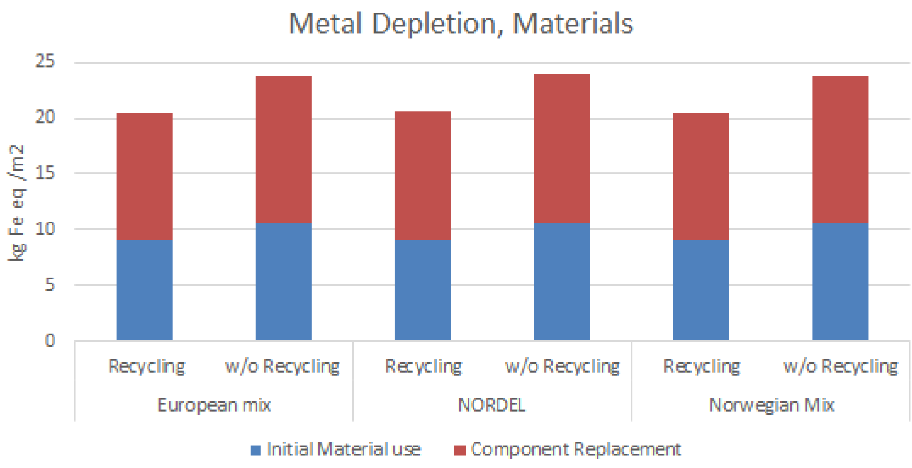


(c) Human toxicity, materials.

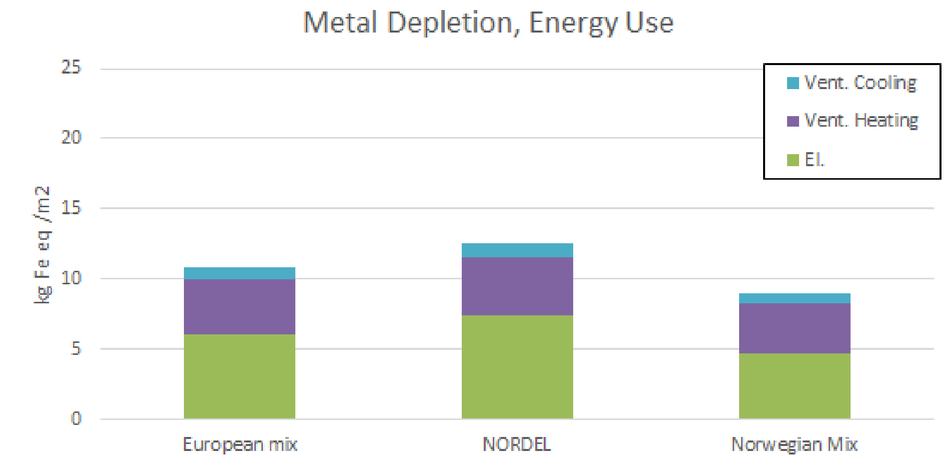


(d) Human toxicity, energy use.

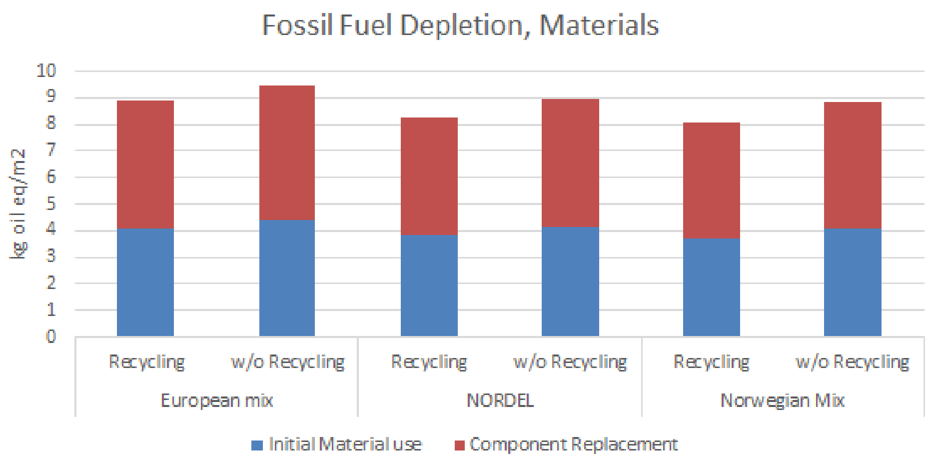
Figure 21: Impacts for materials and energy use for climate change and human toxicity for the conventional LCA.



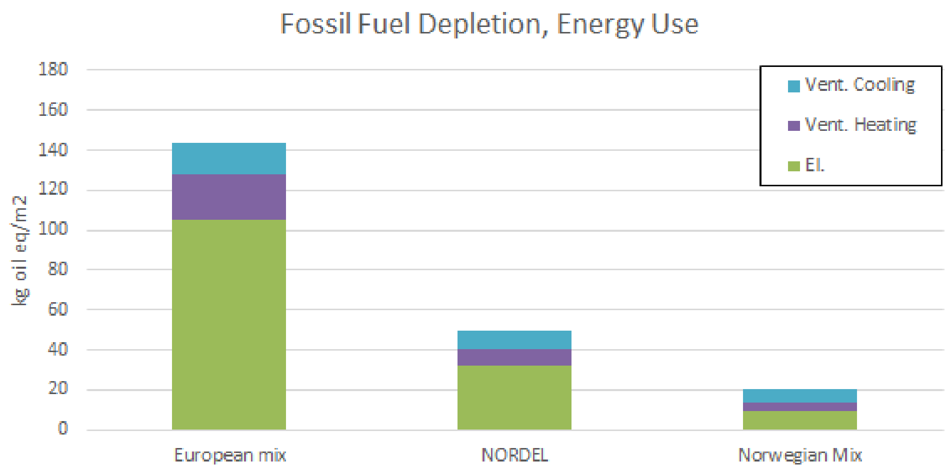
(a) Metal depletion, materials.



(b) Metal depletion, energy use.



(c) Fossil fuel depletion, materials.



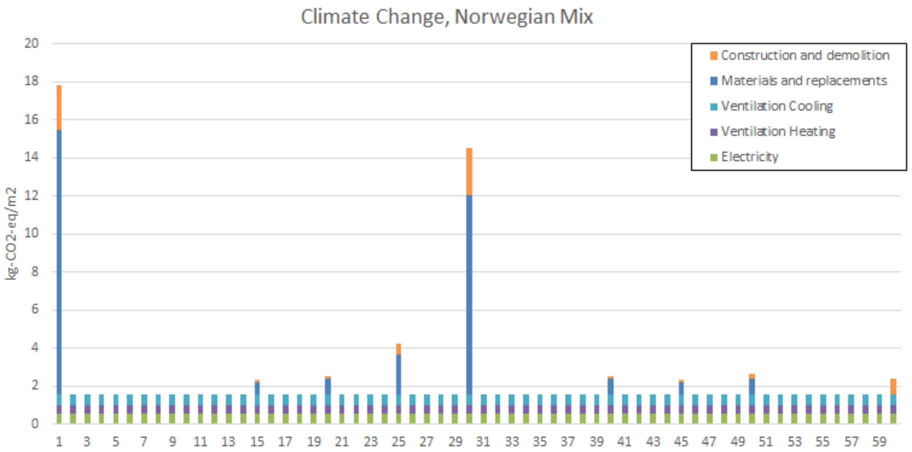
(d) Fossil fuel depletion, energy use.

Figure 22: Impacts for materials and energy use for fossil and metal depletion for the conventional LCA.

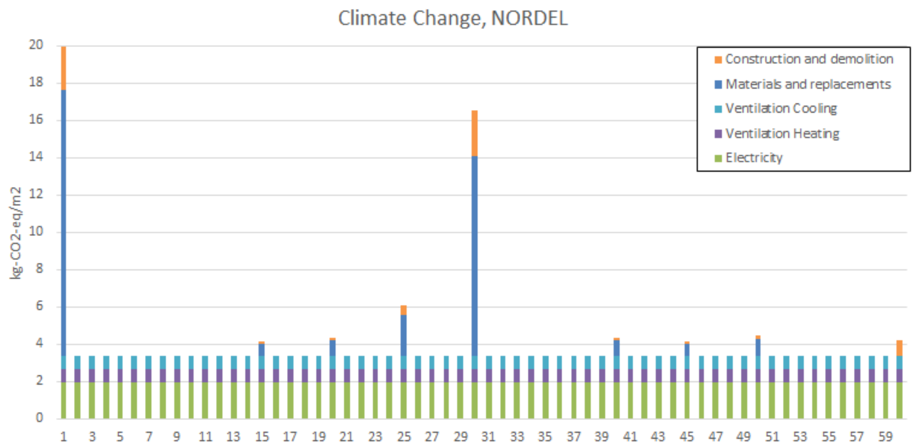
5.1.2 Temporal Results

To show the distribution of the impacts over the lifetime of the building, the impacts calculated in the conventional LCA are presented for each year of the expected lifetime. Additionally this makes it easier to compare the results of the conventional LCA with the results from the dynamic LCA. Thus, results are shown specifically for climate change, since the dynamic LCA only encompasses this impact category.

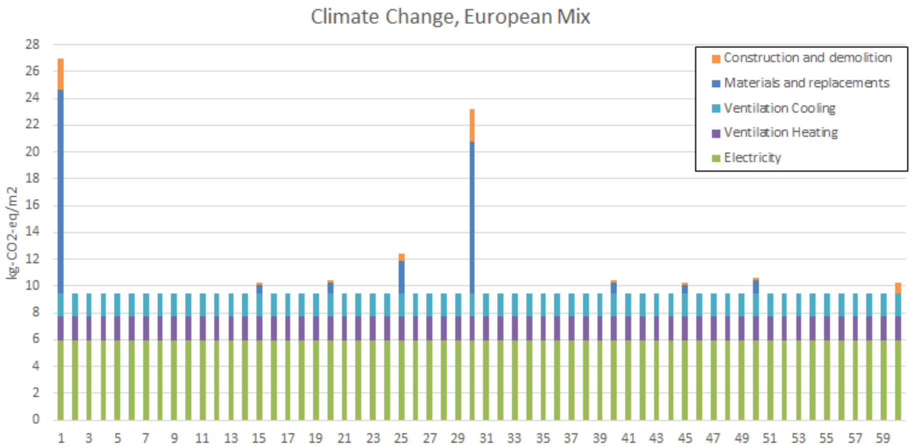
Figure 23 shows the impacts of GHGs for each year of the construction, with the largest contribution to GWP seemingly occurring at year one and year 30, at the installation of the ventilation components. Energy use however, has a larger total impact, due to the yearly emissions occurring throughout the lifetime of the building. This is especially true for the more carbon intensive electricity mixes, like the European mix.



(a)



(b)



(c)

Figure 23: Impacts to climate change throughout the lifetime of the building, using results from the conventional LCA for **(a)** Norwegian el. mix, **(b)** NORDEL and **(c)** European el. mix.

	Climate change kg CO_2 eq/m^2	Human toxicity kg 1.4 DB eq/m^2	Metal depletion kg Fe eq/m^2	Fossil depletion kg Oil eq/m^2
Air terminals	2.43	3.14	1.28	0.69
Duct fittings	3.16	4.04	1.57	0.84
Ducts	16.98	21.45	8.38	4.53
Other duct comp.	3.14	5.94	2.80	0.87
Air handl. units	5.27	10.68	6.51	1.33
Total	30.98	45.25	20.55	8.27

Table 16: Contribtution from different ventilation components to all impact categories of the conventional LCA.

5.1.3 Distribution and Uncertainty of Embodied Material Impacts

The inventory of embodied emissions in the ventilation components have been thoroughly researched in this thesis. Therefore, it is possible to investigate the embodied in greater detail, both with respect to the distribution of the embodied impacts over the different parts of the ventilation system, and considering its uncertainty. The results are similar for the different scenarios (electricity mix and amount of recycled content). Thus, a fixed NORDEL electricity mix and a standard recycling rate of 36% secondary and 64% primary steel is used in this analysis. The contribution for different components with different scenario choices is given in Digital Appendix F.

Table 16, shows the impact of different ventilation components as presented in section 4.4.3. The contribution from different components to the impact categories for the NORDEL supply mix is shown graphically figure 24. The remaining graphs for different supply mixes are given in appendix X as they follow the same pattern shown in figure 24. Ducts have the largest contribution to all impact categories, with air handling units having a larger relative contribution for metal depletion and human toxicity than for climate change and fossil depletion.

The uncertainties of the embodied emissions calculated from the Monte Carlo simulation are shown in table 17 with the percentage deviations of the 95% confidence interval given in figure 25. Figure 33 shows the distribution of the simulation results for Climate Change in a histogram, with the remaining impact categories given in Appendix B. The red lines show the cut-off for the 95% confidence interval as given by the percentages in table 17. Note that the uncertainties from human toxicity for metals are inherently large because of considerable uncertainties concerning the exposure of metals and fate of the metals deposited to the environment.

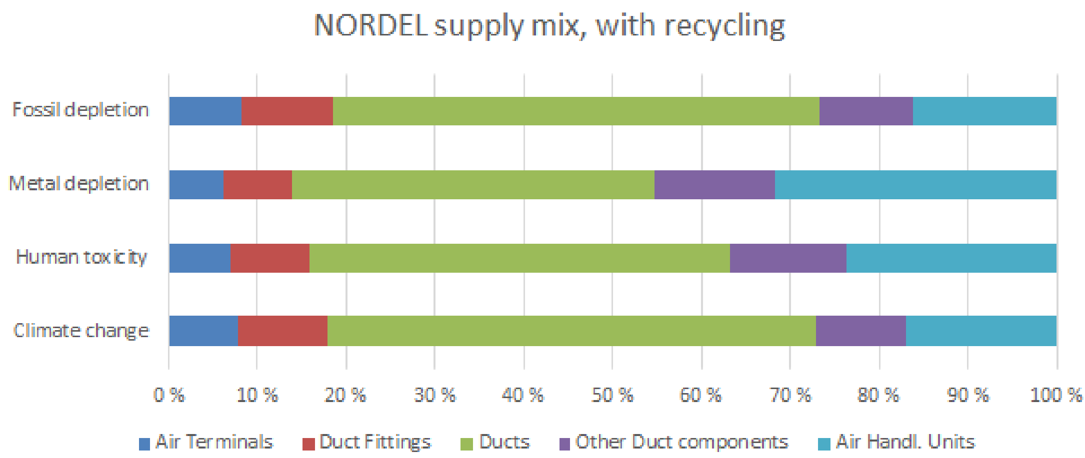


Figure 24: Contribution to embodied impacts from different ventilation components for the NORDEL electricity mix

Impact category	Unit	Mean	2,5%	97,5%
Climate change	kg CO2 eq	31.04	27.22	35.84
Fossil depletion	kg oil eq	8.29	7.01	9.80
Human toxicity	kg 1,4-DB eq	51.08	-666.36	781.63
Metal depletion	kg Fe eq	20.60	9.48	35.67

Table 17: Monte Carlo Simulation results of embodied material impacts for all impact categories assessed in the studies. The percentiles show the values at the cut-off 95% confidence intervals, as indicated by the red lines in figure 33.

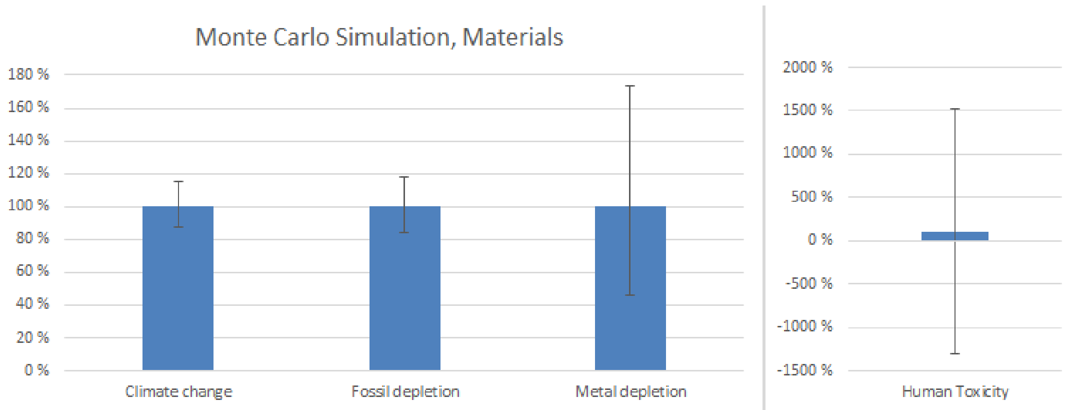


Figure 25: Monte Carlo simulation of embodied material impacts for the ventilation components.

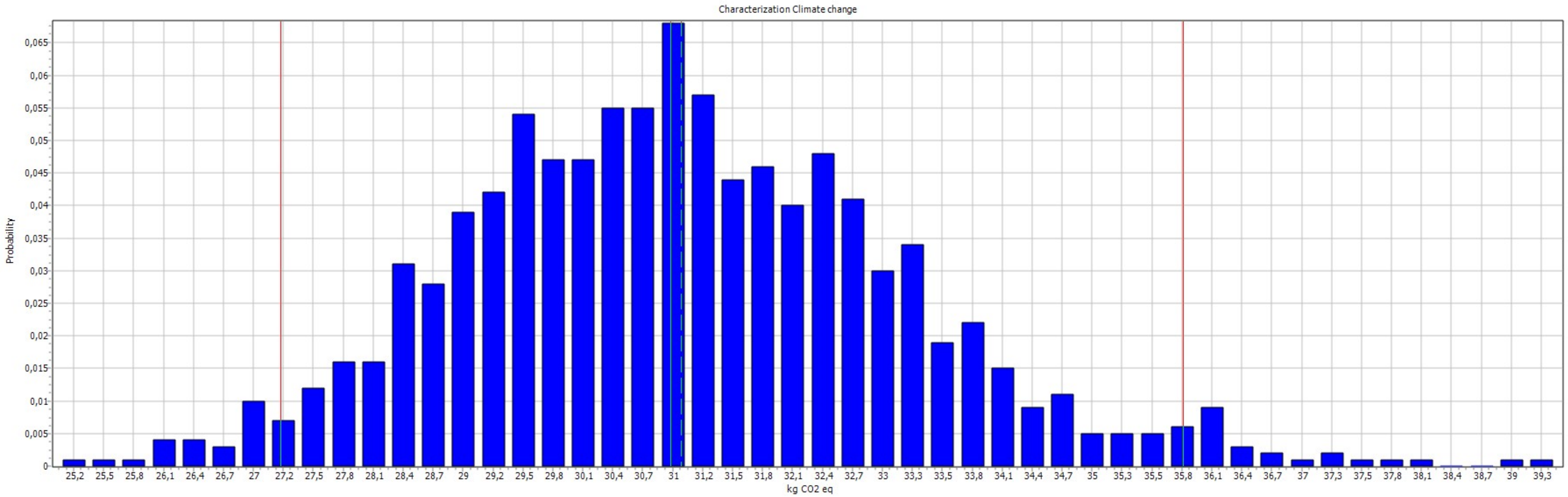


Figure 26: The results of the Monte Carlo simulation on ventilation components for Climate Change. The red lines show a 95% confidence interval.

5.2 Dynamic LCA

The Dynamic LCA show impacts to climate change with a more precise modelling of the temporal effect of the GHGs. The standard amount of secondary steel was used in this assessment which is 36% secondary steel and 64% primary steel.

5.2.1 Impact Factors for Dynamic Electricity Mixes

For the dynamic LCA, a changing supply mix changing with time was implemented, as outlined in the methodology section. The impacts in kg CO_2 equivalent per kWh for the supply mix scenarios for only electricity, heat pump and district heating are shown in figure 27.

The Norwegian supply mix is kept static while the others change linearly every year. The Very Optimistic forecast sees the largest reduction in impacts per kWh, while the Realistic Optimistic scenario only sees a small change until the year 2050.

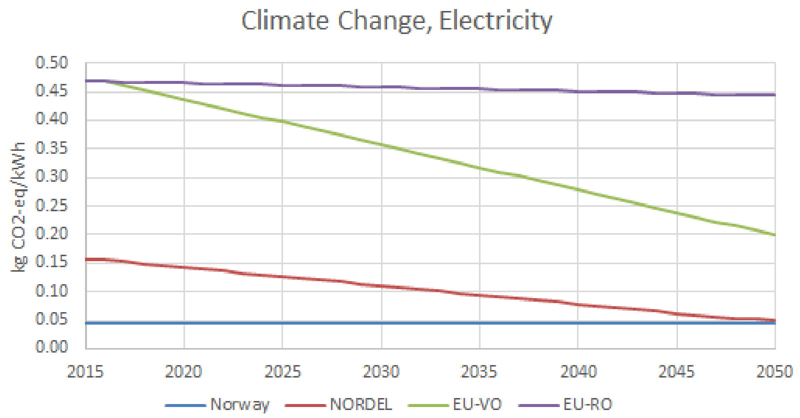
Comparing the three different energy supply technologies, the electricity obviously varies most with the supply mix. The heat pump will also vary considerably, while the district heating system is less dependent on electricity, due to the fact that other fuels are more significant in this technology.

5.2.2 Instantaneous Impact

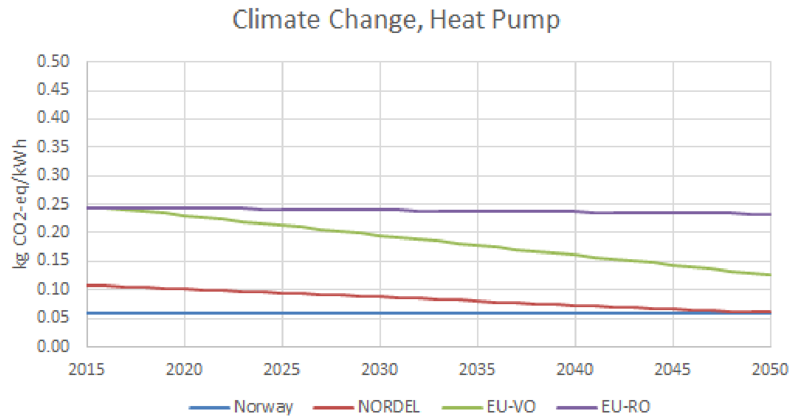
The instantaneous impact shows the instantaneous radiative forcing in W/m^2 at any given year during the 100 year analysis period of the assessment. The results are given per UFA of the building being 14966 m^2. Note that the building's lifetime is 60 years, but the Global Warming Potential is assessed over a 100 year time period. Thus, the dynamic LCA shows the actual physical impact of the emitted GHGs throughout the time period assessed in the study.

Figure 28 shows the instantaneous impact on climate change from GHGs over the time period of the study. A more detailed breakdown of the instantaneous impact between impacts associated with the ventilation components, and impacts from energy use in the ventilation system for the NORDEL mix is shown in figure 29. Similar graphs for the remaining electricity mixes are found in Appendix C.

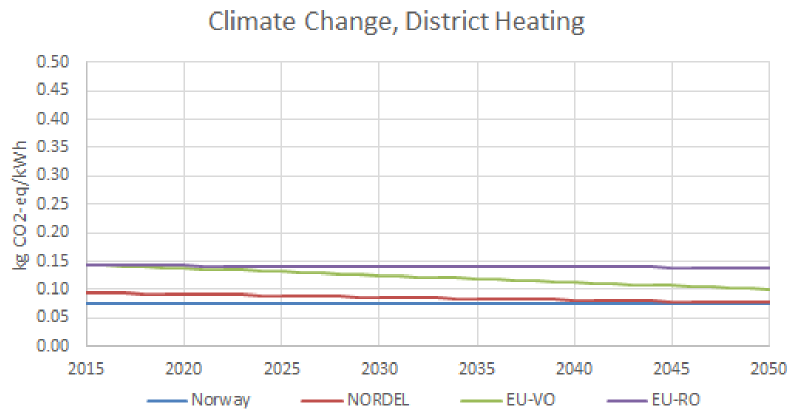
The instantaneous impact increases as new emissions are added each year, while the "tail" of the GHG impacts from earlier emissions still is in effect. Spikes can be seen for material replacement, with a especially large spike occurring at year 30, when the main duct system is replaced. Since both demolition and construction services for the new ducts is included the impact from construction services has a larger relative contribution later in the life cycle, than the beginning. At year 60, a spike can be seen for demolition, and the resulting impacts till year 100 are from the lasting effects of GHGs, which are not insignificant. These results are further discussed in section 6.4.



(a) Electricity

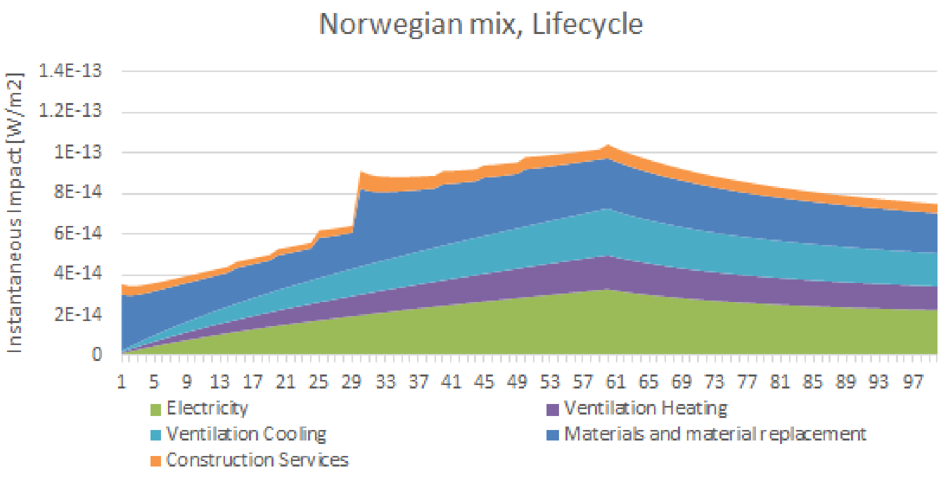


(b) Heat Pump

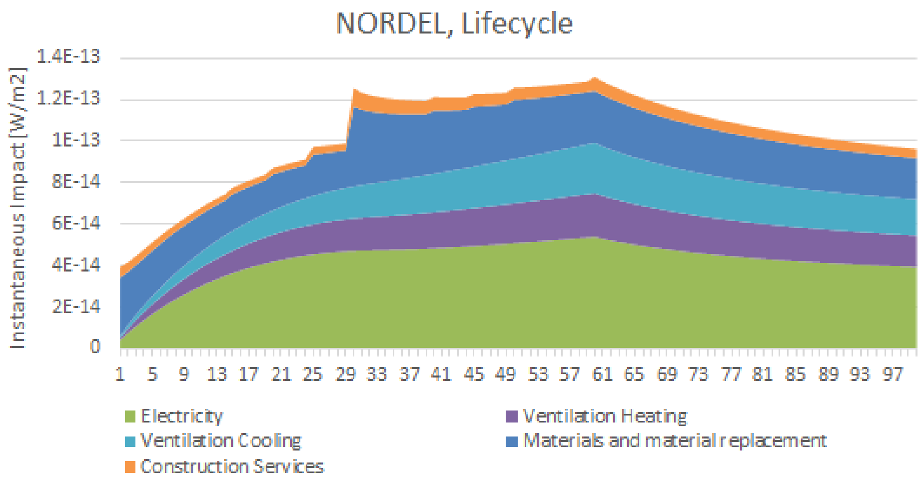


(c) District Heating

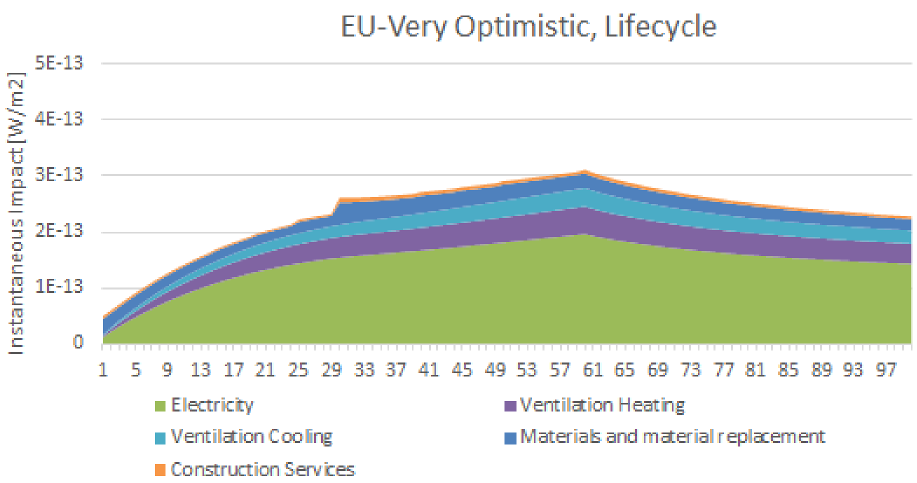
Figure 27: Impacts to climate change per kWh of all energy supply technologies assessed in the Dynamic LCA for different electricity mix scenarios until year 2050.



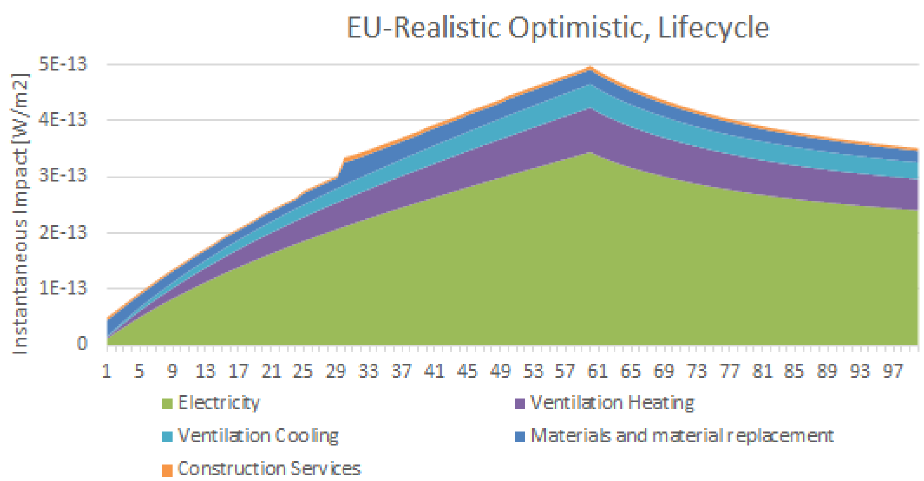
(a) Norwegian Mix, Lifecycle.



(b) NORDEL, Lifecycle.

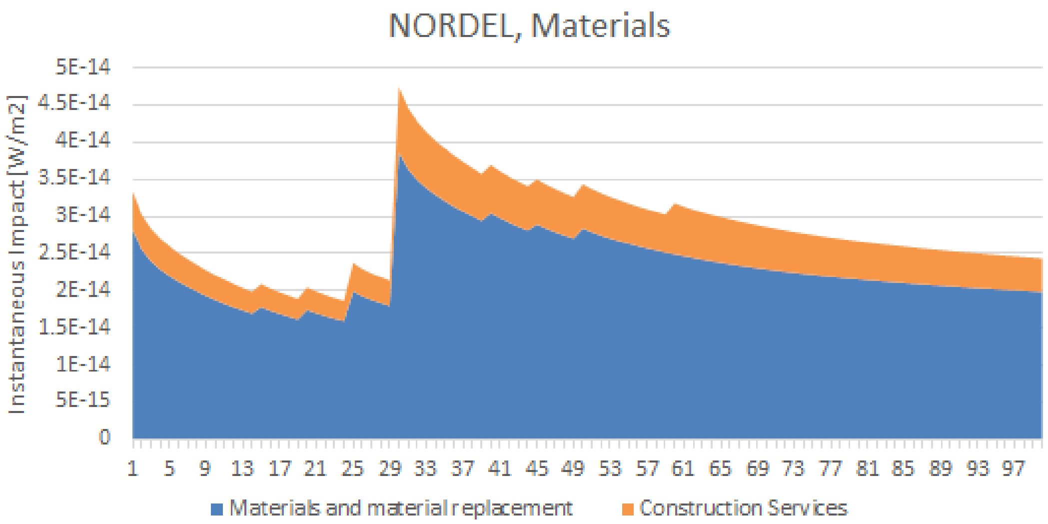


(c) European Mix Very Optimistic, Lifecycle.

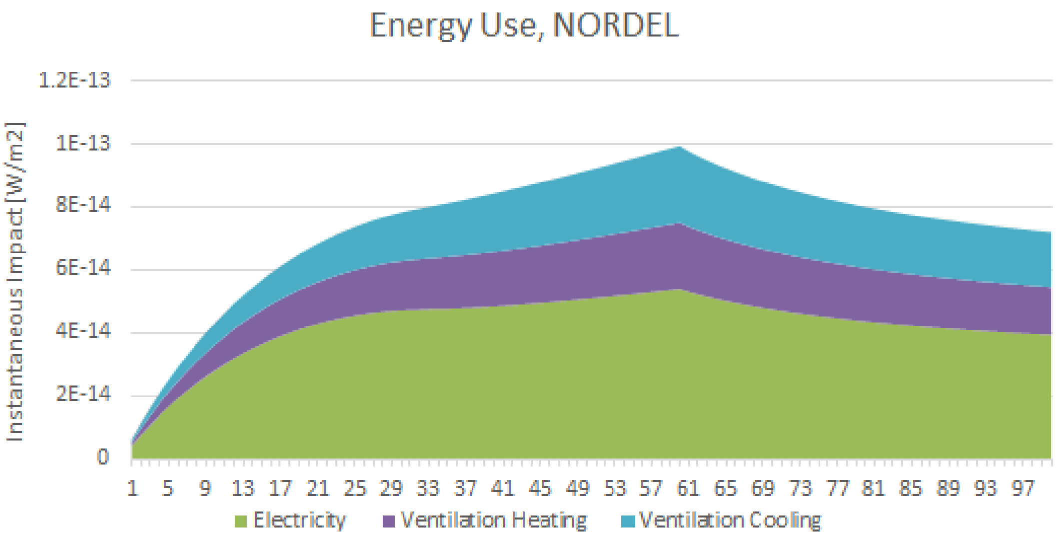


(d) European Mix Realistic Optimistic, Lifeycle.

Figure 28: Instantaneous impact (W/m^2) per m^2 floor area from the office building for different electricity mixes. Note the difference in secondary axis values between the upper and lower graphs.



(a) Impact from embodied emissions.



(b) Impact from energy use.

Figure 29: Contribution to the instantaneous impact for the **(a)** embodied emissions of the ventilation materials, and **(b)**impacts from energy use throughout the 100 year analysis period of the study.

Global Warming Potential, kg CO_2 eq/m^2							
Supply Mix	Norwegian Mix		NORDEL		European Mix	VO	RO
Method	Conv.	Dyn.	Conv.	Dyn.	Conv.	Dyn.	Dyn.
Initial material use	13.92	-	14.25	-	17.40	-	-
Component replacement	16.35	-	16.72	-	20.29	-	-
Materials (Dyn.)	-	26.59	-	26.81	-	27.63	27.93
Constr. and demolition	6.86	5.77	6.86	5.77	6.86	5.77	5.77
Electricity	33.50	25.17	116.81	49.08	358.71	169.57	266.99
Vent. Heating	27.47	12.97	44.06	17.76	103.62	41.92	61.46
Vent. Cooling	33.53	17.81	40.89	19.27	104.00	26.70	32.70
Total	131.63	88.32	239.59	118.69	610.87	271.59	394.86

Table 18: A comparison of impacts for GWP from the ventilation system, divided between embodied material impacts, and energy use impacts, for different electricity mixes and calculation methods.

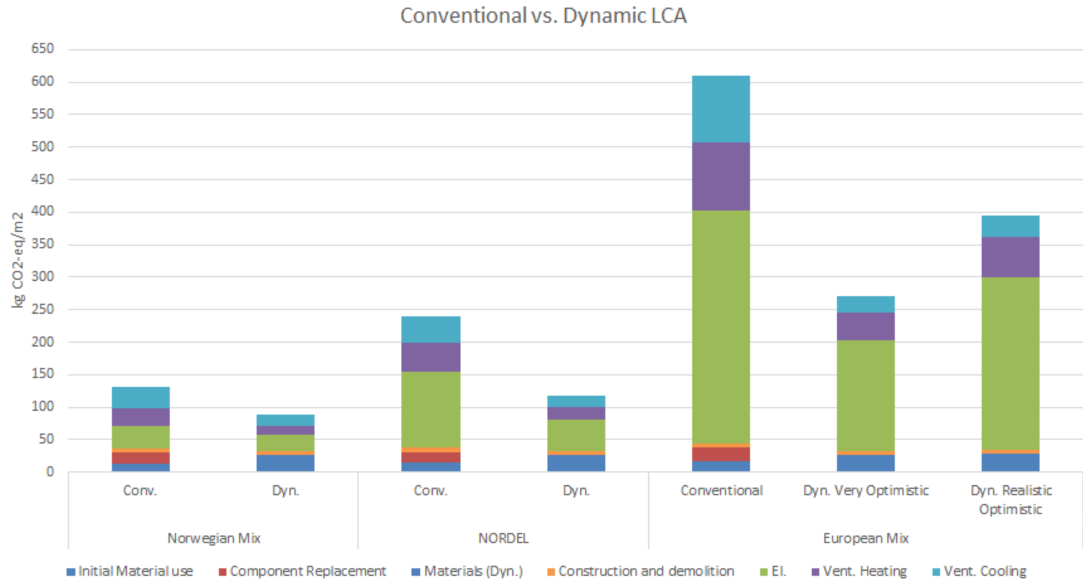
5.3 Conclusive Results

5.3.1 Comparison of the Conventional and Dynamic LCA

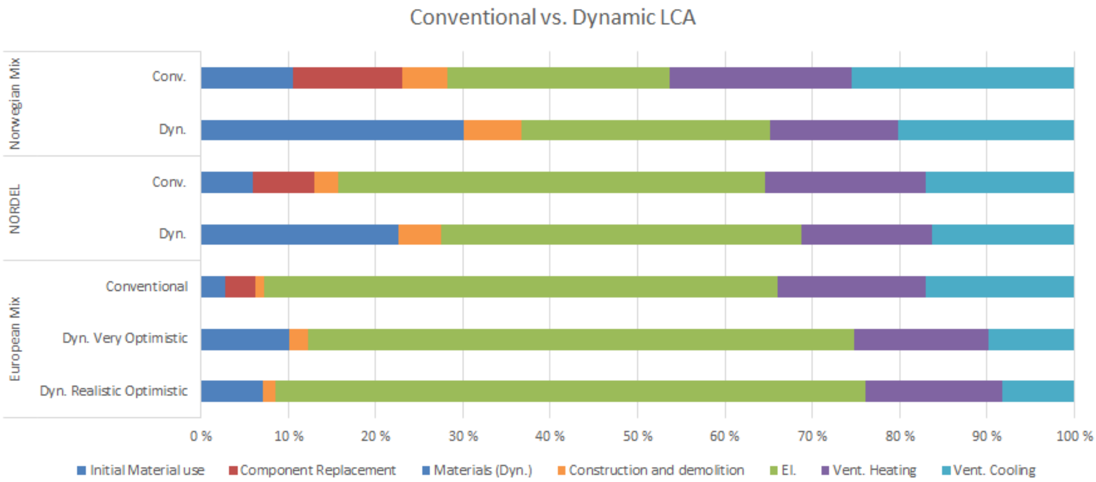
The radiative forcing in the Dynamic LCA can be converted to the equivalent unit of CO_2 equivalents, and thus one can compare the results from the dynamic LCA with the results from the conventional LCA method. All results are for the standard recycling rate, and are shown in table 18. Grapically, figure 30 shows the absolute and relative contribution to climate change from all electricity mixes and calculation methods.

The results show the dynamic LCA consistently giving a lower impact to Climate Change for all electricity mixes, with a largest reduction where the energy emissions are most important: in the case of the European mix. It is worth noting that the NORDEL and European Very Optimistic electricity mix has considerably lower emissions factors later in the life cycle in the dynamic LCA than in the conventional LCA. Therefore the difference in GWP cannot solely be attributed to the difference in methodology in these two cases, but also to the differences between emissions factors for the electricity mix.

It is also clear that the balance between the relative contribution of embodied emissions and energy emissions varies for the different calculation methods, showing the largest difference for the NORDEL electricity mix with 16% embodied emissions in the conventional LCA, and 27% embodied emissions in the dynamic LCA.



(a) Absolute impacts.



(b) Relative contibution.

Figure 30: **(a)** Absolute impacts and **(b)** relative contribution to climate change for all electricity mixes and calculation methods with a fixed standard recycling rate.

Global Warming Potential (kg CO_2 eq/m^2)							
Supply Mix	Norwegian Mix		NORDEL		European Mix		
Method	Conv.	Dyn.	Conv.	Dyn.	Conv.	Dyn. VO	Dyn. RO
Space Heating	22.08	16.29	35.52	18.88	83.48	32.00	42.61
Vent.Heating	27.47	12.97	44.06	17.76	103.62	41.92	61.46
Hot Water	20.19	11.48	29.86	14.27	71.75	28.36	39.76
Fans	33.50	25.17	116.81	49.08	358.71	169.57	266.99
Pumps	2.90	2.18	10.12	4.25	31.07	14.69	23.13
Lighting	52.75	39.64	183.95	77.29	564.89	267.03	420.46
Technical equip.	90.99	68.38	317.31	133.33	974.44	460.63	725.29
Vent. Cooling	33.53	17.81	40.89	19.27	104.00	26.70	32.70
Total Ventilation	94.50	55.96	201.76	86.11	566.33	238.18	361.15
Total Building	283.41	193.93	778.52	334.13	2291.97	1040.90	1612.39

Table 19: Climate change impacts for all energy consumption as given by the Simien simulation.

5.3.2 Climate Change Impacts of Total Energy Use, Abels Hus

To put the impacts from the ventilation system somewhat in perspective with environmental impacts of the entire building, the energy use from ventilation is compared with the energy use for the entire building given in section 4.4.5 from building simulations. The results are presented for the same methodologies applied earlier, with varying electricity mix and standard recycling rate.

All impacts to climate change are shown in table 19, and graphically in figure 31. Figure 32 shows the dynamic impact to climate change for the NORDEL electricity mix. The dynamic results for the remaining electricity mixes are given in Digital Appendix F.

The results show the ventilation impacts ranging from 22% to 33% of total impacts, with the dynamic LCA consistently giving a lower contribution for total impacts. Technical equipment and lighting are the two largest impacts and electricity to drive the fans in the ventilation system are also considerable.

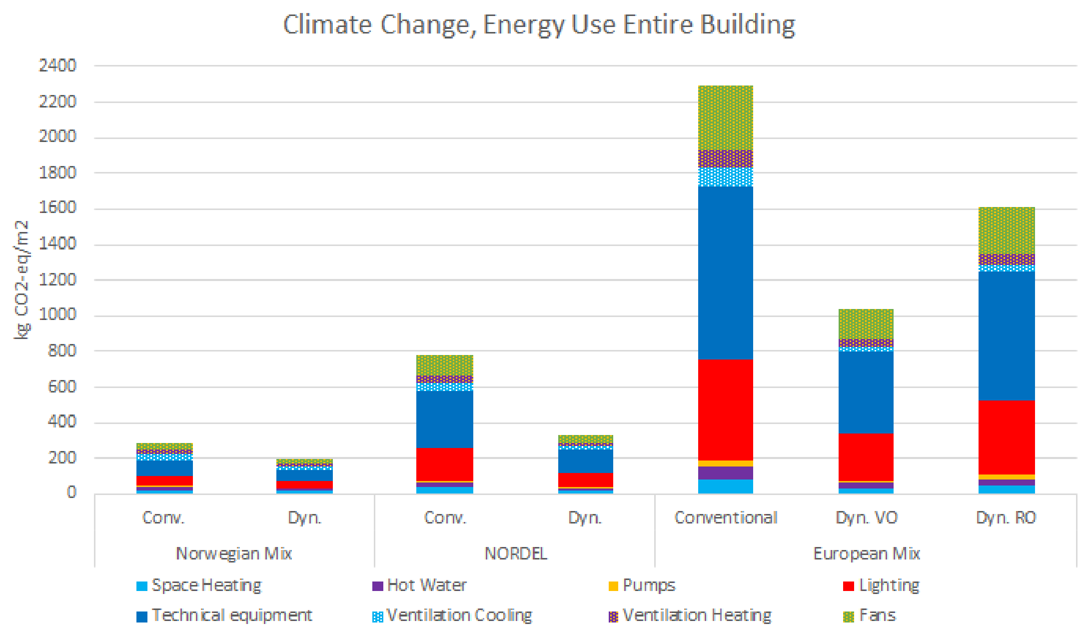


Figure 31: Total impacts from energy for all calculation methods and supply mixes, climate change.

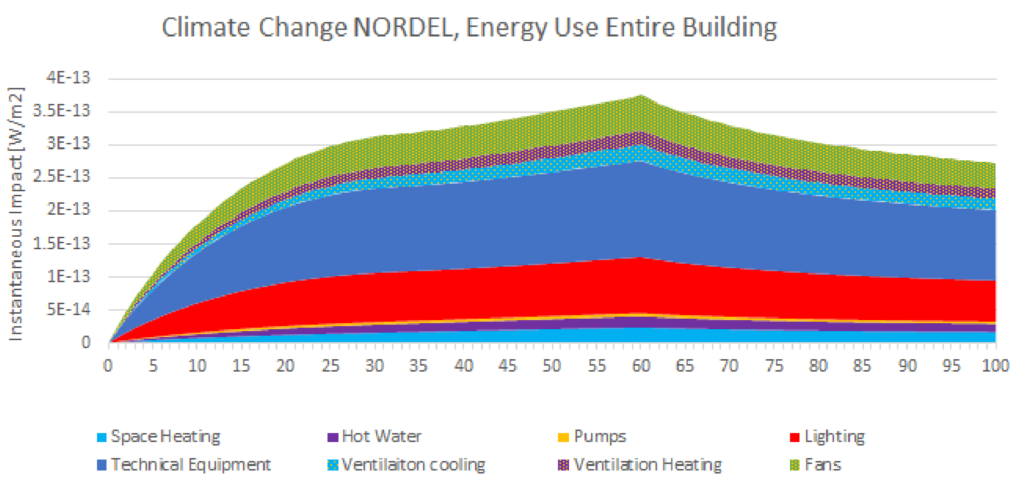


Figure 32: Instantaneous impact for the NORDEL electricity mix, in the dynamic LCA.

6 Discussion

In this section the results from the LCIA are discussed in further detail. The results are compared to the impacts found in the literature study, and the differences between the Dynamic and Conventional LCA are discussed. Possible uncertainties are outlined and the implications of the results for future research and policy makers are discussed.

6.1 Main findings

The results clearly indicate that energy use throughout the use phase has a larger environmental impact than embodied emissions in the ventilation components, as is expected from the literature review. An exception to this is for metal depletion where the embodied impacts are the majority, but in the same order of magnitude. This is also expected and easy to justify given the fact that the vast majority of the ventilation system consists of steel and other metals.

Since energy consumption in the use phase constitutes such a large share of total impacts, the results are very sensitive to the choice of electricity mix with variations of one order of magnitude between the cleanest Norwegian mix and the realistic-optimistic European mix. The embodied emissions in the ventilation components however, are not very sensitive to the choice of electricity mix. This is because electricity is not the main process in the production of ventilation components, where fossil fuel consumption is more prevalent.

The change from the standard recycled content to only primary steel is found not to have a large contribution to the total impacts. Changing the recycled content to only primary steel gave an increase in total impacts to climate change of 4% for the Norwegian mix and 0.8% for the European mix. This is mainly because the original recycled content does not contain a large amount of secondary steel. If the future recycled content in steel for ventilation systems was to increase, the lack of supply of steel scrap in the global steel cycle could have a larger impact on climate change than status quo from a consequential viewpoint. Additionally, human toxicity impacts are higher for secondary steel than primary steel, although they are in the same order of magnitude. There is however a large uncertainty associated with human toxicity from metal production.

When comparing the impacts from the ventilation system to the rest of the building, it is apparent that the impacts from the ventilation system are not insignificant in the context of the entire building, as they can constitute up to 22%-33% of impacts from energy consumption in the use phase. This is mainly due to the large impacts from the electricity used to drive the fan. It is important to remember that the ventilation system in this specific building serves an additional purpose than just to ventilate the air, that is ventilation heating and cooling. This could cause this specific system to contribute a larger percentage of impacts than other buildings.

For the embodied impacts of ventilation components, no conclusions can be made on the contribution to the total building impacts as it is outside the scope of the study. The ventilation components, can however be studied in greater detail, as there is a high resolution of the material results due to the comprehensive inventory modelling.

6.2 Contribution from Different Ventilation Components

This part of the disscussion is based on figure 24 in section 5.1.3. Since many of the ventilation components consist of similar materials, the embodied impacts throughout the ventilation system are mainly proportional to the weight of the components. There are however some differences across impact categories and components, mainly for the air handling units, which contribute a large amount of impacts compared to their mass.

Impacts to climate change and fossil fuel depletion are distributed similarly to each other. This is to be expected, given the large impact fossil fuels have on climate change. The majority of the impacts come from the production of ventilation ducts, since this is the most abundant category in the system as well as it having a fossil fuel heavy production. Important processes are the production of primary and secondary steel, and the zinc coating around the ducts, because of the sheer amount of material being consumed.

Human toxicity sees a slightly larger contribution from the air handling units compared to climate change. This is because of the disposal of sulfide associated with production of copper in the electronic parts of the air handling units, which contribute around 20% of total embodied impacts to human toxicity. Another 30% comes from the disposal of sulfide in zinc production. Due to the large uncertainties associated with Human Toxicity it is difficult to assess the significance of these small changes in distribution.

The main parts contributing to metal depletion are of course the steel components, but copper has a relatively larger characterization factor for metal depletion than for climate change. Therefore, the copper in the air handling units will have a larger contribution to metal depletion compared to its contribution to climate change.

The Monte Carlo simulation gives weight to the results of embodied material impact of the ventilation components. The process of applying uncertainty through the pedigree matrix is quite generic, thus the found values will only be approximations of the real uncertainties of the processes. Nevertheless, some parts of the inventory are modelled with a high deviation from the mean value, and still the total uncertainty of the system is deemed acceptable for all impact categories, except for human toxicity. As already mentioned human toxicity, especially for metals, has a high inherent uncertainty due to the variation in fate and exposure of the substances. Additionally, some of the processes were shown to be distributed with a normal distribution, instead of the lognormal distribution usually applied in Simapro. This might partially explain why human toxicity was allowed to attain a negative uncertainty, something which is not otherwise possible with the lognormal distribution.

6.3 Agreement with Literature

The results are not easily compared with the previously found literature, as many factors differ for previous studies. However, some parallels can be made which lend credibility to the precision of the results. In general, the results from the conventional LCA with the Norwegian electricity mix, coincide well with the ventilation impacts found in the analysis of a Zero Energy Building found by Dokka et al.[49]. These results are comparable since the building uses standard building practices with the only addition being photovoltaic panels delivering the required electricity to satisfy the zero energy concept. When the embodied impacts from ventilation components are compared with this case, the 0.5 kg CO_2 eq/m^2yr (excluding construction services) are comparable to the 0.38 kg CO_2 eq/m^2yr found in the ZEB assessment, albeit somewhat higher. The larger precision of this study would explain the higher impact found here.

The impacts from energy consumption from ventilation fans are also comparable to Dokka et al.[49], though these are all based on Simien simulations and thus have the same background. The result of 0.56 kg CO_2 eq/m^2yr are comparable to the value found in Dokka et al. [49] which is 0.8 kg CO_2 eq/m^2yr for both fan and pump work. This could explain the slightly higher value in the analysis of the ZEB office as well as assumptions regarding the electricity mix applied which is not clear in the ZEB study.

When looking at the total results for the ventilation system for the European mix, the closest comparison available is for the analysis of HVAC systems in the U.S.[31], although the electricity mix with the lowest impact in the American Study still was higher than the European average. The lowest impact in the American case was for climate zone 3B1 with an impact 260 kg CO_2eq/m^2yr for all HVAC equipment in the office building. The European value yields 10kg CO_2eq/m^2yr for only ventilation impacts, which seems somewhat low. The fact that the American case consists of about 15% natural gas for the HVAC installations (outside of the electiricty mix) would also increase the impacts considerably. There tends to be more cooling necessary in the American climate, which could lead to an increase impacts. The American study was also based on a top-down analysis which in general will give a higher value than the process based LCA.

6.4 Differences in Methodology

It is apparent from the conclusive results that the choice of methodology has a considerable influence on the results and impact distribution throughout the life-cycle. It is important to note that the methodologies themselves do not change the environmental impact, but they only reflect the difference in scope as outlined earlier. The dynamic LCA method, compared to the conventional LCA, decreases the emissions from energy use more than the emissions from embodied impacts, because the dynamic method inherently gives less weight to emissions occurring late in the life cycle. The main part of the embodied impacts happen before year 30, while the energy use happens every year until year 60. Thus, energy emissions occurring at year 40 in the dynamic method are given a weight of "GWP 40" compared to the conventional LCA.

Granted, the dynamic supply mixes in the dynamic LCA will also contribute to a lower GWP in the Nordic and European case. However, the emission factors for the Realistic Optimistic case of the European mix do not change substantially as shown earlier. Since the GWP is lower for the dynamic Norwegian case as well, even though the Norwegian supply mix is kept static, the difference in methodology still has a considerable impact on the Life Cycle Impact Assessment results.

With a somewhat static supply mix, in the case of the Norwegian mix and European Realistic Optimistic mix, the dynamic LCA gives a 33-35% smaller impact to climate change than the conventional LCA. Adding a dynamic supply mix with a cleaner mix later in the life cycle

(NORDEL and EU Very Optimistic), results in a 50-56% decrease in total impacts compared to the conventional LCA.

The dynamic LCA also offers additional insight that the conventional LCA does not. We see that the graphs showing the environmental impacts of GHGs in a temporal perspective for the two methods give two completely different pictures of the temporal impact profile of the ventilation system. The graphs showing the temporal emissions of greenhouse gases in the conventional LCA give the impression that the largest impact occurs at the beginning of the life-cycle. The dynamic LCA however, shows this not to be the case in reality. The largest instantaneous impact occurs quite evenly between 30 and 60 years after construction, with a peak at 60 years for the European supply mix. This is because a greenhouse gas will have an effect in the atmosphere for a long time after emission, which the dynamic analysis shows in a more concrete way.

6.5 Possible Uncertainties and Errors

The results prove quite robust regarding uncertainties in the embodied emissions, both when comparing them to other studies, and when considering the uncertainties from the Monte Carlo simulation. However, there are still possible errors that might influence the precision of the results in certain ways.

The environmentally extended input-output model used for the calculation of construction and demolition services is a crude model, and the uncertainties associated with it are unknown. Additionally, impacts from scheduled yearly maintenance and impacts related to the labour of operating the ventilation system have not been considered, although the exchange of filters in the air handling units is included in the inventory of the air handling units. The impacts from yearly maintenance and operation could be included with the combination of cost tables and environmentally extended input-output tables, but more detailed emission factors for ventilation services are needed to calculated this. Only impacts from construction services (construction and demolition) to climate change were considered in this study. Construction services will also affect the remaining impact categories, though these impacts should not considerably change the results or conclusions from this study.

Actual energy consumption for the building could be higher than the calculated value for low energy office buildings. On average a Norwegian study found energy consumption in low energy buildings to exceed calculations by 5 kWh/m^2a[50]. This would further increase the impacts from energy use, but as this value will vary, it has not been included in the analysis.

The ventilation system is controlled through the Variable Air Volume ventilation control system Wise, provided by Swegon AS. Only the part of the Wise system directly connected to the ventilation ducts, like flow and fire dampers is included in this study. Clearly, there are additional electronic components like control systems for the ventilation system, and these have an unknown impact. If a further analysis of the BIM model would be conducted, these impacts would be revealed when the electronic components are studied in more detail. The electronic components will shift the distribution of impacts for the ventilation systems even more towards the material side.

The results are only as accurate as the life cycle inventory. Excessive extrapolation for the ventilation components can lead to errors as there might be differences in production and handling of larger ventilation components. However, the mass balance of steel is conserved through the use of data sheets for all components. Since steel has by far the largest largest impact on the materials, the results seem sufficiently accurate.

Considering the precision of the total mass of the system the plumbing, heating and sanitation engineers responsible for the building model, state from experience that additional material inputs are around 10% of the total materials in the model. This must be taken into consideration when considering the total mass of the system. Additionally, waste on the construction site was not accounted for in this study. Gustavsson et al.[51] give percentages of total materials which are wasted on the construction site. They state 7% of insulation waste, 15% of steel reinforcement waste and 5% waste for most other materials. This could be improved on by increasing the total material use a proportionate amount.

It is also possible that the lifetime of the components was overestimated, since in reality new tenants would often need a restructuring of the ventilation systems when changing the layout of the offices. This would lead to an even greater increase in material impacts. Even though the total mass of the materials seems somewhat higher than the estimated amount, these small errors should not deviate form the general conclusion of the study.

6.6 Implications for Future Research and Policy Makers

The results give weight to the previously described trend of material emissions having a larger and larger share of the total environmental impacts in a buildings life cycle. Policy makers should have an increased focus on the embodied impacts of buildings, as there is a potential for decreased embodied emissions through increased recycled content and better waste management [3]. Alternative solutions, like a hybrid natural ventilation should also gain more focus as it has been shown as a functioning solution, among others, for an office building in Austria [52].

The methodology also reveals a need for a complete integration of LCA into building modelling. To ease this intergration, national BIM standards are needed. Components should be classified and standardized according to NS 3420 "Specification texts for building, construction and installations"[53]. If these standards classifications are integrated into both the BIM model and the LCI database, a seamless LCA can more easily be conducted.

Standards Norway is working in cooperation with industry actors to develop a link between NS 3420 and BIM [54]. Here the report cites the need for a standardized library of building components, and distinguishes between "type information", and "instance information" in BIM objects. Instance information denotes information about a specific BIM object in a specific project at a specific location, while type information is more generic information about the building component. Instance information should be collected from the specific BIM model, while type information could be collected from a standardized database. This has resulted in the creation of the Norwegian standard NS 8360 which standardizes names, types and characteristics of BIM objects. While this standard was published in June 2015 and not available at the time of the creation of the model the study is based on, standardization of BIM files will be a great advantage for sustainable building design in the years to come.

7 Conclusion

This study has thoroughly outlined the impacts associated with the life cycle of the ventilation components in Abels Hus. While the study only represtents one building, some general conclusions can be drawn that apply mechanical ventilation systems in general. Impacts from energy consumption are still the majority throughout the life cycle, but there is an increased addition from the embodied emissions, especially for other impact categories. This trend will be amplified if the supply mix moves towards more sustainable energy production technologies. However, there is a large uncertainty of the impacts for human toxicity and the main take-away message from these results must be the relative contribution from different components and life cycle stages.

As shown, the conventional LCA methodology does not sufficiently describe the environmental impacts over such a long time period as 60 years, while still keeping consistent with the time horizon. Dynamic LCA methodologies better reflect the actual impacts to climate change occurring within a given time horizon and even more emphasize embodied material emissions which tend to happen earlier in the life cycle. The dynamic LCA methodology, though more time-consuming, will yield a lower GWP than the conventional LCA, which is not necessarily an advantage in itself, but better shows the actual impacts of the system.

With the increasing complexity and material consumption of modern ventilation systems, one can question the cost effectiveness of these solutions, both from an economical and ecological perspective. Innovative ventilation systems like hybrid natural ventilation could prove to be a more environmentally friendly solution, but only if they also satisfy requirements for the indoor environment and thermal comfort experienced by the inhabitants of the building.

If the material take-off methodology can be applied on standardized building models with constant component names and inventory data extended to an entire building, this could make a "one-click" LCA, with a high level of detail possible. Such a solution could be very attractive from a commercial perspective and would provide a great benefit for the construction sector as well as researchers developing sustainable building solutions. Developments in Norwegian BIM standards should be monitored to explore this opportunity further.

8 Future Work

If there is a standardization of building components in BIM, the methodology from this study can be applied to remaining parts and discipline of construction where the end-goal must be a ”one-click” LCA based on a building model, with possibilities for variation in local parameters. If a big enough LCI database is constructed, one can easily calculate the environmental impacts associated with different buildings, with a high resolution and transparency as to the results. It is expected that the embodied material impacts will have a larger impact on the whole building than the ventilation system, because of the high energy use applied to the ventilation system.

The dynamic LCA method is a time consuming methodology, as all emissions have to be manually plotted to Excel. One cannot distinguish different contributions in one Excel file, and a more user friendly method should be developed, with the optimal method being an intergration of the dynamic LCA in Simapro.

It is necessary to improve the LCI database for ventilation components. Here, manufacturers can provide a greater transparency for their EPDs as well as gathering reliable data from other studies. From this, a more detailed LCA can be preformed, taking into consideration the possible errors outlined in section 6.5.

To better model the impacts related to construction and service activities, a more detailed composition of the input-output models i needed. This could make it possible to model scheduled maintenance and service activities related to ventilation systems in the future.

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Appendix A Total Results for all Impact Categories in the Conventional LCA

Climate Change ($kg\ CO_2\ eq/m^2$)	Norwegian Mix		NORDEL		European mix	
	Rec.	w/o Rec.	Rec.	w/o Rec.	Rec.	w/o Rec.
Initial material use	13.92	16.35	14.25	16.62	15.21	17.40
Component replacement	16.35	19.08	16.72	19.39	17.81	20.29
Constr. and demolition	6.86	6.86	6.86	6.86	6.86	6.86
Electricity	33.50	33.50	116.81	116.81	358.71	358.71
Vent. heating	27.47	27.47	44.06	44.06	103.62	103.62
Vent. cooling	33.53	33.53	40.89	40.89	104.00	104.00
Total	131.63	136.79	239.59	244.62	606.21	610.87

Table 20: Environmental impacts to climate change for all scenarios, divided upon embodied emissions and energy use.

Human Toxicity ($kg\ 1.4\ DB\ eq/m^2$)	Norwegian Mix		NORDEL		European mix	
	Rec.	w/o Rec.	Rec.	w/o Rec.	Rec.	w/o Rec.
Initial Material use	20.10	18.81	20.22	18.90	20.87	19.44
Component Replacement	24.89	23.43	25.03	23.54	25.77	24.15
Electricity	15.67	15.67	45.66	45.66	209.93	209.93
Vent. Heating	14.47	14.47	22.54	22.54	52.58	52.58
Vent. Cooling	13.09	13.09	22.86	22.86	30.05	30.05
Total	88.23	85.47	136.30	133.50	339.20	336.15

Table 21: Environmental impacts to human toxicity for all scenarios, divided upon embodied emissions and energy use.

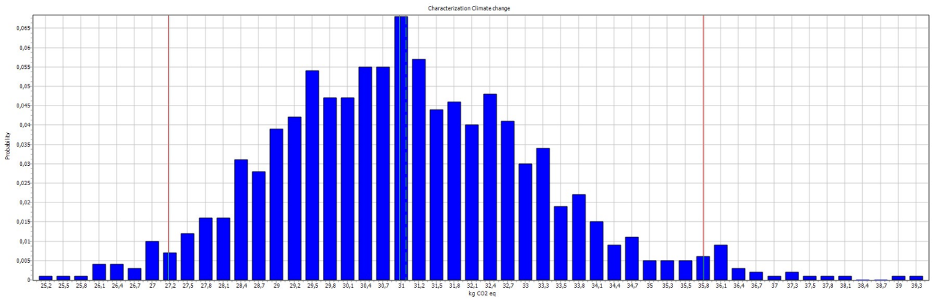
Metal Depletion (kg Fe eq/m^2)	Norwegian Mix Rec.	Norwegian Mix w/o Rec.	NORDEL Rec.	NORDEL w/o Rec.	European mix Rec.	European mix w/o Rec.
Initial Material use	9.00	10.58	9.01	10.58	9.01	10.58
Component Replacement	11.52	13.30	11.53	13.31	11.53	13.30
Electricity	4.73	4.73	7.44	7.44	6.12	6.12
Vent. Heating	3.59	3.59	4.13	4.13	3.88	3.88
Vent. Cooling	0.72	0.72	0.96	0.96	0.85	0.85
Total	29.56	32.91	33.07	36.42	31.39	34.73

Table 22: Environmental impacts to metal depletion for all scenarios, divided upon embodied emissions and energy use.

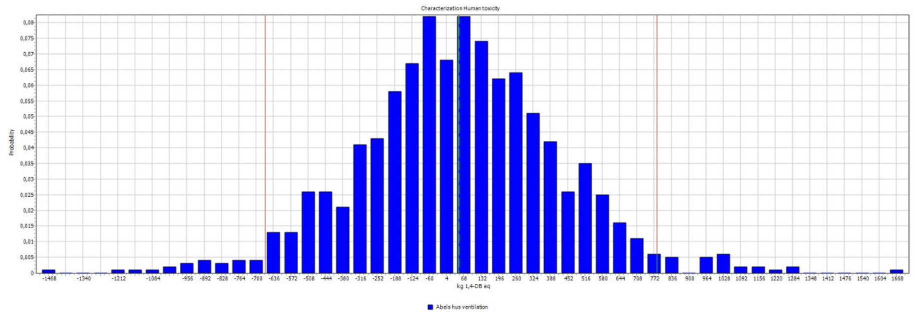
Fossil Fuel Depletion (kg Oil eq/m^2)	Norwegian Mix Rec.	Norwegian Mix w/o Rec.	NORDEL Rec.	NORDEL w/o Rec.	European mix Rec.	European mix w/o Rec.
Initial Material use	3.72	4.07	3.81	4.14	4.10	4.38
Component Replacement	4.36	4.76	4.47	4.84	4.80	5.11
Electricity	9.16	9.16	31.58	31.58	105.12	105.12
Vent. Heating	4.16	4.16	8.62	8.62	22.95	22.95
Vent. Cooling	7.28	7.28	9.26	9.26	15.65	15.65
Total	28.68	29.42	57.75	58.45	152.61	153.21

Table 23: Environmental impacts to fossil fuel depletion for all scenarios, divided upon embodied emissions and energy use.

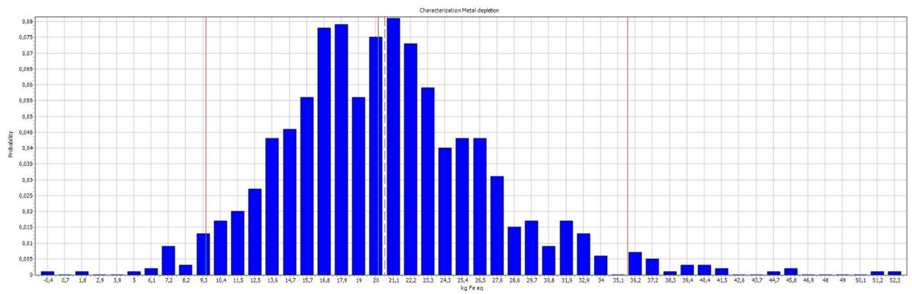
Appendix B Histograms for all Impact Categories in the Monte Carlo Simulation



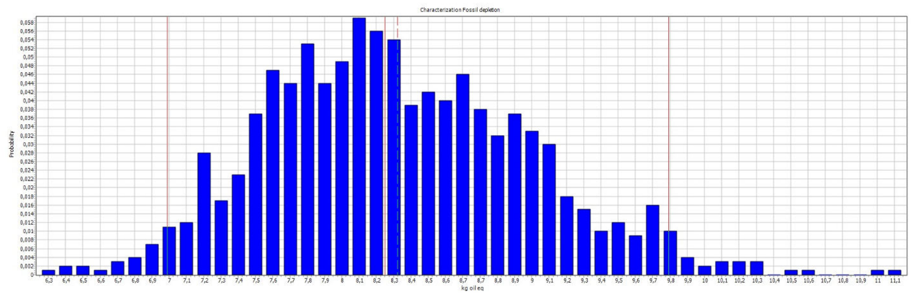
(a) Climate Change.



(b) Human Toxicity.



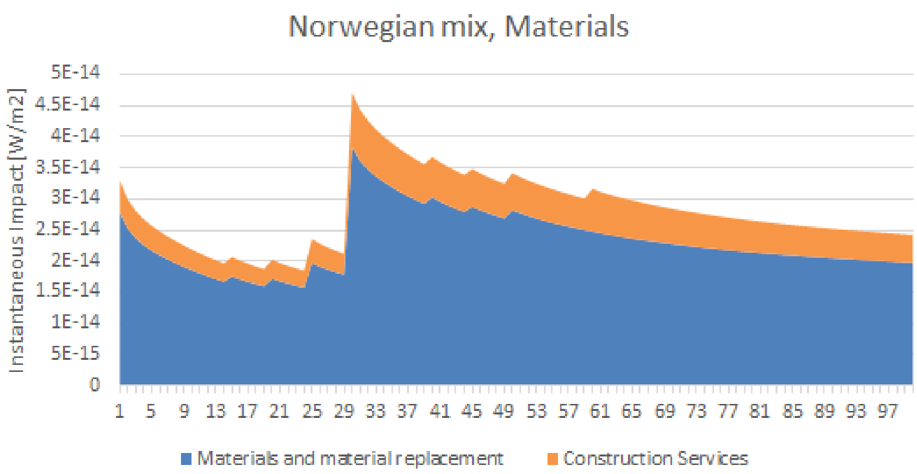
(c) Metal depletion.



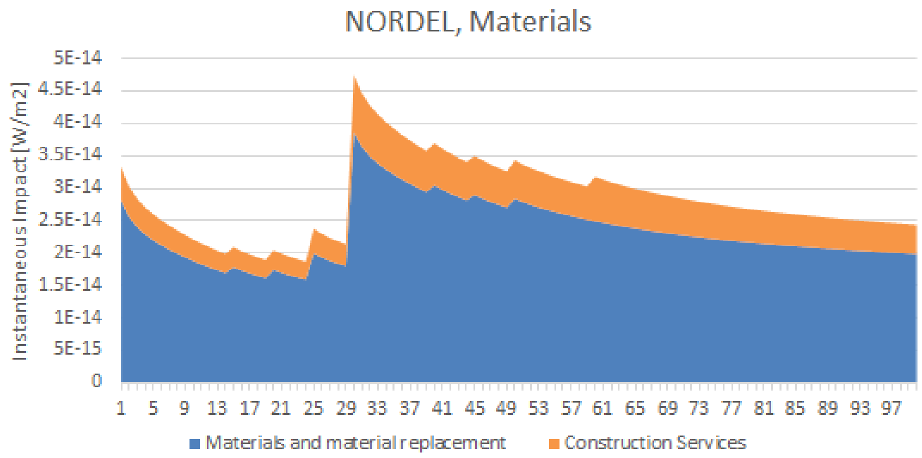
(d) Fossil depletion.

Figure 33: The results of the Monte Carlo simulation on ventilation components for Climate Change. The red lines show a 95% confidence interval.

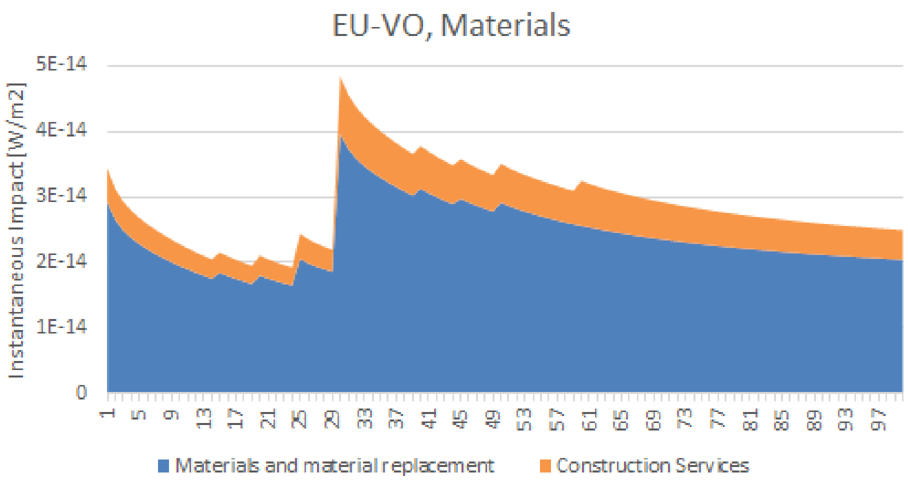
Appendix C Additional Results Dynamic LCA, Material and Energy Instantaneous Impact



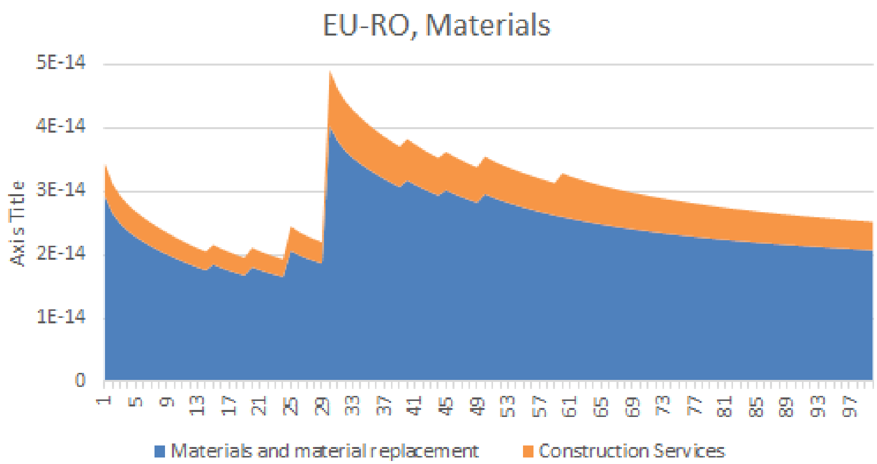
(a)



(b)



(c)



(d)

Figure 34: Instantaneous impact (W/m^2) per m^2 floor area from the office building for different electricity mixes. Note the difference in secondary axis values between the upper and lower graphs.

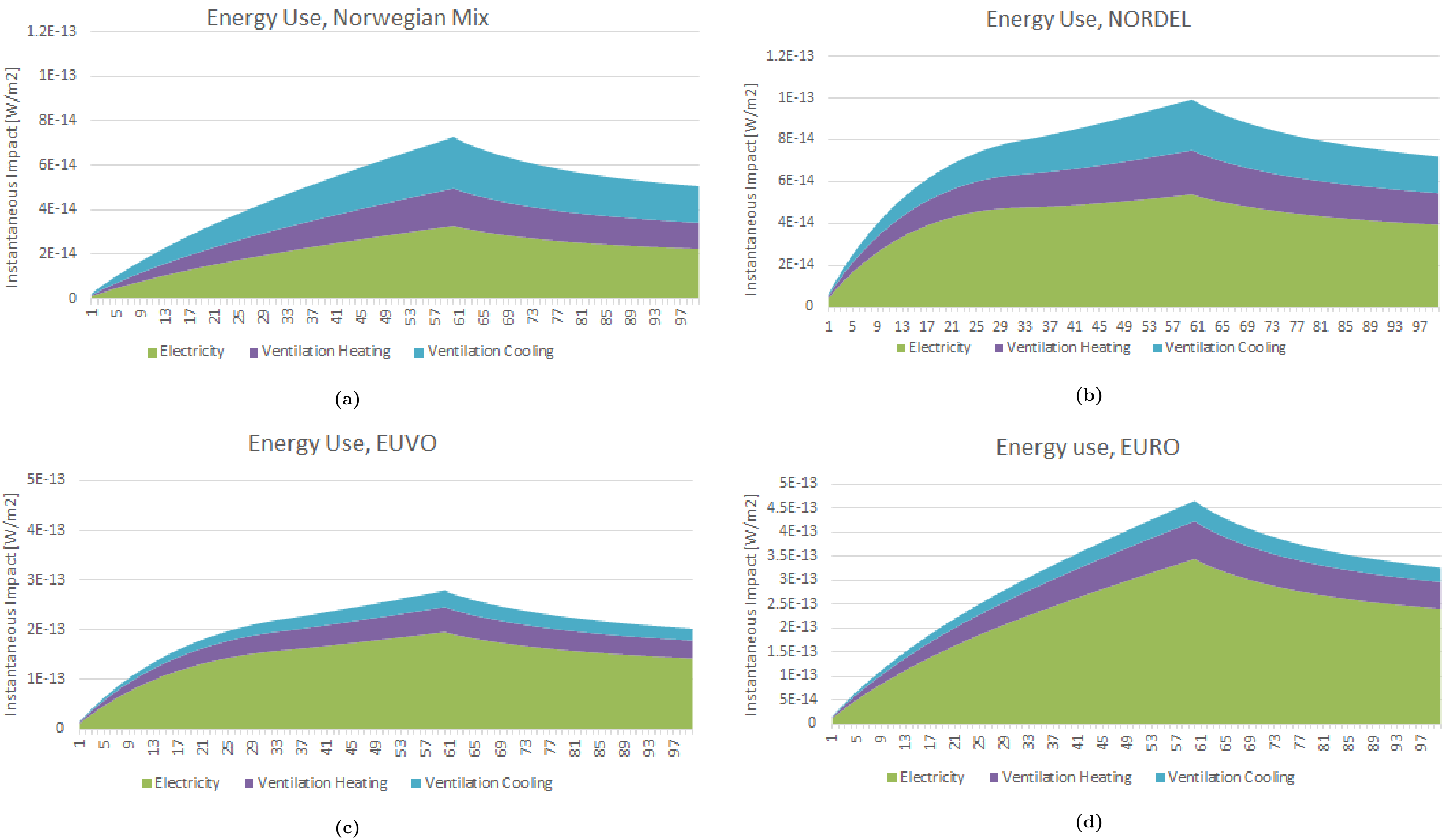


Figure 35: Instantaneous impact (W/m^2) per m^2 floor area from the office building for different electricity mixes. Note the difference in secondary axis values between the upper and lower graphs.

Appendix D Description of the Digital Appendix

Included with the thesis is a digital appendix, containing datasets and calculations performed in excel as well as additional files, too extensive to be included in the thesis. What follows is a description of the files included in the appendix.

Digital Appendix A - Electricity Scenario Supply Mixes: Inventories for the different supply mixes are included. The mixes used in the conventional LCA were for year 2017.

Digital Appendix B - BIM Files: The BIM file for the ventilation system and the entire building is included. It can be opened with the free software "Solibri Model Viewer".

Digital Appendix C - Data Sheets and EPDs for Ventilation Components: All data sheets used to calculate the inventory data are supplied here.

Digital Appendix D - Inventory Data and Material Takeoff Schedules: Contains the original inventory dataset from Jens Tønnesen Larsen with interpolations. Furthermore, the material take-off schedule from Revit is included in a pivot table, along with the calculations done on the components.

Digital Appendix E - Description Files for the Building, Area, Energy Consumption, and Project Description: All buidling description files provided by NCC and used in the report are given here.

Digital Appendix F - LCA Excel Results: Contains detailed results for Both the Dynamic and Conventional LCA methods.

Digital Appendix H - Input Output Tables, Construction Services: The Modified Input-output table is supplied here.