Climate-neutral buildings- impact of existing definitions on building design

Roberts Razna & Nishat Tasnia Aive

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University is Scandinavia's largest research and higher education institution, with eight colleges and a number of research centers and specialized institutions. The university's main campus is in Lund, a small town with a population of roughly 112 000 people. Malmö does, however, have a number of research and education departments. Lund University was founded in 1666 and now employs 6 000 people and has 47 000 students enrolled in 280-degree programs and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international curriculum teaches knowledge, skills, and competencies in energy-efficient and environmentally friendly building design in cold climate regions. The goal is to train highly skilled professionals who will significantly contribute to and influence the design, construction, or renovation of energy-efficient buildings, taking into account architecture and the environment and the behavior and needs of the inhabitants, their health and comfort, and the overall economy. The degree project is the last component of the master's degree program in Energy-efficient and Environmental Buildings (120 credits).

Examiner: *Dennis Johansson (Division of Building Services)*

Supervisor: *Ricardo Bernardo (Division of Energy & Building Design)*

Keywords: Climate neutrality, Climate-neutral buildings, Climate impact, Climate compensation measures, Climate-neutral certifications

Publication year: 2022

Summary

Climate change poses one of the most substantial threats to humanity today. If global greenhouse gas emissions are not reduced drastically in the near future, it can lead to detrimental consequences worldwide. Policies have been developed on a national and international level to promote climate-neutral industries and societies in order to address this issue. In Sweden, the construction industry is responsible for 18% of the country's total greenhouse gas emissions. Therefore, it is crucial not only to understand the impact generated by the construction industry but also to take the initiative to limit and reduce it. Several definitions of climate neutrality for the construction industry have been developed in the past few decades to address this issue, but despite this, there appears to be disagreement regarding what should be included in such a definition.

This study aimed to evaluate three existing climate-neutral definitions and compare how they impact building design. Life cycle costing (LCC) and life cycle profit (LCP) calculations were performed to compare the extent of required compensatory measures for all definitions. Selected definitions were White Architect's definitions, NollCO_2 definition from Swedish Green Building Council, and ZEB definition from the Norwegian Research Institute. For this study, the only life cycle analysis (LCA) indicator that was assessed was Global Warming Potential due to the vast amount of literature linking it to climate change, and aspects like daylight or indoor air quality were not assessed. White Architects provided the case study building, and a methodology was developed following a literature review analysis to assess the certifications under consideration. First, the base-case building was assessed using each definition. After that, changes were made in accordance with the pre-requisites of each definition. Next, total carbon emissions were calculated based on the system boundaries of energy and LCA. Finally, various climate offset measures were explored to ascertain climate neutrality, including production and export of renewable energy, carbon credit purchase, and biogenic carbon storage. These climate offset measures compensate for the climate impact obtained from each definition and establish a net zero emission balance for the building. In addition, a comparison study was done for the accumulated emissions from each life cycle module and their respective need for climate offset measures.

One of the central parts of this study was to assess if a case-study building could be certified as climate neutral according to assessed definitions. Results indicate that the building managed to reach climate neutrality according to White Architect's definition as well as NollCO_2 and the lowest ambition level from ZEB requirements. Despite the same geometry in all the definitions, the same building design couldn't be certified as climate-neutral without incorporating some degree of energy measures. The study also indicated that there are established standard practices that are recognized by all three definitions. This mainly encompasses methods of how emissions from LCA modules are calculated. However, the definitions showed contrasting final results for the same building due to the choice of different system boundaries and alternative methods on how to account for climate offset measures. The total emissions from the same building varied significantly depending on the scope of each certification, for example, for White Architect's definition, total emissions were 1459 tCO_2e, for NollCO_2 1813 tCO_2e, and for ZEB-COMPLETE 4363 tCO_2e. It can also be noted that the building design's impact was different for each of the definitions. The White Architects' definition favors the use of biogenic carbon, and its design is carbon negative throughout the lifespan of the building without requiring any renewable energy production. Because of strict energy requirements, NollCO_2 and ZEB definitions required heat pump incorporation only to be qualified to be assessed for climate neutrality. ZEB definition is

very demanding on energy efficiency and requires on-site renewable energy production to achieve carbon neutrality, while the NollCO$_2$ definition requires a considerably oversized PV system.

Exporting surplus electricity back to the grid is a common principle that serves as a climate compensation measure for all three definitions. There are two common ways to account for what emissions are displaced. One is the average emission factor, and the other is the marginal emission factor. NollCO$_2$ and White Architects' definitions use marginal emissions factor while ZEB definition uses average emission factor accounting, and as both processes account for two different total emissions for compensation measures, very different PV systems were required to achieve climate neutrality.

Climate neutrality for NollCO$_2$ definition could also be achieved with carbon credit purchase and without any compulsory building design changes. The purchase of carbon credits is a relatively inexpensive and simple alternative for achieving climate-neutral building status and seems to divert responsibility from the building owner and constructor, as carbon credit purchases without any limit or threshold could potentially ignore the importance of climate measure considerations for a building.

Finally, a few reflections from the study are, for example, all certifications should address the unclarity and disagreement of energy type (primary energy or delivered energy), energy carriers, and energy quality (emissions) considered in the calculations. Among all three certifications, the ZEB definition provided the most clarity regarding these points. Perhaps, it would make more sense if all the definition accounts for delivered energy and emissions involving any energy loss during transportation, regulation, transfer etc., could be compensated by the source of energy itself. One more substantial question from this study would be how the same building can account for different amounts of carbon emission at different points of the building's lifetime. It can be seen that the same case study building, at the same time, can be carbon negative and carbon positive according to the different definitions. So why is the same building accounting for different amounts of carbon emission at the same point in its lifespan? Perhaps this is a relatively insignificant question concerning the scale of climate neutrality for the building, but it indicates contradictions between the definitions themselves. Nevertheless, it can be pointed out that the definition of climate neutrality is quite a recent topic, and more research and collaboration is required to achieve consensus and establish a unified framework that all parties can adopt, which is crucial in the subsequent development phases.

Abstract

Climate change poses one of the most substantial threats to humanity today global greenhouse gas emissions are not reduced drastically in the near future, it can lead to severe consequences worldwide. To address this issue, global and national goals have been developed which aim to foster climate-neutral societies and industries. Since emissions from the construction industry are shown to have a significant climate impact, it is crucial to assess their impact and take necessary initiatives. In this regard, several definitions of climate neutrality for the construction industry have been developed in the past few decades to minimize the impact of building construction on the environment and climate. Despite this, there appears to be disagreement regarding what should be included in such a definition. This thesis aimed to investigate different definitions of climate neutrality in the construction sector, focusing on 'climate-neutral buildings' and how these impact building design. Three certifications were investigated: White Architects, NollCO_2 from the Swedish Green Building Council, and Zero Emission Buildings (ZEB) from the Norwegian Research Institute. A methodology for assessing the certifications under consideration was developed following a literature review analysis that provides a relevant context for the study. Total carbon emissions were calculated based on the system boundaries of energy and LCA for each of the definitions. Furthermore, climate neutrality was ascertained with the climate compensation measures considered from each definition. Attention was paid to various climate offset measures to balance the climate impact obtained from each definition.

The results from the study indicate that the building managed to reach climate neutrality according to White, NollCO_2, and the lowest ambition level from ZEB definition requirements. Despite the same geometry in all the definitions, the same building design couldn't be certified as climate-neutral without incorporating energy measures like heat pump integration. The study also showed that each definition has divided opinions regarding the choice of system boundaries and approaches to achieving climate neutrality. All certifications agreed to include A1-A5 modules in the climate impact calculations except for the lowest ambition level of ZEB. Moreover, all the definitions provided consensus to account for the emission of operational energy. The contrast here was seen primarily in terms of what type of energy was being accounted for. Various climate measures were considered to balance the climate impact, which essentially comprised of the following: production and export of renewable energy, purchased climate compensation, and storage value of biogenic carbon in wood. In addition, while PV systems from all three certifications are likely to have a certain impact, particularly in NollCO_2 and ZEB, it is evident that PV emissions outweigh other emissions in the A1-A3 module, unlike the White certification. Furthermore, different PV system sizes were incorporated in all the climate-neutral definitions linked to carbon emission compensations which inferred a difference in cost associated with climate neutrality.

Acknowledgments

We would like to convey our heartfelt gratitude to Ricardo Bernardo, our master's degree supervisor, for encouraging and supporting us throughout this project, without whom this dissertation would not have been possible. We also would like to thank our co-supervisors, Marie-France Stendahl (White Architects), who has helped us tremendously with the information on the studied building and guided us throughout the project with invaluable advice and feedback. A special thanks to Rafael Campamà Pizarro (LTH) for sharing his valuable knowledge and expert advice and giving access to the Optima (EBD computer) for aiding simulations. All this has helped in every stage of this formidable topic and has inspired us to rise to the challenge and explore the captivating possibilities within this domain.

Last but not least, our sincere gratitude to our family and friends for their continued motivation and support throughout this thesis.

Abbreviations

A_{temp}:	Heated floor area
BBR:	Boverket's Building Regulations
BTA:	Gross area of a building
CO_2:	Carbon dioxide
CO_2e:	Carbon dioxide equivalent
CS:	limate Studio
EPD:	Environmental Product Declaration
EU:	European Union
GH:	Grasshopper
GHG:	Greenhouse gas
GWP:	Global Warming Potential
HB:	Honeybee
HR:	Heat Recovery
HVAC:	Heating Ventilation & Air-Conditioning system
IPCC:	Intergovernmental Panel on Climate Change
kg CO_2e:	Kilogram of Carbon Dioxide equivalent
kWh:	Kilowatt hour
kWpeak:	Kilowatt peak
LB:	Ladybug
LCA:	Life Cycle Assessment
LCC:	Life cycle costing
LCI	Life Cycle Inventory
LCP:	Life cycle profit
MSEK:	Million Swedish Krona
MW:	Mega Watt
NPV:	Net Present Value
ROI:	Return on Investment
SAM:	System Advisor Model
SCOP:	Seasonal Coefficient of Performance
SGBC:	Swedish Green Building Council
SHGC:	Solar Heat Gain Coefficient

List of Terms:

Biogenic carbon - Carbon originated from biological sources or living things.

Carbon dioxide sinks - Natural repositories that take in atmospheric carbon dioxide. It mainly comprises of the sea, forests, and soil. However, these are constrained in terms of their ability to absorb new emissions as well as their ability to grow in scope and area.

Climate action - Has been used by SGBC as a collective noun to describe policies that lessen, prevent, or regulate greenhouse gas emissions.

Climate compensation - A procedure outside the boundaries of the product system that prevents, reduces, or eliminates the relevant quantity of greenhouse gas emissions in order to offset all or part of the climate impact.

Climate impact - Impact of greenhouse gas emissions on the earth's climate, which results in higher temperatures.

Climate neutral - Having no impact on the greenhouse effect (same as being Zero Carbon or net zero climate impact)

Embodied climate impact - This corresponds to the environmental impact that the building material may have. It is distinct from the impact on the climate that is related to energy use during operation and may involve a variety of comprehensive interpretations.

Greenwashing- Marketing products that are more environmentally friendly than they actually are provides the environment a false impression of their actual climate impact.

Renewable energy sources- Energy sources without fossil origin.

Contents

1. Introduction

1.1 Background

Climate change can be defined as long-term changes in average weather patterns and temperature shifts. Greenhouse gases (GHG) like carbon dioxide and methane disrupt the balance of the climate systems and are directly linked global warming effect and climate change. As a result of burning fossil fuels, GHG emissions trap heat in the atmosphere and raise global temperatures over time (IPCC, 2022). The majority of energy needs are met by fossil fuels like coal, oil, and natural gas, which are affordable and versatile. However, their unrestricted use increases the atmospheric concentrations of GHG at an alarming rate, and sectors like transportation, agriculture, energy, and buildings are the leading emitters (United Nations Environment Programme, 2020).

The most recent Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2022b) stated that greenhouse gas concentration in the atmosphere had its highest levels in 2 million years. Moreover, carbon dioxide levels in 2019 reached a new record high of 148% compared to pre-industrial levels (WMO, 2020). This has led to severe consequences, such as extreme climate events involving acute drought, increased precipitation, or severe storms (Swedish Environmental Protection Agency, 2019a; IPCC, 2007). Therefore, aiming toward climate neutrality by the middle of the twenty-first century is crucial if the global temperature is to be prevented from rising above 1.5 degrees Celsius, which is deemed safe by IPCC. To combat this issue, the Sustainable Development Goals (SDGs) (2015), Paris Agreement (November 2016), and other international frameworks with the primary goal of adapting to environmental impacts and financing them as well as reducing emissions have all been put in place by the United Nations (UN). For example, one of the Paris Agreement agendas is to raise awareness of climate change and increase worldwide response to sustainability. Additionally, it aims to limit global warming to 1.5 degrees Celsius compared to pre-industrial levels resulting in a notable reduction of impacts associated with climate change consequences (UNFCCC, 2015).

Furthermore, in line with these agendas, the European Green Deal has been formulated by the European Commission to address environmental problems in society. Through this, the EU will be resource efficient, modern, and competitive, with a target of net-zero GHG emissions by 2050 (European Commission, 2019). Since all EU policies are moving in this direction, Sweden has also set a target with a new environmental policy framework which includes legislation that must be followed to achieve the goals of the Paris Agreement by 2045 (UNFCCC, 2017). On top of this, 21 Swedish pioneer cities already want to reach these targets by 2030. The climate policy framework was implemented in 2017 and means that greenhouse gas emissions from activities in Sweden will be at least 85% lower in 2045 than in 1990. Further measures can be taken to bring the remaining reductions to zero, eventually contributing to negative emissions. The milestone targets towards the long-term goal indicate that by 2030 and 2040, emissions are to be 63% and 75% lower than in 1990. The National Board of Housing, Building, and Planning states that Sweden's construction and real estate sectors alone account for 18% of the country's total greenhouse gas emissions (Boverket, 2018). Globally, the same figure is 38% (UNEP, 2020). With the world's population approaching 10 billion figure, (Adams et al., 2019) predict that housing development will be doubled, requiring a lot of energy and raw material. Due to the fact that it already contributes significantly to global GHG emissions and is projected to rise, the building and real estate sector is vital. Therefore, one of the most effective strategies to prevent further climate change would be to reduce the emissions in this sector. To accomplish these goals, the building sector must work rapidly towards climate neutrality. In this regard, a measure that takes effect in 2022 focuses on specific aspects of a building's life cycle wherein the National Board of Housing, Building and Planning also address how the entire life cycle, along with major renovations, should be included at a later date (Boverket, 2018, 2019).

Various voluntary certifications, such as LEED, BREEAM, Miljöbyggnad, and the Nordic Ecolabel, were developed to encourage sustainable construction (Karlsson et al., 2019). However, as the climate goals become more demanding, certifications are starting to impose higher standards on building performance, specifically in the form of climate impact and climate-neutral buildings. This could play a key part in reaching stated environmental goals. Additionally, environmental certification systems have also proven to be an effective way of increasing climate-friendly measures in other countries, according to the National Board of Housing, Building, and Planning, indicating that such certification tools can be an effective strategy for improved environmental work (Boverket, 2018). Although it is not entirely possible to construct buildings without affecting the environment, therefore, climate actions, sometimes in conjunction with climate compensation measures, must be used if climate-neutral construction is to be achieved (Zuo et al., 2012). However, there are many uncertainties about what defines a climate-neutral building or ways to achieve them, specifically when it comes to compensatory measures.

1.2 Motivation

In order to reduce the climate impact of the construction sector, the Swedish government intends to introduce requirements for the client to submit a climate declaration in connection with the construction of a new building. However, The Swedish certification of NollCO_2 for climate-neutral construction projects, for example, is an expansion of previous environmental certifications in Sweden that did not exclusively focus on climate impact but also included other aspects. This can be compared to climate initiatives like energy efficiency, renewable energy generation, and purchased climate compensation (SGBC, 2020a). Other international projects and accompanying certification tools and standards exist, with varied characteristics, tactics, and definitions based on national directives and conditions, for example, Zero Emission Building in Norway and Net Zero Carbon Building by the UK Green Building Council. The core principle of climate-neutral definitions is to reduce the climate impact associated with emissions in the construction sector. That can be done by setting a framework and regulations on emissions in the construction industry. Research and development in this field are essential for establishing legislation that controls this methodology as there is no agreement on the idea of "climate neutrality" or a single method for achieving it. This thesis will primarily focus on analyzing definitions from Nordic countries for a multi-family dwelling in Sweden.

1.3 Objectives

This thesis aims to gain insights on the impact of different definitions of carbon-neutral buildings in building design and compare their costing/economic feasibility. The fact that compensation measures and climate impact reduction strategies differ within different definitions indicates that perceptions of what a climate-neutral building is (or should be) differ and need to be further determined. The aim of the work is to shed light on these differences and thus problematize climate neutrality in the construction sector.

1.4 Research questions

- What is the impact on building design based on different definitions?
- Is it always possible to achieve a climate-neutral building according to several definitions? If so, how?
- Is it possible to reach carbon neutrality in a reasonably economical manner? How do the different definitions compare in this aspect?

1.5 Limitations

Climate neutrality is a prominent topic both nationally and internationally, and various methods, norms, and individual parties have decided to define this idea in relation to the building sector. However, from these tools, only three different definitions were evaluated due to the project's time constraints, and this project aims to explore climate neutrality for a case study building. It is worth mentioning that the embodied and operational CO_2e represents all the greenhouse gases combined which are calculated under the environmental category of Global Warming potential (GWP). The GWP is the only indicator of LCA that has been considered in this study. Evaluating the environmental impact of buildings requires a full LCA to account for other important factors such as involving toxicity, depletion of resources, air quality etc. which were not considered in this study. However, these issues should be addressed when investing sustainability of the construction sector to be more thorough. This study was not based on exhaustive research to have an optimal design option for the certifications. Geographical factors would affect the choice of EDPs, thus differ in results. The study does not consider investigation for any daylight and Indoor Environmental Quality (IEQ) assessment. Detail ventilation system design considerations were outside the scope of this study. Only Photovoltaic Panels (PV) were looked into when examining the renewable energy integration, and no solar thermal collector use was investigated. Moreover, while there were some economic evaluations, the social or ecological issues were not considered. Furthermore, the study's goal was not to take a stance with the most appropriate definition but rather to illustrate how they differ, what underlying arguments are offered, and the obstacles associated with them.

1.6 Disposition

This report begins with an introduction to describe the topic, the background and the problem, the research questions, the aims, and the goals. The introduction is followed by the method, which describes the outline of this research, followed by the theoretical framework and the empirical study, which underlines a thorough study of the subject. The result section indicates the outcomes attained in this study, followed by a discussion where the authors reflect on some of the key points, challenges, and contradictions faced in this research. Finally, conclusion part displays the most crucial finding from this study.

1.7 Contribution

Both authors were engaged in all parts of this study and worked together with the energy and LCA software, finding relevant information and literature related to the assessed certification and setting up the calculations for energy, LCA, and LCC. Roberts Razna concentrated more on the specification for material quantification, calculation of life cycle stages, and LCC for relevant material costing. At the same time, Nishat Tasnia Aive focused more on energy simulations, finalization of LCA emission results for balancing, and sizing the compensatory measures along with their respective LCC and LCP involved. All the calculations and results were scrutinized and agreed upon by both authors. Moreover, the report writing was divided into equal parts for each chapter. Nishat Tasnia Aive was responsible for report structuring, editing, illustrations, and finalization, while Roberts Razna dealt with the figure and table edit, referencing, and finalization. Finally, both the authors analyzed the results and made a conclusion based on their discussion.

2. Literature review

2.1 Climate impact

The environmental impacts of buildings consist of two categories, operational impacts and embodied impacts. Many LCA indicators can be used to assess these "impacts," like global warming potential (GWP), acidification potential (AP), ozone depletion potential (ODP), as well as other midpoint and endpoint categories. For example, GWP is a midpoint indicator and refers to the product's contribution to the global warming effect and is calculated in carbon dioxide equivalents (CO_2e). Because of its high impact on the environment and ecosystem stability, it is the primary indicator for this study.

Embodied emissions refer to emissions from the extraction of raw materials, processing, manufacture, transportation, and construction. They are influenced by construction methods and attributes of selected building materials (Ibn-Mohammed et al., 2013). On the other hand, heating, lighting, ventilation, air conditioning, and other energy expenditures reference operational emissions. Operation emissions are created during the use phase of the building and are influenced by the occupants' behaviors (Breton et al., 2018). In the past, most building constructions focused on reducing operational impact because former research (Ramesh et al., 2010; Sartori & Hestnes, 2007) indicated that operational impacts of a building were higher than embodied impacts. However, recent findings show that reduction in operational energy leads to increased embodied impact, especially in modern low-energy design homes. As a result, embodied emissions account for an increasing percentage of total building emissions and, according to some reports (Anand & Amor, 2017) can reach 46% of a building's total emissions. This trend is illustrated in Figure 2.1.

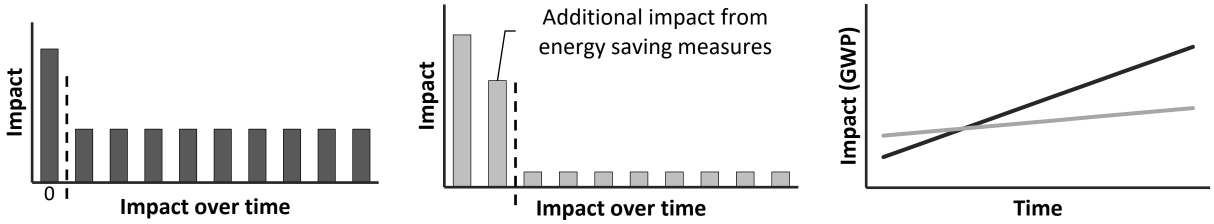

Figure 2.1 Comparison between operational and embodied impact over time

If, for example, operational energy is derived from sources with low carbon emissions most significant part of the total building emissions will be from the material selection. According to (Fouquet et al., 2015a), this changing trend indicates that materials selection is essential in assessing climate neutrality in the building sector. According to the European Commission and SGBC, climate neutrality identifies with low use of high emission energy, energy efficiency, high resource efficiency, and circularity (Adams et al., 2019). And as stated by (Liu, 2019), well-developed design decisions could give the best return on the investment as well as reduce carbon emissions. Therefore, initiatives like material reuse, renovation, and material adaptation for future use will be more critical in new and future construction designs.

2.1.1 Climate impact from the construction sector

According to (IEA, 2018), in 2017, buildings generated nearly 40% of annual global CO_2 emissions, of which 11% were building materials and constructions, as shown in Figure 2.2.

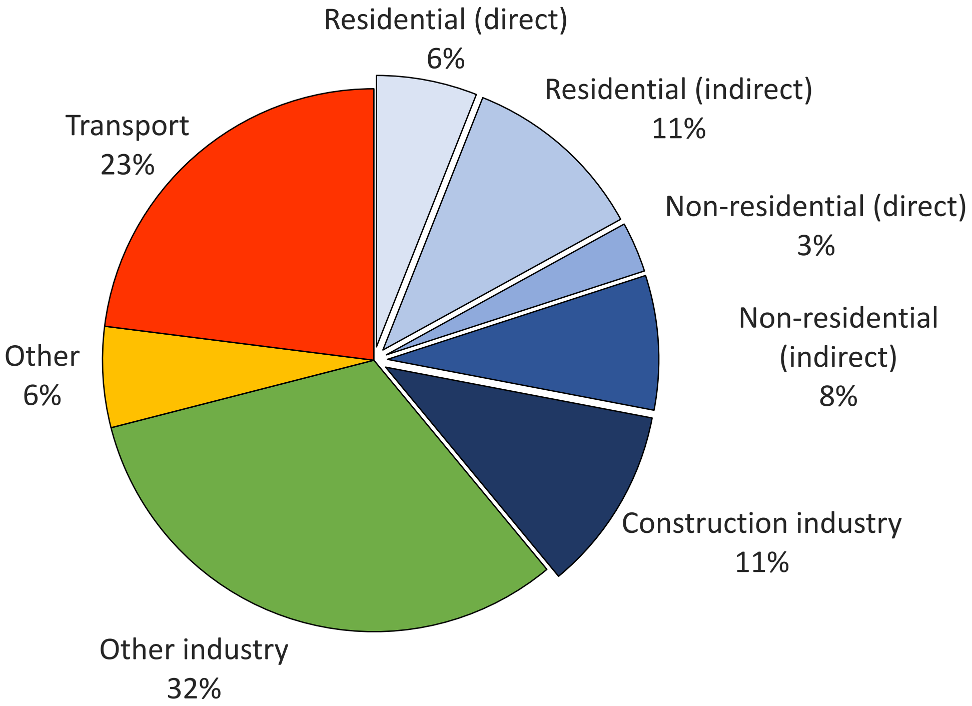

Figure 2.2 Global share of buildings and construction final energy and emissions, 2017

Material demand is the primary factor determining the amount of embodied carbon in a building. Cement and steel used in building from 2000 to 2015 increased by 4% by weight annually. Many countries are heavily dependent on reinforced-concrete framing, with the most considerable contributions coming from China, followed by India and Southeast Asia (IEA, 2018). Concrete is considered as the material that has the most significant climate impact due to the large amounts of CO_2 released in the concrete production process, associated with the energy-intensive production process and the chemical reaction that produces it (Miller & Moore, 2020). More innovative composite material structures can offer more substantial carbon reduction from building structures but currently contribute a minimal market share. Biomaterials, such as wood, hemp, and straw, are often viewed as renewable and sustainable materials. They can be produced locally and require relatively low energy input during production and processing, and products like that can contain about 50% of carbon by their dry mass (Breton et al., 2018). Nevertheless, wood and composite materials are not the primary choices of structural materials in European residential buildings, attributing only to approximately 19% of the market and contributing to a much smaller share in the non-residential buildings sector. Significant changes in how concrete and cement is produced and used in the building industry as well as how cities are designed, built, and managed will be needed to meet the goals set out in the Paris Agreement and the SDGs (Lehne & Preston, 2018)

2.2 Life cycle assessment (LCA)

Providing society with services and products contributes to various environmental impacts, therefore, measuring and comparing the environmental impacts of human activities is a fundamental requirement for sustainable development (Sharma et al., 2011). Life-cycle analysis (LCA) is a systematic methodology tool for assessing the potential environmental impacts of a product system throughout its life cycle and is a recommended method for measuring the amount of GHG emissions related to building construction and operation. LCA can promote the development of sustainable construction because it provides a better understanding of construction impacts on embodied and operational energy (Lehne & Preston, 2018). The procedure for LCA is widely adapted in the field, and the process is governed under Organization for Standardization ISO 14000, the series of international standards addressing environmental administration.

European standards like EN 15804 (core rules for the product category of construction products) and EN 15978 (calculation method, based on Life Cycle Assessment) provide consistency and are a well-established framework for Environmental product declaration (EPDs) and LCA calculation. The methodological framework for LCA consists of four phases:

- The goal and scope phase establishes the functional unit, system boundaries, allocations, and assumptions.
- The life cycle inventory phase involves collecting and incorporating information on physical material and energy flows in various product lifecycle stages.
- Life cycle impact assessment environmental impacts of various flows of material and energy are assigned to different environmental impact categories
- life cycle interpretation deals with the interpretation of results from both the life cycle inventory analysis and life cycle impact assessment

Building system boundaries are divided into four modules A, B, C, and D. Each module is subdivided. LCA can involve various processes and stages of a product's lifespan Table 2.1.

Module A1-A3 Product stage: Consists of raw material extraction and processing, processing of secondary materials, material transportation to the manufacturer, and manufacturing. Included in this process are waste management and disposal of residual products.

Module A4-A5 Construction stage: Include transportation of materials and products to the building site, including emissions from deliveries and empty reruns. Building site machinery and emissions related to energy used on the building site and water use. Emissions associated with material loss during transportation and waste material treatment during construction.

Module B1-B7 Use stage: Is considered as emissions from the use stage of the building. Modules B1-B5 are associated with the building structure, while B6-B7 are emissions from the operation of the building. Use-phase stages are difficult to estimate as not all have existing methodologies which allow them to be estimated accurately.

Module C1-C4 End of life stage: End of life process starts with the end of product functionality. Output considers demolition, dismantling, sorting, and transportation of waste, its treatment and disposal, and possible recycling processes, including energy and water use.

Module D Benefits and loads outside the system limits: Module D is reported separately and aims to provide information on environmental benefits from product reuse, possible recyclability, and other secondary uses (SS-EN 15804).

Table 2.1 Life cycle assessment stages according to standard EN:15978

Building assessment information		
Building life cycle information	**Stages**	**Description**
Product stage (A1-A3)	A1	Raw material extraction, processing
	A2	Transport
	A3	Manufacturing
Construction process stage (A4-A5)	A4	Transport to the building site
	A5	Construction installation process
Use stage (B1-B7)	B1	Use
	B2	Maintenance
	B3	Repair
	B4	Replacement
	B5	Refurbishment
	B6	Operational energy use
	B7	Operational water use
End of life stage (C1-C4	C1	De-construction
	C2	Transport
	C3	Waste processing
	C4	Disposal
D – Benefits and loads beyond system boundaries	D	Reuse, recovery, recycling potential

LCA is an established methodology, but its use is not without difficulties. Because of the complexity and time required to collect data for all systems boundaries, designers typically find integrating it into the decision-making process challenging (Meex et al., 2018). In addition, method choices, data, and system boundaries can differ, which indicates an inconsistency linked to assumptions and interpretation. Some researchers advocate that the LCA process can be simplified using only the data generated during product manufacturing (A1-A3). This is based on the approximation that 70% - 80% of the GWP impact is generated during this stage. However, recent research indicates that the other life-cycle stages can significantly impact the results, and this less complex approach can provide inaccurate information (Hoxha et al., 2020). When assessing biobased materials and products in LCA, end of life is a critical aspect to consider. By excluding C1-C4 modules from assessment, there is a risk of biased or inaccurate results when only positive biogenic carbon uptake is considered (Fouquet et al., 2015b). An added challenge with bio-based materials is that they belong to multiple systems, each able to claim the benefit of carbon capture (Taverna R et al., 2007).

2.3 Climate compensation

Term climate compensation in this study refers to mechanisms that compensate for product emissions by reducing, removing, or preventing CO_2e emissions (ISO 14021, 2017). According to (IVL, n.d.), standard climate compensation measures can be derived from solar energy production, carbon capture and storage (CCS), and replantation of biogenic material. In addition, several certifications have been developed to ensure the compensation measures positively impact the climate, including Clean Development Mechanism (CDM) and Gold Standard (GS). The GS for the Global Goals represents standard certification programs for non-governmental projects that are reducing emissions under the CDM, the Voluntary Carbon Market (VCM), and other initiatives related to climate and development. As illustrated in Figure 2.3, climate compensation measures can be seen as a balancing measure of CO_2e emissions for a building system.

According to (Lützkendorf & Frischknecht, 2020), there is an ongoing debate about the timing of CO_2e emissions and carbon compensatory measures. As stated in chapter 1.1, climate change poses a severe problem in the near future, therefore, mitigation actions need to have immediate action on emissions. There are many different approaches to climate compensation measures in the construction sector, therefore, a choice for prioritizing balancing measures in climate-neutral definitions should be carefully evaluated to understand what should be prioritized and how the different strategies can be combined (Lützkendorf & Frischknecht, 2020).

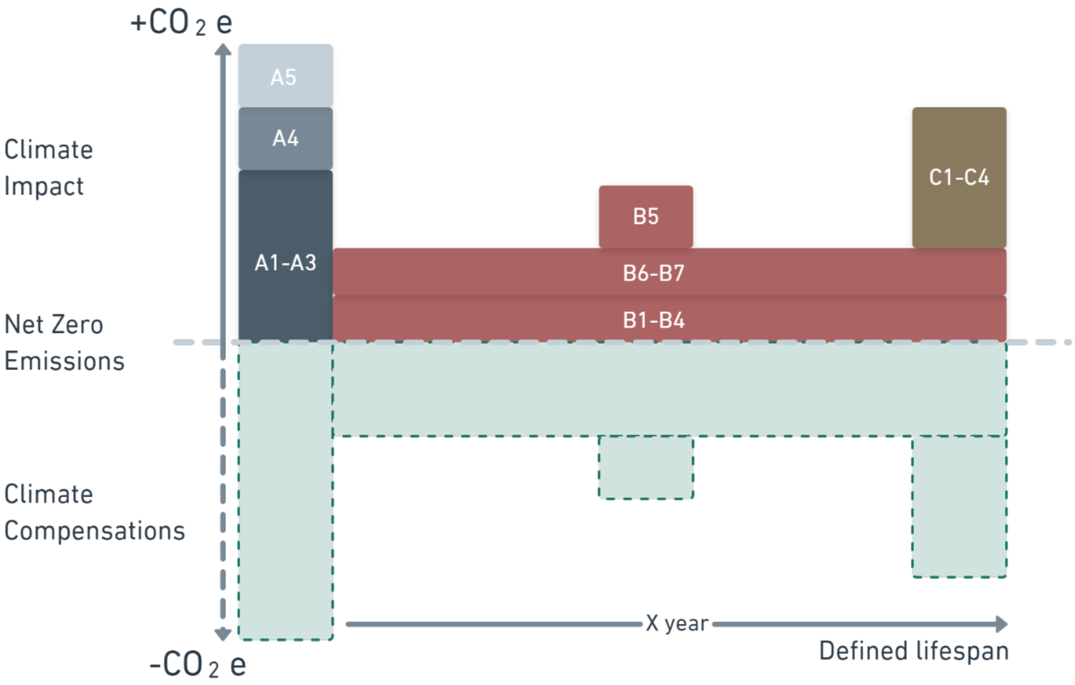

Figure 2.3 Balancing climate impact with climate compensation measures

2.3.1 Renewable energy supply

According to various sources (IEA, 2018), the global primary energy consumption around the world is planned to increase. With increased depletion of natural resources and a rise in GHG emissions will require a significant shift from fossil fuels as a dominant energy source to other sources of energy, for example, renewable energy (E. P. Agency., EPA, 2020). Renewables are the fastest-growing energy source for buildings, rising 4.1% annually. Despite this growth, renewables met only an estimated 14.3% of total energy demand in buildings in 2019 (REN21, 2021)

Renewable energy for buildings can be divided into two categories, onsite generated and offsite generated. Offsite generation includes renewable energy delivered to the electricity grid (IEA, 2018). Energy generated within the boundary of a building site is referred to as onsite generation, which includes the conversion of solar, wind, or thermal energy. These are great options for renewable energy sources, but each has its benefits and drawbacks. Geothermal, ocean energy, and hydro are heavily dependent on geographical location, with later most two usually being large-scale projects that cannot be implemented without prior detailed analysis and plan. In addition, many reports show that hydro energy is responsible for a large part of habitat destruction (Ezcurra et al., 2019). Small-scale hydropower plants have been proposed to counter this controversy (Manders et al., 2016). For wind energy, large wind turbines in windy areas are required, while wind energy can be harvested on a smaller scale, it is not particularly desirable due to its poor architectural integration and generated noise.

Solar energy is more easily adaptable and can be implemented on a smaller scale. Solar PV can "convert" sunlight into "emission-free" electricity; however, it still emits GHG from the extraction and processing of raw materials and the manufacture and assembly of PV systems (Müller et al., 2021). China is a leading manufacturer of solar PV panels, accounting for approximately 70% of the market worldwide (IEA, 2022), while the market share for PV panel production in Europe is only 1.8%. On the other hand, according to (Müller et al., 2021), PV systems produced in China (820kg/kW$_P$) have a much more significant environmental impact than panels produced in Europe (420kg/kW$_P$). Furthermore, according to (Lindahl, 2020) in Sweden installation rate of PV continues to increase rapidly, for example, a total of 400 MW was installed in 2020, which means that the annual Swedish PV market grew by 42 % compared to the 281 MW that was installed in 2019, as seen in Figure 2.4.

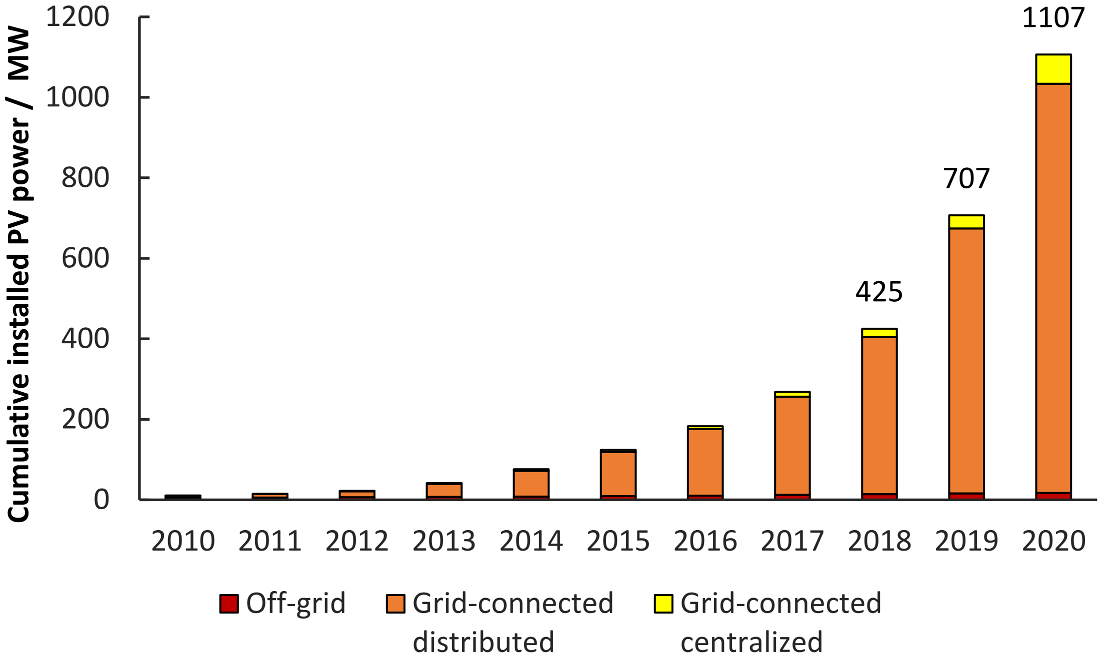

Figure 2.4 The annual installed PV capacity in Sweden (Lindahl, 2020)

In 2020 PV production in the Swedish electricity mix represents a very small share of 0.5%, as seen in Figure 2.5. Most electricity consumed in Sweden is produced with hydropower or nuclear power. It is worth noting that a large part of PV production is self-consumed by consumers and is not registered in the statistics from "Svenska Kraftnät".

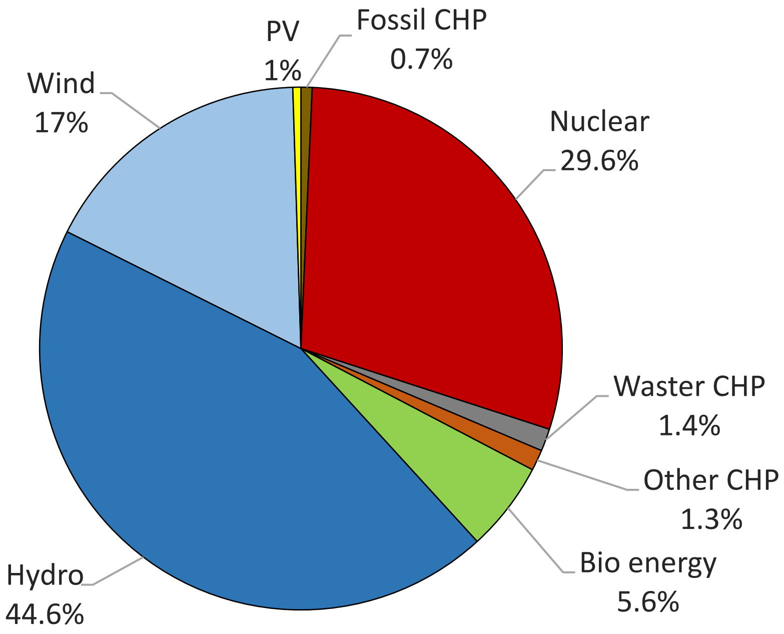

Figure 2.5 Total electricity supply in Sweden in 2020 (Lindahl, 2020)

Emission factor

The emission factor is a coefficient that converts activity data into the quantity of a pollutant (GHG emissions) released into the atmosphere. These factors are expressed as the weight of the pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant, as indicated in Equation 1 (E. P. A. EPA, 2007).

$$Emission\ E(t) = activity\ data\ A(t) \cdot emission\ factor\ EF(t) \qquad \textit{Equation 1}$$

According to (E. P. A. EPA, 2007), factors like these can help to estimate emissions from various sources. Human activity emits different kinds of GHG with different physical characteristics. They are converted to CO_2 equivalents to have a common scale and better represent their impact on the environment.

As building operational energy represents a large part of the buildings' emissions, there is growing interest in reducing emissions from electricity generation. Conventional solutions for this problem include renewable energy production, energy efficiency, and energy conservation. However, involvement from both the energy supply-side and energy demand-side will displace energy and, therefore, emissions from conventional energy generators (Siler-Evans et al., 2012).

Average emission factor and marginal emission factor

There are two conventional techniques in environmental analysis to assign responsibility for pollution, average emission factor (AEF) and marginal emission factor (MEF). AEF assigns equal responsibility from different pollution sources to different participants in a power system. For example, in a grid where 50% of power is generated with an emissions factor of 100 $kgCO_2e/MWh$ and 50% is generated with 0 $kgCO_2e/MWh$, the average emissions factor would be 50 $kgCO_2e/MWh$. When accounting for energy export (displacement in the grid), the emission factor is the same for imported and exported energy (Corradi, 2019).

An argument can be made here that deciding to use more or less electricity at any point in time will not cause all power plants to increase/ decrease their production equally. The MEF estimates environmental consequences by considering incremental changes in carbon emissions due to a change in demand. By considering MEF when displacing electricity in the grid, only the “worst” emission power plants are impacted since an increase or reduction in electricity demand only affects power plants that can quickly turn on/off their power generation and have the spare capacity. Therefore, exported energy emissions will displace emissions from “worst” power plants and not the average emissions in the grid (Zheng et al., 2016).

2.3.2 Biogenic carbon

Term biogenic carbon refers to carbon derived from or contained in biomass, and it can be captured as CO_2 from the atmosphere through the process of photosynthesis during biomass growth (Brandão et al., 2013). As a result of this process, carbon is broken down, some is lost in plant and microbial respiration, and some is transferred to the soil, resulting in long-term carbon storage (Harris et al., 2018). The term “carbon sequestration” is referred to active carbon dioxide removal from the atmosphere by natural or artificial processes. Whereas “carbon storage” refers to the process of sequestering carbon within a product for an extended period of time, resulting in an impermanent reduction of CO_2 concentrations in the atmosphere (Arehart et al., 2021). Biogenic carbon can also be emitted back into the atmosphere in the form of carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4) from oxidation, combustion, digestion, or similar processes of biomass degradation (Brandão et al., 2013).

As stated by (Breton et al., 2018), three main benefits of using biomaterials are increasingly recognized. First, they can reduce GHG emissions associated with material extraction and manufacturing. Second, biomaterials can temporarily store biogenic carbon within themselves. And thirdly, they can reduce GHG emissions by replacing other, more emission-intensive construction materials. These potential benefits explain why green building grading systems, for example, LEED, increasingly encourage the use of certified wood products and other bio-based, reused, and recycled materials.

Biogenic carbon uptake and release

Several accounting methods have been proposed to calculate potential climate impacts resulting from carbon sequestration and the temporary storage or release of biogenic carbon in LCAs. Based on (Hoxha et al., 2020), there are two main approaches when assessing the impact of the biogenic carbon uptake and release in traditional LCA's for buildings.

The first method, or the '0/0 method', assumes that a bio-based product's CO_2 emissions at the end of its life will be balanced by the equivalent CO_2 sequestration during its growth. In this approach, biogenic carbon is disregarded entirely by excluding it from the LCA as there is no consideration of biogenic CO_2 uptake (0) and release (0). Figure 2.6 depicts the approach for a wooden product used in a building, the distinction between a forest system, a building system, and a potential subsequent product system. The building system is subdivided according to LCA modules. Module D is shown as a distinct, separate system. Biogenic CO_2 is not taken into account in any module. Module C only models the release of methane because it has a more significant influence on Global warming potential than CO_2 (Hoxha et al., 2020).

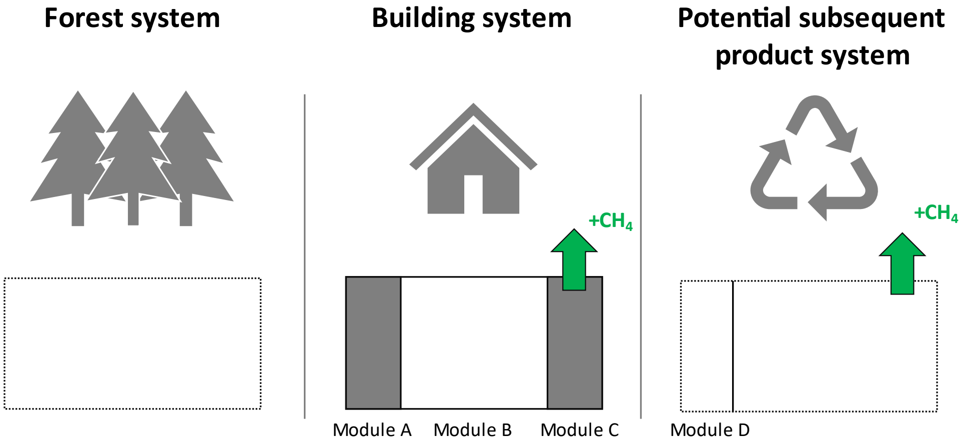

Figure 2.6 The 0/0 approach to model biogenic carbon uptake and release (Hoxha et al., 2020)

The second approach, referred to '–1/+1' method, tracks all biogenic carbon flows over the building life-cycle. This approach considers both biogenic CO_2 uptake (–1) and release (+1) and the transfer of biogenic carbon between the systems, as seen in Figure 2.7. Biogenic CO_2 uptake during the forest growth is transferred to the building system and reported as a negative emission in module A, and at the end of the life of the building (module C), biogenic CO_2 is released back into the atmosphere. (Hoxha et al., 2020).

A closer look at building LCA and biogenic CO_2 accounting in EPDs reveals that not all biogenic CO_2 removals are present in the final product. Figure 2.8 shows where biogenic carbon enters and exits the system in the LCA of a product. Some carbon removals are lost in the process, for example, in production as a co-product (pallets, pulp, or paper) or combustion. At the end of the building's lifespan, biogenic CO_2e are released back into the environment, or the carbon content is further relocated to a subsequent product system (in the case if the material is recycled or otherwise repurposed). The biogenic carbon balance should be zero across its LCA for all product systems in this approach (Hoxha et al., 2020; Pittau et al., 2018).

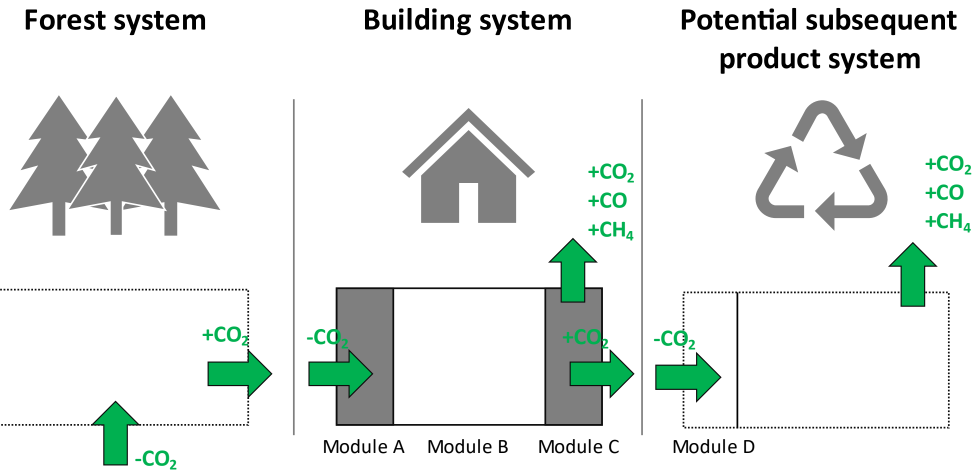

Figure 2.7 The –1/+1 approach to model biogenic carbon uptake and release (Hoxha et al., 2020)

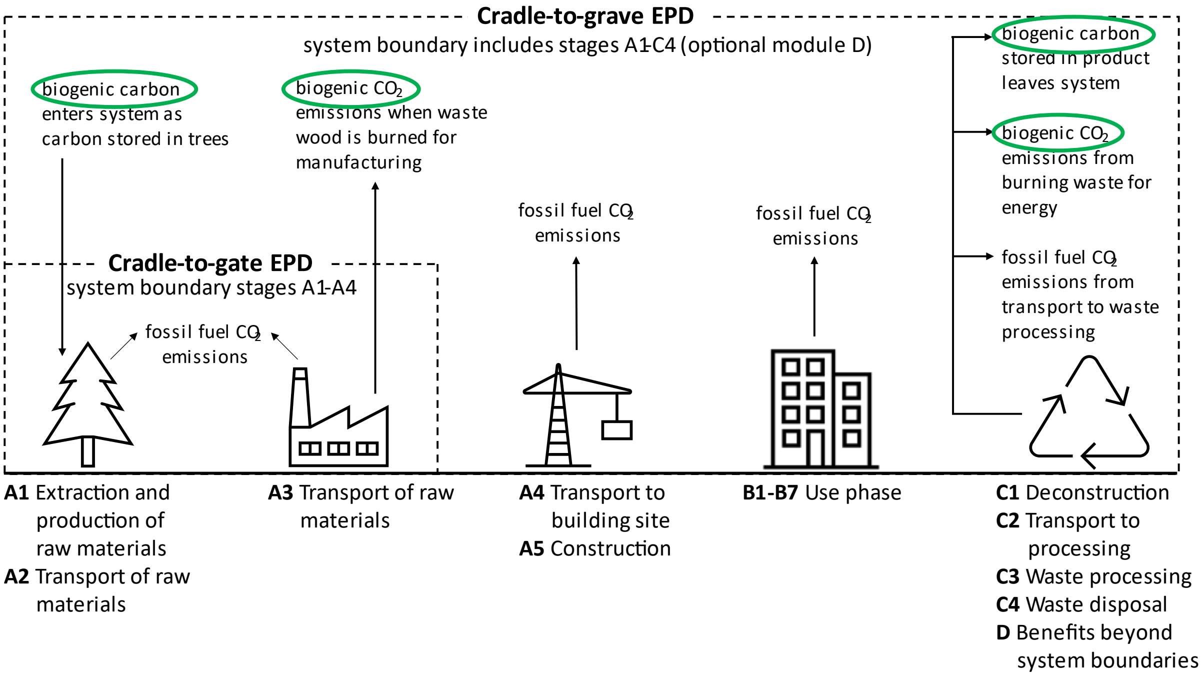

Figure 2.8 Biogenic carbon flows in LCAs stages (TallWood Design Institute, 2019)

The main advantage of the –1/+1 method is that it provides an overview of all biogenic carbon flows. It may, however, result in misleadingly positive results if only the product manufacturing and construction stages (module A1-A3) are analyzed in LCA, taking into account the positive effects of biogenic CO_2 uptake without reporting its release at the end of life (Hoxha et al., 2020).

In traditional LCA, one of the most critical issues with the carbon footprint of products as defined by (ISO/TS 14067, 2013) is that they do not consider the impact of the timing of the carbon emissions and the significance of the rotation periods related to the biomass growth. (Pittau et al., 2018) study indicates that not all biobased products can be considered carbon neutral. For example, timber products have a more extended rotation period due to slower forest growth than fast-growing bio-based materials, such as straw and hemp, which have a short rotation period and have a larger potential to mitigate GHG emissions by sequestering carbon from the atmosphere. Dynamic techniques have been developed to represent the impact of time better, but they are not widely adopted for biogenic carbon calculations in LCA standards.

Another critical element in accounting for biogenic carbon is land use and land-use change (LULUC). According to (Erb et al., 2018), potential vegetation would store around 53-58% more carbon under current climate conditions without human intervention. Carbon sequestration and carbon release significantly impact atmospheric CO_2 concentrations. An increase in the amount of biomass used in, for example, manufacturing, material, and energy industries, will reduce forest biomass stock levels compared to their potential. Therefore, forest administrators would have to manage forests for productive capacity and to maintain and increase global carbon storage potential (Hoxha et al., 2020).

2.3.3 Carbon credits

The permission to release one ton of CO_2 or an equivalent amount of other GHG (tCO_2e) that has been removed from the environment is represented by a tradable certificate known as a "carbon credit" (CFI Team, 2022). This allows projects with lower carbon emissions to sell their carbon allowances to others who have exceeded the specified limit. This strategy functions as a compensating mechanism that counterbalances the amount of carbon dioxide and other greenhouse gas emissions in the atmosphere in order to decrease the effects of global warming.

The carbon market is regulated by governments and international organizations that have set up annual limits on the amount of GHG that can be released into the atmosphere. If businesses and projects emit more than this allowable limit, they are required to offset the exceeding amount through carbon credit purchase. On the other hand, they can also sell the amount they save as credits through some stringent regulatory processes which certify their carbon neutrality. Some of the major organizations that thoroughly manage this process through various programs and initiatives are the Gold Standard, VERRA, and Plan Vivo, to name a few. The Verified Carbon Standard (VCS) program launched by VERRA quantifies each ton of carbon dioxide equivalent (CO2e) into a VCU (Verified Carbon Unit), which can be purchased by the end-user as a means of offsetting their emissions (VERRA, n.d.). According to Ecosystem Marketplace, the price of carbon offset ranges from USD $3-6 per ton, depending on the project, its location, the carbon standard utilized, and the project year (Second Nature, 2022). The Swedish market is also actively involved in reducing climate impact through the use of the Voluntary Carbon Offset (VCO) (Hwargård, 2020).

2.4 Climate-neutral buildings and certifications

Many different terms like ‘climate friendly’, ‘carbon neutral’, ‘Paris compatible’, ‘climate neutral’, and ‘climate positive’ have been coined to delineate the actions against global warming and reduction of environmental impact, however, their definition and underlying purpose has somewhat been ambiguous (Lützkendorf & Frischknecht, 2020). Regardless of this fact, these terms have still garnered interest among organizations, governments, and companies globally and are being used to convey their role in mitigating climate change. ‘Climate neutral’, as explained by the (European Commission, 2019), is about reducing the emission of greenhouse gases as much as possible and compensating for any residual emissions that could add to global warming. One of the main reasons for the popularity of this term among different companies is that it provides an opportunity to market themselves as meeting the obligation toward achieving net-zero greenhouse gas emissions without jeopardizing their businesses (Ziegler, 2016).

On the other hand, the concept has received negative criticisms as well, mainly because it is perceived as not specifying anything to cap the emissions rather than helplessly depending on the natural process of planting trees as a compensation for the emissions. In addition to this, the term could also be confusing in a way since it could be phrased as ‘not contributing to any form of emissions’, which is untrue in the case of manufacturing different products and daily items (What Next, 2020). Moreover, it is not linked to any effort from the organizations or companies to reduce their emissions to a considerable extent or go to zero, therefore it could not be considered a long-term solution and could also lead to ethical, social, and ecological challenges (Ziegler, 2016).

Despite this, there is a hope that the concept could develop and present itself more conspicuously when applied to the construction industry, where it is evident that GHG emissions would be continued and could only be balanced through other climate measures (Lützkendorf & Frischknecht, 2020; Zuo et al., 2012). Figure 2.9 shows the illustration of climate neutrality, with emissions on one side and climate compensations on the other.

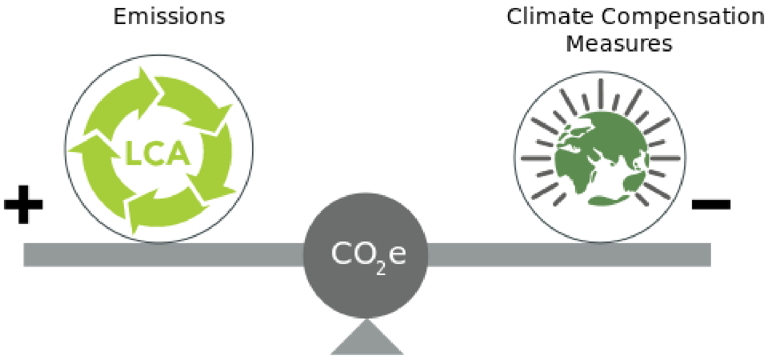

Figure 2.9 Balance for climate neutrality

2.4.1 White Architects (Sweden)

Background

The White Architects climate-neutral definition is a more recent and simplified definition for climate-neutral building compared with other definitions such as NollCO₂ and ZEB, making the certification more attainable to the public. The White definition bases some of its framework on existing definitions and closely follows calculation methods from NollCO₂. The core goal of this definition is to create long time value and have the lowest possible environmental impact from construction projects (White Arkitekter, n.d.).

Functional unit and system boundary

The climate impact of the building from a life-cycle perspective is calculated for the period of 50 years. LCA modules considered are A1–A3, A4–A5, and B6 according to SS-EN 15978. The functional unit for reporting climate impact is $kgCO_2e/m^2A_{temp}$. Building parts that are assessed for definition, sorted according to BSAB codes (*Appendix E*) and are as follows:

- Loadbearing structural components (BSAB 15, BSAB 27)
- Buildings envelope (BSAB 41, BSAB 42)
- Non-loadbearing interior walls (BSAB 43, BSAB 44)

Rules for calculation

GHG emissions from materials, transport, construction processes, and operational energy use, including end-user-related energy (A1–A3, A4–A5, B6 according to SS-EN 15978, are considered in the calculation. Life-cycle data from materials, products, and building components are retrieved from open-access databases with generic data or product-specific Environmental Product Declarations (EPDs). For operation emissions, GHG emissions linked to the building's total operational energy demand shall be worked out for the calculating period. Total energy demand should include building-related "regulated energy" and end-user-related "non-regulated energy" use within the property boundary. For buildings over two stories, at least 10% of the regulated energy must be balanced within the property. In this case, the percentage of renewable energy has been derived from assumptions through the organization's experience. The Swedish code (Chapter 9. BBR CODE) or Norwegian building code (NS 3720) specifies the list of these regulated and non-regulated energy (loads). The general lighting in an office building is an example of regulated energy. However, if lighting fixtures are added to each table, that is considered non-regulated energy. If the building density is less than two floors and designed with a passive heating cooling approach, then 100% of the on-site green energy could be considered.

Carbon capture or renewable energy sources are required to balance the calculated climate impact from materials, construction, and buildings operation. The effect of carbon reduction methods must be reported separately (White Arkitekter, n.d.).

Climate compensation measures

Climate compensation measures accepted by White Architects' definition include renewable energy generation within the property boundary, outside the property boundary, and the positive impact of sequestered carbon in biogenic materials, see Figure 2.10.

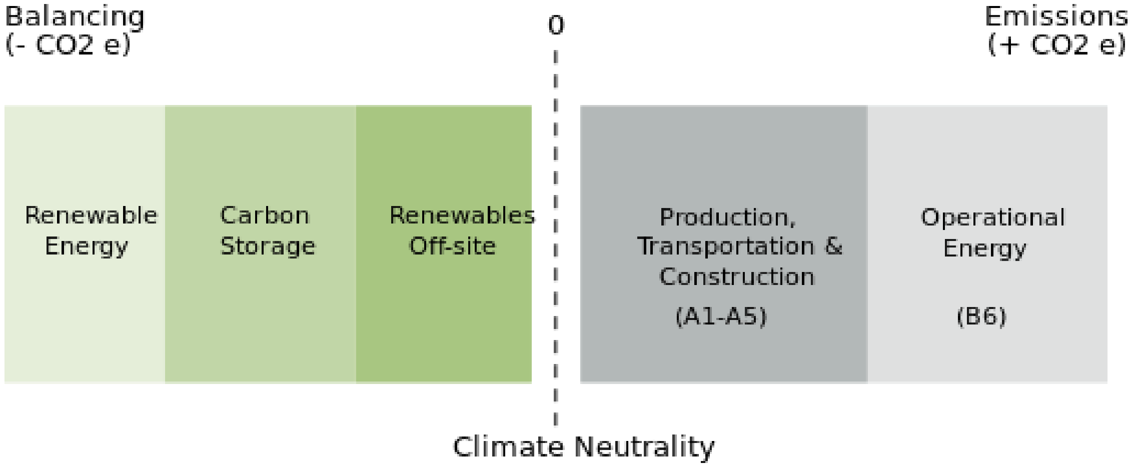

Figure 2.10 Net zero carbon balance in white (White Arkitekter, n.d.)

The building between 1-2 stories must achieve net surplus annual energy production within the property boundary. Exported surplus energy is valued (from an emission perspective) as a marginal displacement for fossil energy production. Building with more than two stories can also add renewable energy production outside building system boundaries, provided the energy source is verified annually (White Arkitekter, n.d.).

2.4.2 NollCO$_2$ (Sweden)

Background

NollCO$_2$ is a building certification system. The system focuses on decreasing climate impact during the project's operation, construction, and design phases, as well as balancing emissions that occurred during those stages with climate compensations to achieve net-zero climate impact across the building's lifetime. This certification was developed by the Sweden Green Building Council (SGBC), a member of the World Green Building Council and one of Sweden's prime member organizations for sustainability and certification in the building environment (WGBC). As specified by NollCO$_2$, there are no different levels of climate-neutral certification. A project is categorized as climate-neutral or not climate neutral. The certification applies to new constructions and larger additions/ extensions (SGBC, 2020a).

Prerequisites for certification

According to NollCO$_2$, before the building can be certified with its climate-neutral certification, it must fulfill specific requirements, and the building must have a complementary certification at a minimum level. These certifications can be from Miljöbyggnad level Silver, BREEAM-SE level Very Good, LEED level Gold, or Nordic Ecolabelling (Svanen). In addition, the energy use of the building has to fulfill energy class B requirements with a 25% improvement compared to traditional BBR buildings (Boverket, 2020).

Functional unit and system boundary

Following the Swedish National Board of Housing, Building and Planning's suggestion to the Government on climate declaration (Boverket, 2019), NollCO$_2$ uses a 50-year projected building service life. The 50-year period begins with the occupation of the structure (SGBC, 2020a). The functional unit for reporting climate impact according to NollCO$_2$ is kgCO$_2$e/m^{2}BTA as per the National Board of Housing Building and Planning's proposal on climate declarations.

LCA calculations in this certification system follow SS-EN 15978 standard. Landscaping and work outside of the building perimeter are excluded from calculations. *Appendix E* shows the building elements and service systems that are included in the scope of the assessment. Except for module D, which refers to benefits and loads outside system boundaries, all life cycle modules are considered within this certification system (SGBC, 2020a).

Rules for calculation

Raw materials are extracted, processed, and manufactured into building materials, products, and systems based on the total quantity amount (measured in kg) in the project multiplied by the respective environmental impact data (kgCO$_2$e) from the Environmental Performance Data (EPDs) for each element. If the project does not specify a material/ product/ system or the suppliers do not provide an EPD, generic climate data can be used. As part of project registration, products under stages A1-A3 shall not exceed the project-specific limit value expressed in kgCO$_2$e/m^{2}BTA. The climate impact of transporting materials and products to and from the construction site (Module A4) is calculated by adding up the climate impact of all transporting components from the manufacturing factory gate to the construction site. The A4 stage also includes transporting materials, equipment, machinery, sheds, and other construction equipment to and from the site. Standard values for distances from "Byggsektorns MiljöBeräkningsverktyg" can be used for the transportation of building components according to this certification (SGBC, 2020a).

Waste production, transportation to the construction site, and waste/final disposal are all included in the climate impact of a building site and are considered under the A5 module. Products such as, doors, windows, etc. that are not further processed on the job site might be set at 2% waste in this module. The waste rate for materials used in large numbers and subsequently processed on-site (gypsum boards, wood, pipes, wires, and so on) can be set at 10%. 5% can be set aside for other garbage. Climate data from "Ökobaudat" for final handling may be used (SGBC, 2020a).

Energy use at the construction site is also reported along with the available EPD. This module should also consider water used at the construction site and the amount of water (m^3) which are planned to be used or which has been used along with any available EPD. The limit value of A4-A5 is 55 kgCO$_2$e/m$_2$ BTA as set by the certification (SGBC, 2020a).

B1-B3 modules are not calculated within the criteria due to a significantly lesser impact as well as complexity in predicting the emissions impact during these stages (SGBC, 2020a).

The climate impact for both B4 and B5 modules is determined from the accounting tool "Zero CO$_2$ Climate Impact Certification.xlsx", which utilizes the data from the component life obtained from the EU Levels, quantities of building components from A1-A3 modules, emissions impact from transport module in A4, waste disposal in module A5 and assuming that an equal amount of product or material is replaced in the system. The amount of climate impact during the B4 module is determined on the grounds of waste processing of the old material and the impact from the production, transport, and installation of the new material under replacement (SGBC, 2020a). Climate data obtained for manufacturing, transport, and installation is set to zero in 2050 since the goal is to become climate neutral by this year. The amount by which a product is refurbished is shown in percentage with a conversion interval set for each product (SGBC, 2020a).

When designing, an energy calculation is made based on the building's estimated energy use, which must show that the building meets the requirements according to the National Board of Housing, Building and Planning's Building Regulations (BBR) chapter 9 Energy management (SGBC, 2020b). The climate impact of both the property's and operations' energy use provided and produced on-site must be recorded. According to NollCO_2, a key feature of the B6 module is that only the surplus of renewable energy becomes a climate compensation measure (more on this in the next section); its utilization is calculated using a life cycle-based emission factor. The calculations must also be based on an electricity mix with an estimated 22 kgCO_2e/MWh emission factor. Similarly, a 60 kgCO_2e/MWh emission factor is used for district heating. Furthermore, both factors should follow a linear decrease function to zero by 2050 (SGBC, 2020a).

The water use in the B7 stage is calculated on the basis of EU Level (s) water tools that present standard figures in the form of kgCO_2e / m^3 drinking water per floor area. This water also includes water use from the ventilation system. Loose equipment in B1-B7 (including washing machines, computers, etc.) is excluded (SGBC, 2020a).

NollCO_2 states that when a project reaches its end of service life, its climate impact derives from deconstruction, waste transport, and waste processing and disposal since the Swedish government plans to reach climate neutrality by 2050, meaning that Swedish waste processing will also have to be carbon neutral. If the building is at its end of life before 2050, the climate impact C1-C4 is interpolated based on current C1-C4 values for the building elements.

Climate compensation measures

The climate-neutral concept in NollCO_2 certification is defined by EN ISO 14021 standard, while LCA calculations follow standard EN:15978. The term “climate neutral” in the NollCO_2 system indicates a net-zero climate impact, as indicated in Figure 2.11. NollCO_2 considers the construction, operation, and end-of-life of a building can accommodate climate actions, or offsets, to balance the total climate impact to zero (SGBC, 2020a). Renewable electricity generation is an essential concept of NollCO_2. The certification considers only the surpluses that are produced by a renewable system. Afterward, these are traded on the electricity market to substitute coal power (in other European nations) which, according to this certification, can offset the negative climate impact of the buildings. Production can be located on-site or off-site (SGBC, 2020a).

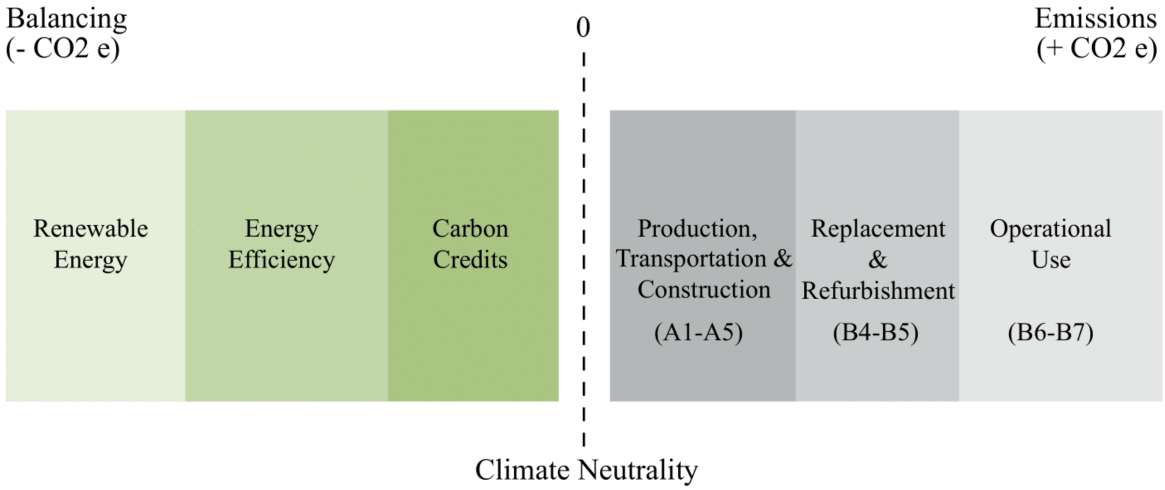

Figure 2.11 NollCO₂ net zero balance (SGBC, 2020a).

The energy sources that are accepted as renewable according to the IPCC 2014 include wind power, solar energy, and other sources like rock heat, hydroelectric, wave and tidal energy, biomass, gas from sewage treatment plants and landfills as well as biogas (SGBC, 2020a). The reference value for an electricity saving is the same as for the production of renewable electricity in NollCO₂, i.e., the average value of the hourly reference value of the emission factor for coal power for 2018, which according to the IPCC 2014, were 820 kgCO₂e/MWh (IPCC et al., 2014). According to the WRI GHG Protocol's guide for grid-connected electricity projects, the reference value for electricity energy efficiency projects is calculated in the same way as for projects with the production of renewable electricity (Callahan et al., 2011; SGBC, 2020b).

A fundamental principle of NollCO₂ is new technology and materials that improve energy efficiency. All installations of materials and technology are aimed at increasing energy efficiency. NollCO₂ also considers climate compensation through carbon credit purchase. Generally, a single credit corresponds to a tCO₂e of carbon emission from a project. According to the Stockholm Environment Institute, the climate compensation projects that have been deemed credible and effective for their purposes are VERRA, Verified Carbon Standard (VCS), Gold Standard, and Plan Vivo (SGBC, 2020a).

2.4.3 Zero Emission Building (ZEB)

Background

With comprehensive strategies for improving energy efficiency and reducing emissions, the Norwegian construction sector has demonstrated a significant interest in making the transition to a more sustainable business. Evidently, a green wave had started as a result of more stringent national requirements on energy efficiency (Fufa et al., 2016). The International Energy Agency (IEA) and the Energy Performance Building Directive (EPBD) have both contributed to the definition of a Zero Emission Building (ZEB), which was developed by the Norwegian research center for carbon-neutral buildings. This concept places more emphasis on greenhouse gas emissions than on energy consumption, which had previously gotten a lot of attention(Dokka et al., 2013).

Net Zero Energy Buildings (net ZEB)

A 'nearly zero-energy building,' according to EPBD, is a structure with a very high energy performance with nearly zero or very low quantity of energy requirement covered mainly through the energy from renewable sources on-site or locally (European Parliament and the Council 2010). However, in contrast to an autonomous building, the term 'net-zero energy building' (net ZEB) was coined to underline the concept of an annual balance between energy imported from and exported to the energy grid (Sartori et al., 2012). Thus, a net ZEB suggests that the building generates the same amount of energy from renewable sources as it consumes for operation. Figure 2.12 shows that the net ZEB balance is obtained by lowering energy consumption (X-axis) through energy efficiency measures and producing enough electricity or thermal energy to earn sufficient credits (y-axis) to offset the remaining operational energy (Fufa et al., 2016). This definition may be further expanded by integrating a life cycle perspective, which includes the primary energy use of the building during operation and the embodied energy (e.g. life cycle demand from materials, transport, and construction) and end-of-life energy (Fufa et al., 2016).

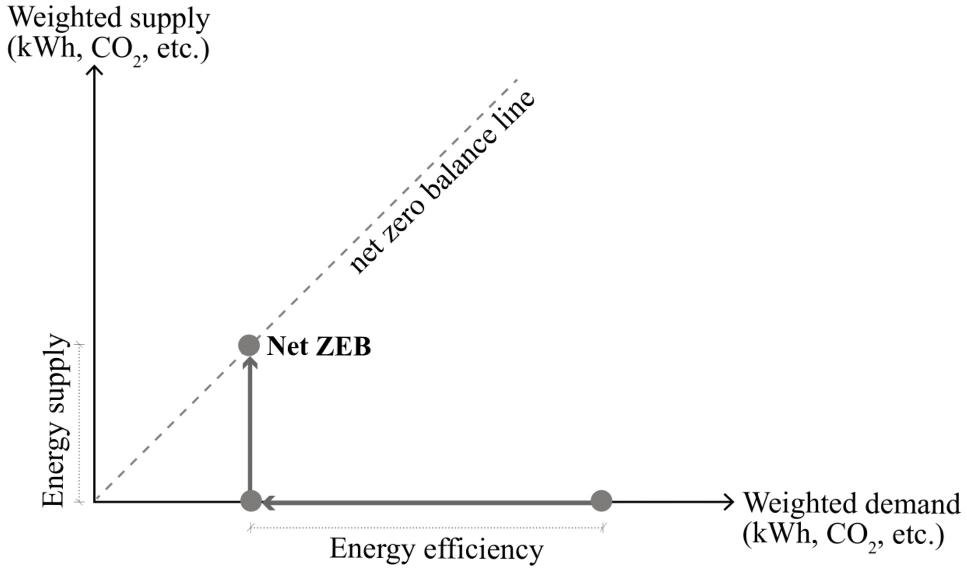

Figure 2.12 Net ZEB balance concept (Sartori et al., 2012).

Zero Emission Building (ZEB)

A ZEB is a highly energy-efficient building where on-site renewable energy production compensates for CO_2 emissions from the building (Kristjansdottir et al., 2014). The core idea of ZEB is that there are different ambition levels where different building types can be included depending on how the system boundary is defined. The lowest level should be simple to achieve with fewer resources to encourage more people to build climate friendly. Though buildings differ in terms of climate conditions, size, and other factors, a smaller apartment building, for example, may satisfy the higher standards more readily than larger, more complex buildings (ZEB, 2017). In the ZEB definition, instead of energy demand and generation as in the net ZEB, the balance is measured in terms of associated GHG emissions during the lifetime of the building. Moreover, to achieve carbon-neutral buildings ZEB definition requires maximum climate impact minimization through smart material choices, well-thought-out design, and innovative solutions that address both built-in climate impact and energy needs (Wiik et al., 2018).

ZEB Ambition Levels

According to NS-EN 15978, the ZEB research center has set out different levels of zero-emission buildings to be achieved at different stages of its life cycle (Fufa et al., 2016).

- ZEB-O÷EQ: The emissions from all operational energy (O) in stage B6 would be compensated through renewable energy production except for energy use for equipment and appliances.
- ZEB-O: The emissions from all operational energy (O) in stage B6 would be compensated at this level.
- ZEB-OM: The emissions from operational energy (O) and embodied emissions during the production of materials (M) in stages A1-A4 plus replacement stage B4 are compensated by renewable energy generation.
- EB-COM: Similar to ZEB-OM but with additional consideration for emissions during the construction (C) and installation of materials in the A5 stage.
- ZEB-COME: This is also similar to ZEB-COM but includes compensation measures for emissions during the end of life (E) in stages C1-C4.
- ZEB-COMPLETE: An ideal level where emissions from each and every stage of the life cycle, namely A1-A4, B1-B7, and C1-C4, are compensated for in this level. The emissions during stage D beyond system boundaries can be considered at this level.

Table 2.2 compares the different ambition levels for ZEB, the lowest of which is ZEB-O/EQ, which includes only operational energy in B6, excluding technical equipment and appliances, and the highest is ZEB-COMPLETE which covers the full life cycle (Fufa et al., 2016). It also illustrates the relationship between the levels and the modular lifecycle stages in NS-EN 15978: 2011. The lifecycle stages (A1-A5, B1-B7, C1-C4) mandatory for the different ZEB ambition levels are presented in green. Module D can be included as additional information in ZEB COMPLETE. However, the most successful pilot project achieved ZEB-COME, the second-highest level, which includes A1-A5, B4, B6, and C1-C4 (de Wolf et al., 2017).

Table 2.2 System boundaries for each of ZEB ambition levels (Fufa et al., 2016).

ZEB Ambition Levels	**System Boundary NS-EN 15978:2011**																
	A1-A3 Product Stage			A4-A5 Construction process		B1-B7 Use Stage							C1-C4 End of life				D Benefits & Loads
	A1- Raw material supply	A2- Transport to manufacturer	A3-Manufacturing	A4-Transport to site	A5-Installation into building	B1-Use	B2-Maintenance (incl.Transport)	B3-Repair (incl.Transport)	B4-Replacement (incl.Transport)	B5-Refurbishment (incl.Transport)	B6-Operational energy use	B7-Operational Water use	C1-Deconstruction/ Demolition	C2- Transport to End of life	C3-Waste processing	C4- Disposal	D-Reuse, recovery, recycling
ZEB-O/EQ											🟩 ***						
ZEB-O											🟩						
ZEB-OM	🟩	🟩	🟩						🟩 **		🟩						
ZEB-COM	🟩	🟩	🟩	🟩	🟩				🟩 *		🟩						
ZEB-COME	🟩	🟩	🟩	🟩	🟩				🟩		🟩		🟩	🟩	🟩	🟩	
ZEB-COMPLETE	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

* End of life stage of the replaced material is not included
** Transport (A4), Installation (A5) or End of life stage of replaced materials are not included
*** Operational energy (B6) of the equipment or appliances is not included

Functional unit and system boundary

Currently, the ZEB uses 1 m^2 of heated floor area over a service lifetime of 60 years as the functional unit for a complete building analysis (Kristjansdottir et al., 2014). Energy consumption per person is regarded as a complementary indicator to energy efficiency (Green Power Alliance, 2010). ZEB uses LCA calculations based on EN 15978 and international standards ISO 14040 and ISO 14044 to assess climate-neutral buildings. The calculation is based on Norwegian EPDs. When data is inaccessible, generic Life Cycle Inventory (LCI) data from Ecoinvent is used. These computations should be conducted in a consistent and credible manner so that construction projects may have objective comparisons (Dokka et al., 2013).

Rules for calculation

Emissions from all the building materials and components, excluding the fixed interiors, sanitary equipment, telecommunication, automation, and outdoor installations, are considered in the life cycle stages. Except for the two lowest levels, ZEB-O/EQ and ZEB-O, all levels include emissions from materials. However, to maintain the consistency of the calculation, emissions from equipment and appliances should also be included in the material inventory for embodied emission accounting in subsequent ambition levels of ZEB-O and higher, as the operational energy use includes the equipment and appliances for these levels. A Recommended list of included building materials and components according to NS 3451: 2009 is shown in *Appendix F*.

The ambition level of ZEB regulates the considerations of the emissions in modules A4 and A5. The material selection has a negligible impact on the processes in A5, which is also relatively not influential for screening in a simplified LCA, as seen in Wittstock et al. (SSB, 2011). Generic data accounting and detailed LCI calculation data should be used when measuring the impact of all the construction processes, including earthwork, transport of goods, construction workers, construction machinery, and construction waste. All the statistics regarding the transport of materials and waste and emission factors for the A4 stage can be calculated and documented in detail through the use of Google maps for measuring the distances and EPDs for calculating the emissions factors.

While calculating for the construction and installation stage A5, it is essential to consider the production, storage on-site, and transport of ancillary materials as well as the individual energy consumed during the installation and waste production until the end of the waste stage based on LCI data. Although the transport of workers to and from the construction site was not taken into account as per Section 7.4.3.2 (NS-EN 15978 2011), studies have shown that the transportation details of workers, the electricity, and fuel consumed during each commute have a significant impact on the calculations in this stage and should, therefore, be considered (Fjeldheim et al., 2015). The current approach, according to ZEB Research Center, is to consider an approximate loss of 10% for the building materials during the construction installation stage as there is insufficient data involving the same, although there is scope for further research in this area to suggest a more concrete value for the loss during this stage (Dokka et al., 2013).

There is a legal requirement to transfer all wastes to waste handling stations. Moreover, in some cases where a new development or demolition project is larger than 300 m^2 or construction projects which produce more than 10 tons of waste, a waste management plan is needed which serves to separate and recycle a minimum of 60% of the waste on-site before transferring it to the waste facilities (KRD, 2017)

All buildings generally undergo renovation and refurbishment during their lifetime, during which parts of the building or material are either replaced or reused. This process has a significant impact on the emissions over a service life of a building. It is always beneficial to use reused material within the building to cut down on any new emissions, which then can be excluded from the emissions analysis. However, this is contrary to EN15978 (2011), which states that the emissions allocated from the previous use should be considered according to the percentage of the estimated technical lifetime of the material or component. If a building undergoes a complete refurbishment, its lifetime is wholly renewed and reset to 60 years.

Several considerations need to be made regarding the number of replacements and whether energy-efficient processes have been considered during these replacements based on which the calculation needs to be made. The estimation of embodied emissions for the replaced components are generally made from their respective product category rules (PCR), considering an average lifetime of 60 years along with their rate of replacement (NPCR 012rev, 2012), (Dokka et al., 2013). A case has been made in ZEB when assessing the emissions impact for PV modules which are presumed to be replaced after 30 years in order to gain a 50% reduction of environmental impact (IEA 2011, SENSE 2008) (Dokka et al., 2013).

As suggested in EN 15978 (2011), the rate of replacement of a product can be calculated from the following Equation 2 (Dokka et al., 2013).

$$Number\ of\ replacemnts\ of\ prodcuts\ (j) = E[Reqsl/ESL(j) - 1] \qquad \text{Equation 2}$$

Where, Reqsl is the required service life of the building, 60 years, for example, in ZEB,
j is the product,
ESL is the estimated service life for the product j,
E is the rounded factor of the nearest whole integer.

The estimated rate of replacement and technical lifetimes for different components of an apartment building are listed below in Table 2.3, according to the market analysis conducted by Prognosesenteret (a Norwegian body working on construction market research) (Dokka et al., 2013).

Table 2.3 Technical service life of selected building elements in Norway

Construction Part	Flooring	Inner wall covering	Ceiling	Inner Doors	Roofing	Facade	Outer Doors	Windows
Replacement freq. for Apartment	32.3	37.5	147.6	59.8	46.4	43.1	49.1	50.7
Technical Life-time of Apartment	25.0	30.0	110.0	50.0	35.0	40.0	40.0	35.0

The operational energy of a building shall be determined in accordance with the standard NS 3031: 2007 (Calculation of energy performance of buildings) (Fufa et al., 2016). In addition, the standard (NS 3940: 2012) must be followed when calculating the heated floor space (BRA). In this stage, the lowest level of ZEB needs to consider the operational energy of the building. However, the highest level of ZEB considers energy use for all the delivered energy used in the building (Dokka et al., 2013).

When a building is rendered inoperative and can no longer be used, the materials and components are then demolished and transferred to waste facilities for disposal, thus commencing the end-of-life stage C1-C4 (EN 15804). A component is considered to have come to its end of waste state if it has a diminished market value, does not pass the relevant technical evaluations neither has any significant environmental impact. The end of life of a material is evaluated in the respective stage if it attains the end of waste state during the A4-A5 stages or B1-B7 stages.

C1 - Deconstruction/ demolition:

This module defines the deconstruction stage, where a building or component is demolished and sorted on site. The energy consumed during this stage is equivalent to the energy during its installation due to insufficient data (Fjeldheim et al., 2015).

C2 - Transport from construction to waste treatment:

This stage consists of the transportation of the demolished material to waste facilities for disposal.

C3 and C4 - Waste processing and disposal:

The wastes is processed during this stage for reuse and recycling (C3), including wastes that fail to reach their end of waste state (C4) and need to be disposed of. The data usage for these processes is collected from the current national waste accounts for materials.

Climate compensation measures

According to the Norwegian ZEB Research Center, one of the climate compensation measures is renewable energy production on-site, although off-site energy from renewable sources can also be used in some cases. Some basic ground rules have been laid out for the production of electricity and thermal energy, one of which implies that the production of excess renewable energy must be taken into account. This energy should first cover the building's total energy use, after which the excess production can be accounted for as compensation for the climate impact during the lifetime of the building. The on-site renewable energy production is considered irrespective of its source and can be either from solar, wind, or bioenergy (Hestnes & Eik-Nes, 2017). An integration of different renewable energy sources can also be used within the site along with provision for storage to facilitate annual energy supply. Given the fact that this is the sole climate measure to balance the emissions with a setup of different types of ambition levels, ZEB could be considered more ambitious than any other definition (Wiik et al., 2018). The fundamental concept for qualification as a climate-neutral building is through extreme reduction of climate impact. Thus, net-zero can solely be achieved by the production of renewable energy on-site or off-site, a factor required to upgrade to an additional ambition level of ZEB known as ZEB-COMPLETE. This essentially means that the total emissions related to the complete life cycle emission of a building should be compensated for in all the phases of A1-A5, B1-B5, B6-B7, and C1-C4 (ZEB, 2017).

ZEB has also investigated other climate measures to compensate for the emissions and achieve neutrality, namely through waste incineration and biogenic carbon storage, though there is scope for further research within this domain (Fufa et al., 2016; Hestnes & Eik-Nes, 2017).

3. Methodology

A case study building was obtained from White Architects to conduct this study. First, three different definitions of carbon neutrality were evaluated for the base-case building. After that, modifications were implemented to reach carbon neutrality according to each definition, accompanied by a comprehensive analysis to see the impact of these definitions on the respective building design. The selected definitions were from Zero Emission Building (ZEB, Norwegian Research Institute), NollCO$_2$ (Swedish Green Building Council) and White Architects. The ZEB definition was chosen as this was one of the first frameworks for climate neutral buildings. The NollCO2 definition was chosen as the case study building was from Sweden. Lastly, the definition from White Architects was selected as the base case study building was obtained from the respective organization. Defining a method to assess this building's climate neutrality according to several definitions was an important aspect of the study. As shown in Figure 3.1, the first step was to simplify the building in terms of construction material and floor layout (more detail in section 3.1). In the next step, simulations were performed to determine if the respective prerequisite criteria for energy demand and limit values for LCA from each of the definitions were met. If these requirements were not met, necessary passive or active measures were adapted. Details for this step are explained in sections 3.2 and 3.3. If the result from this step corresponded with the requirements of the respective definitions, then further calculations were made as a penultimate task to obtain the total carbon emissions based on the system boundaries of energy and LCA for each of the definitions. Finally, carbon neutrality was ascertained through carbon offset to coincide with the climate compensation measures considered in each definition.

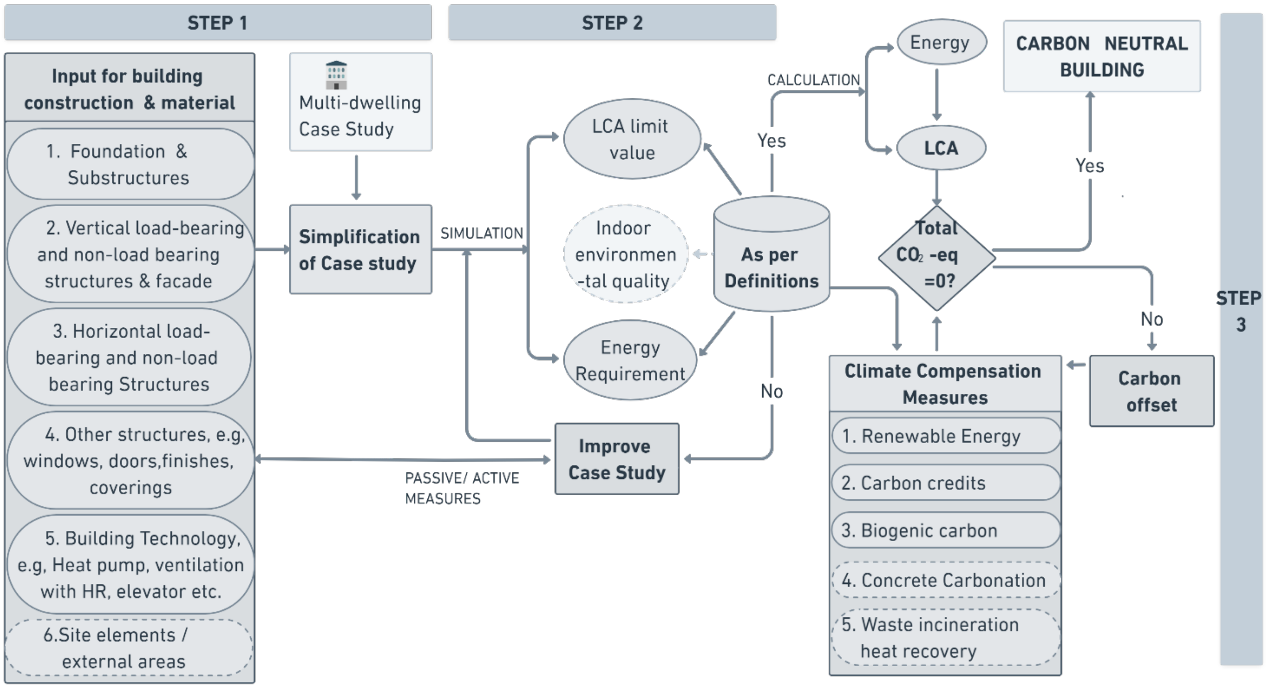

Figure 3.1 A flowchart illustrating the overall methodology of the performed study

Carbon neutrality was assessed under each definition as well as their respective compensation measures, followed by a number of comparative and sensitivity analyses, see Figure 3.2. The purpose was to explore how compensation measures toward a carbon-neutral building might change with an alternative construction. This was done for the White definition, where an alternative concrete load-bearing structure was considered to replace the original KL-wood for the building. For the definition of NollCO$_2$, an investigation was carried out on how the emission factors of energy based on different sources might influence the requirement for carbon neutrality. Additionally, the impact of marginal and average emission factors on carbon neutrality was also assessed for one of the ambition levels from ZEB. Furthermore, life cycle costing (LCC) and life cycle profit (LCP) were performed to compare the extent of compensatory measures for each scenario from the definitions. Lastly, comparisons were made among the emissions accumulated from each life cycle module for all the definitions and their respective need for compensatory measures.

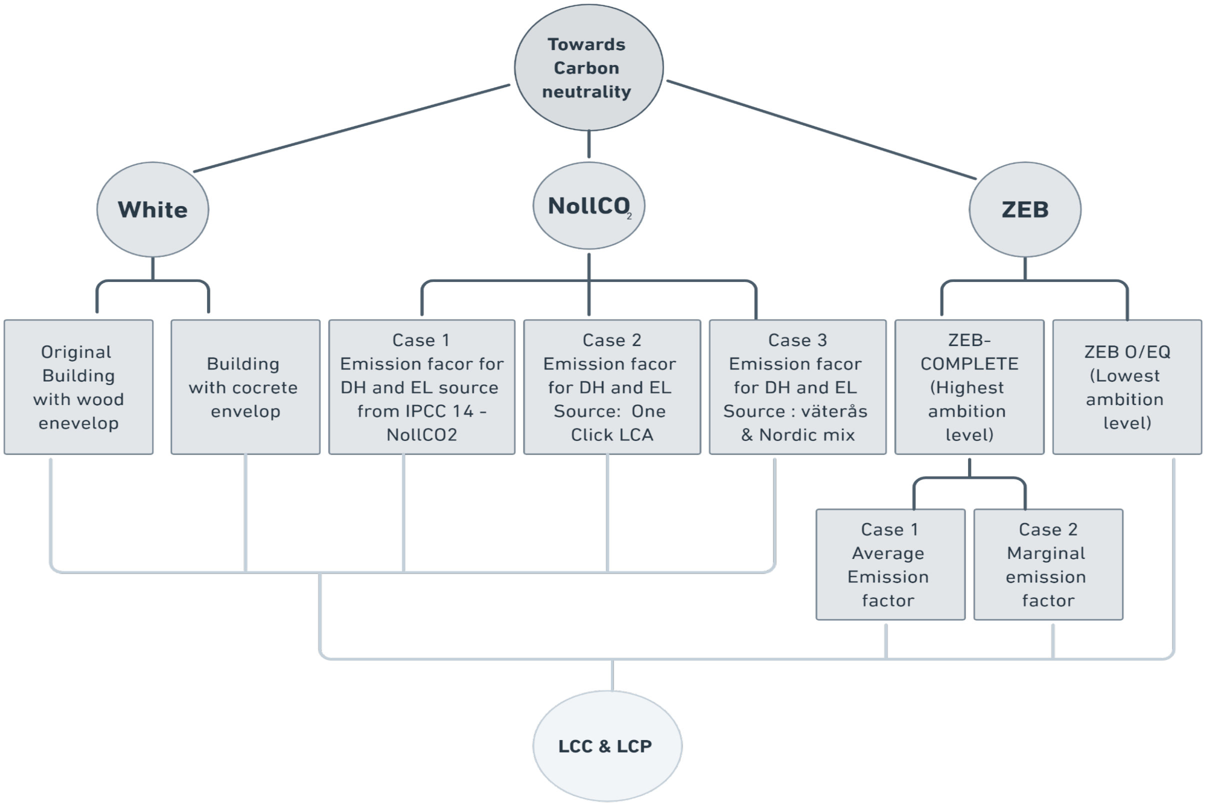

Figure 3.2 A schematic diagram showing the study consideration from each of the definitions

3.1 Case study: Information on analyzed building

The building under study is located in Kv Högne, Västerås, Sweden (coordinates 59°36'51.4"N, 16°33'03.8"E). The original building was a two-story garage building where four additional floors of garages and dwellings were constructed. Floors 1 & 2 were garages, floors 3 & 4 were a mix of garages and apartments, and the top two floors were only apartments. For the simplification and representativity of the study, all six floors were considered identical to the topmost floor. The apartment layout can be seen in *Appendix A*. Each floor consists of 21 apartment units: eleven studio apartments of 34 m^2 each, four one-bedroom apartments ranging from 54-60 m^2, and six two-bedroom apartments ranging from 71-73 m^2, respectively. The heated floor area (A_{temp}) is 1208 m^2, and the total floor area (BTA) is 10202 m^2.

For simplification purposes, the building components (facade, floor, roof, etc.) were considered to have uniform characteristics, unlike the original building, which had complex construction characteristics for the components. For example, the original case-study building had three types of exterior wall construction which varied in thickness, material properties, and layers. However, for this study, one type of exterior wall was considered. Material quantities for the adapted typical floor were extracted from the Revit model provided by White Architects. Detailed information on the HVAC system was not available, therefore, an ideal air load was simulated when calculating the energy demand for the building. The heat recovery of the ventilation system was 83%. In addition to this, there was no cooling system within the building.

3.2 Energy calculations

At first, the heat loss coefficient of the construction elements (U-value) and the average heat loss coefficient (U_m) of the entire building envelope were determined (detail in section 3.2.1). Then, the Rhino model was used for the simulations to determine the space heating demand of the building, more detail in section 3.2.3. The hot water demand was considered according to SVEBY recommendations. All other energy demands from electricity fans, pumps, property electricity, HVAC loss, and airing were obtained from White Architects. Afterward, primary energy demand was calculated according to BBR 29 using Equation 3 (Boverket, 2020). Inputs related to this are shown in Table 3.1.

The calculated primary energy value was regarded as the base case and used for the definitions from White Architects. The household electricity was 30 kWh/m^2 for the building as per information from White Architects and was implemented in the calculations for each definition where necessary. The assumed household electricity profile can be seen in *Appendix B*.

Further energy measures were applied to satisfy the pre-requisites or any limit values for the different categories of the certification NollCO_2 and ZEB. This is explained more in detail in section 3.5. Here, the primary energy factor indicates the loss from the energy sources due to energy distribution, regulation, production, transfer etc. but the final energy use or the delivered energy does not account for this loss.

$$EP_{pet} = \frac{\sum_{i=1}^{6}\left(\frac{E_{uppv,i}}{F_{geo}} + E_{kyl,i} + E_{tvv,i} + E_{f,i}\right)\cdot VF_i}{A_{temp}} \qquad \text{Equation 3}$$

Ep_{pet} = Buildings primary energy number
A_{temp} = Heated floor area, m^2
F_{geo} = Geographical adjustment factor
VF_i = Primary energy factor per energy carrier
$E_{uppv,i}$ = Energy for space heating, kWh/year
$E_{kyl,i}$ = Energy for air conditioning, kWh/year
$E_{tvv,i}$ = Energy for hot tap water, kWh/year
E_f = Property energy, kWh/year

Table 3.1 Considered energy carriers and primary energy factors in the design

Source	**Energy Carriers**	**Energy Use/ (kWh/m²/year)**	**Primary Energy Factors (VF_i)**	**Primary Energy Use/ (kWh/m²)**
Simulation	Space heating	30.4	0.7	21.3
SVEBY	Hot water	25	0.7	17.5
White	HVAC loss	5	0.7	3.5
White	Electricity fans pumps	7.5	1.8	13.5
White	Property electricity	2	1.8	3.6
White	Airing	4	0.7	2.8
Total	-	**73.9**	-	**62.2**

3.2.1 Heat loss calculation

U-average was calculated from the U-values of the constructions seen in Equation 4. These values were taken from the Grasshopper script except for the ground floor, which was hand-calculated with Equation 4. The material properties and details of the hand calculations are mentioned in *Appendix C*. Moreover, a thermal bridge of 20% was considered in the calculation of average heat loss coefficient for the building. Finally, the U-average was obtained from Equation 5.

$$U = \frac{\lambda}{0.457 \cdot B' + d_t} \qquad \text{Equation 4}$$

U value calculation of the ground according to SS-EN ISO 13370:2007

B' = Characteristic dimension of the floor
U = Thermal transmittance between the internal and external environment
dt = Total equivalent thickness for slab on ground floor
λ = Ground conductivity

$$U_m = \frac{\sum_{i=1}^{n} U_i A_i + \sum_{k=1}^{m} l_k \Psi_k + \sum_{j=1}^{\rho} \chi_j}{A_{om}} \qquad \text{Equation 5}$$

Average heat transfer coefficient Um = Average heat transfer coefficient for building components and thermal bridges (W/m^{2}K) determined in accordance with SS-ENISO13789:2007 and SS 24230 (2) and calculated according to the equation below.
Ui = Heat transfer coefficient for building component i (W/m^{2}K)
Ai = The area of the building component i's surface against heated parts of dwellings or premises. For windows. doors. gates and the like. 4; is calculated with the outer frame dimension. The building's entire indoor height is used in the calculations, i.e. from the upper edge of the lower joists to the lower edge of the attic joists.
Ψ = The heat transfer coefficient for the linear thermal bridge k (W/mK).
Lx = The length of the linear thermal bridge k (m)
Xj = The heat transfer coefficient for the point thermal bridge j (W/K).

Table 3.2 Heat loss co-efficient of the constructions and the building

Construction	**Area/ m²**	**U-value /(W/m²·K)**
Ground	1208	0.129
Roof	1208	0.089
Facade	3887	0.129
Window	1254	0.900
Door	281	1.000
U-average/(W/m²·K)	0.33	
Average thermal bridge/ %	20	

3.2.2 Control method for modeling

A basic shoebox model with two different integrated energy scripts (Ladybug Honeybee & Climate Studio within Grasshopper) was evaluated before proceeding with the study building energy model to check the result difference from the hand calculation and to find out any discrepancies. The detail for this is explained in *Appendix D*. All these steps were simulated in different order to check for any inconsistency. The comparison among the three sets of obtained energy use intensity showed very similar values, especially the energy script from Climate Studio is almost in line with the result obtained from the Ladybug-Honeybee script. The highest relative differences were seen in the final step for all three cases, which is understandable since this is where the EnergyPlus weather data came into play, see *Appendix D*.

3.2.3 Energy simulation

A Rhino model with an integrated EnergyPlus script of Ladybug-Honeybee within Grasshopper was used for the energy simulation of the building. The properties for the base case material were assigned for wall, roof, ground floor, windows, and doors, respectively. The building model from Rhino can be seen in Figure 3.3. The solar heat gain coefficient was 0.55. A generic interior construction was considered from the Honeybee library. For the leakage calculation, the airflow intensity was considered to be 0.3 l/s per square meter induced by a blower pressure of 50 Pa (SS-EN 13829) and the typical building pressure of 4 Pa, which gave a leakage of 0.058 l/m²·s. An ideal air load HVAC system was assumed for the building.

Two simulations were performed, one without the ventilation load and the other with the ventilation load without heat recovery of the building. This was because, as demonstrated by the control method study, the heat recovery from the ideal air load HVAC system in Honeybee considers all energy demands, including the demand from space heating. To address this issue, the heat recovery was dimensioned on the obtained ventilation load from the simulations, after which a total heating demand was calculated. In the simulation, without any ventilation load consideration, the heating demand for the building was 25.8 kWh/m² per year, and in the second simulation, which included the average ventilation load of 0.43 l/s·m² for the building, the heating demand was seen to be 52.6 kWh/(m²·year). From these two simulations, a total heating demand of 30.4 kWh/(m²·year) was calculated with the assumption of heat recovery of 83% temperature efficiency.

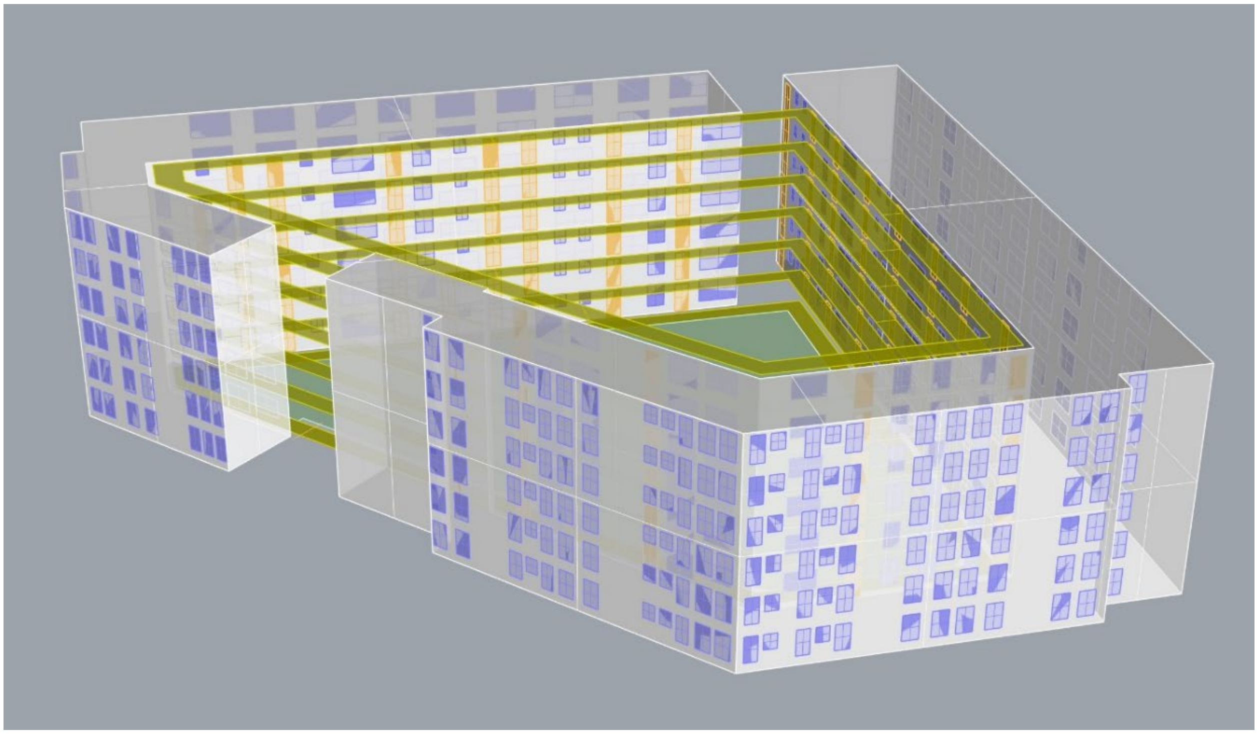

Figure 3.3 3D building model from Rhino

Stockholm EnergyPlus Weather (epw) data was used to run the simulations. All other inputs for parameters such as heating setpoint, ventilation, and internal loads are shown in Table 3.3. The simulations excluded any site surrounding and context considerations.

Table 3.3 Input for energy simulation

Parameter	Input	Schedule	Source
Heating set point	21°C	All year	White
Ventilation	0.43 l/s·m²	All year	White
Equipment load	4.5 W/m²	All year	White
Lighting load	2.3 W/m²	7 hours/day	White
Occupancy	0.03 Persons/m²	Varied (*Appendix B*)	(Swedish Tenant Association, 2022)

3.2.4 Heat pump calculation

To meet any threshold for energy demand from the definitions, the integration of a ground source heat pump in the building was considered. The heat pumps were sized separately for space heating, domestic hot water, and other heating demands. Space heating has a dynamic hourly profile which could be obtained through the energy simulation and, thus, the heat pump was sized to be 140 kW as per the maximum peak hour acquired. Though the hot water demand also has a dynamic consumption profile, due to the lack of data, it was considered constant, and a heat pump of 24 kW was dimensioned for the hot water. To avoid the risk of supplying insufficient heating energy to the building, the total heat pump capacity was intentionally oversized. In this regard, three heat pumps were selected from NIBE with a capacity of 60 kW each, giving a total 180 kW capacity. Different Seasonal Coefficient of Performance (SCOP) for these heat pumps was investigated to meet the energy demand thresholds determined by each definition.

3.3 LCA

The building's life cycle assessment was performed using the One-Click LCA software, its plugin for Grasshopper script, and excel calculations, with a more comprehensive analysis done within its cloud-based platform for the environmental impacts of the LCA modules and building material assessment. One-Click LCA is an automated life cycle assessment software for the construction industry. The tool considers European markets based on the EN 15978 standard and EN 15804 for product EPDs. Both the standards align with ISO 14040 & ISO 14044 used for the North American market. The life cycle stages are defined by EN 15978 and EN 15804.

3.3.1 Calculations for Life Cycle Stages

For the base case, which is according to White Architects' definition, the calculations for A1-A3 modules have been carried out. Corresponding quantities of each building material have been multiplied with respective GWP factors for these materials. These calculations were carried out with the respective EPDs obtained from the One Click LCA database. While choosing the EPDs, attention was paid to select the material with the same conductivity as used in the energy simulation to avoid any inconsistency in the calculation. Since no material specification was provided, the selection of environmental profiles for each material was based on the most appropriate available option, taking into consideration the country of origin and the lowest GWP. All selected EPDs can be seen in *Appendix H*. Environmental profiles for materials and material quantities can be seen in the same table. The assessment considers only the building and its parts. The building site was excluded in this study, along with any construction and deconstruction scenario or waste generation on-site.

For the base case, the impact from material transport (A4) was estimated as the distance (km) to and from the construction site multiplied by the specific climate impact ($kgCO_2e$) of transport used for delivery per ton of material. Since project-specific data for transportation distances were not provided, generic data from the "Byggsektorns MiljöBeräkningsverktyg" (BM) tool was used. It was assumed that all materials (except ready mixed concrete) would be delivered by a large delivery truck with a 9-ton capacity and 100% fill rate having an environmental profile of the GWP 0.0928 $kgCO_2e$/ton/km. Additionally, the ready-mixed concrete would be delivered by concrete mixer truck with approximately 8 m^3 capacity, 100% fill rate, and with an environmental profile for the GWP of 0.13 $kgCO_2e$/ton/km. Any additional trips for the transport to the construction site were disregarded in this study.

The Climate Impact of the module (A5) was estimated as a general value for the average construction site impact in the Nordic region, as stated in the One-Click LCA EPD database per m^2 (GFA). The construction site waste was assumed as indicated in Figure 3.4.

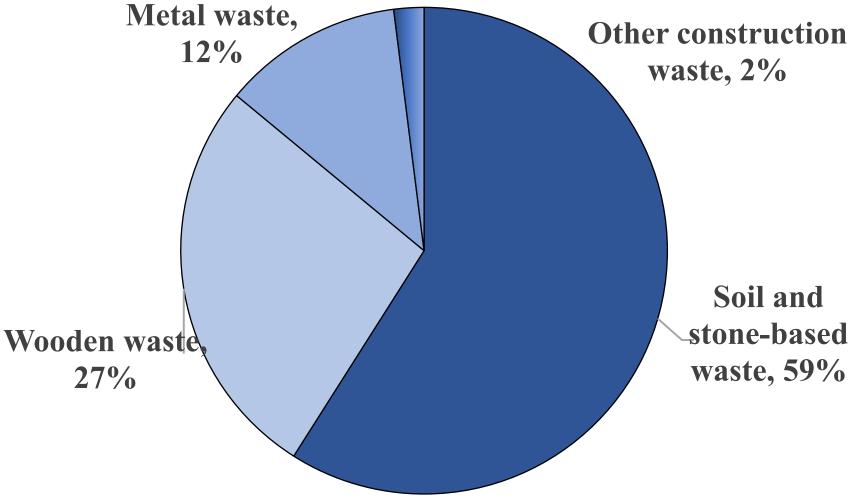

Figure 3.4 Construction waste assumptions

The electricity use assumption was set to 43 kWh/m^2 (GFA) with an emission factor of 0.034 $kgCO_2e/kWh$, and the assumed total use of diesel fuel was 5.2 l/m^2 (GFA) with an emission factor of 3.24 $kgCO_2e/l$. LCA calculations considered the dynamic decrease of operational energy emissions factor stated by each definition. Although the calculation process for each definition is slightly different, all definitions acknowledge linear emission decrease to zero for energy emissions by the year 2050 for $NollCO_2$ and 2055 for ZEB definition.

To calculate the dynamic decrease of the B stage and the overall LCA result to meet the target by 2050, excel calculations were made using linear equations. However, for the C modules, the impact from all the materials with respective stages was extracted from the One Click LCA and was used in Excel calculation. In One Click LCA software accounting for biogenic carbon is only shown as additional information. Neither the negative emissions of storing the CO_2 from the atmosphere in the A1 module nor their release in C3 were included in the GWP results. The value for biogenic carbon accounting is provided by building material EPD. If EPD does not provide the values, the calculation rule for the estimation follows the (EN 16449, 2014).

3.3.2 Control method for LCA

The manual control method was used to validate whether the One Click LCA software recognizes correct geometry surface input and material selection from Grasshopper and used correct environmental profiles for LCA assessment. In excel, corresponding quantities of each building material have been multiplied with the respective materials' GWP factor, provided by the EPD database. The environmental impact of each material was compared with results from the software and indicated no variation between the two calculation methods. Equation 6 was used for the climate impact calculation for the A1-A3 modules.

$$\begin{aligned} &Climate\ impact\ (kgCO_2e) \\ &\quad = Material\ quantity\ (kg, or\ m^3) \\ &\quad \cdot CO_2e\ intensity\ (kgCO_2e/kg\ or\ m^3) \end{aligned}$$

Equation 6

One Click LCA software was not used for the assessment of the B6 module since White Architects, and NollCO$_2$ definition for climate neutrality is based on linear emission factor decrease for operational energy, which could not be set in the LCA calculation tool.

3.4 LCC

In order to have a comparison between the environmental and the economic impact of the definitions, it was essential to carry out an LCC analysis to investigate the economic aspect of any passive or active measures for energy as well as any proposed carbon offset measures. Wikells Sektionsfakta NYB1 (Wikells Sektionsfakta, 2022) was used to determine the initial cost of materials and labor in the construction of technological systems (WS). The chosen source is a Swedish online database that includes costs for new materials, construction, demolition, transportation, and labor and is used for estimating prices associated with the construction works. The online database has different chapters, including building processes (construction and demolition), basic construction, electricity, plumbing, HVAC work, etc.

The LCC analysis quantified the Net Present Value (NPV) and Life Cycle Profit (LCP) for the various carbon offset measures, including different PV systems. The LCP shows accumulated profit, if any, throughout the considered lifespan from the offset measures. Therefore, a positive LCP shows when the investment is profitable. This study focused on roof-mounted PV systems when considering any renewable energy incorporation for carbon offset measures. The economic feasibility of the proposed PV systems was studied with LCC for a lifespan of 30 years. Different LCC scenarios were calculated for each proposed system, accounting for the profit from self-consumption, overproduction, tax reduction, and the combined profit. General assumptions such as a nominal interest rate of 1.6 % (Statens Fastighetsverk, 2020, inflation of 1% (Historic inflation Sweden, 2022), and an average electricity price increase of 2% (Statens Fastighetsverk, 2020) were considered in the LCC calculation. The complete grid-connected PV system price was 11650 SEK/kW$_p$ (Lindahl, 2020), with a value-added tax (VAT) of 25% considered over the system price. For the LCC analysis Equation 7 and Equation 8 were used to find the NPV.

$$A_1 = C_0(1+i)^n$$ Equation 7

$$NPV = A_1\left(\frac{1-\frac{(1+g)^n}{(1+i)}}{1-g}\right)$$ Equation 8

A1 = Accumulated costs in year one for heating, electricity, and maintenance in SEK
C_0 = Running cost in year zero, for heating or electricity in the current money value in SEK
i = Rate of return of the investment in %
n = Lifespan of the life cycle in years
g = Constant electricity price growth rate or constant district heating price increase in %
NPV = Net Present Value of the life cycle cost of the initial cost and running costs in SEK

An operation and maintenance cost for PV systems were set to 64 SEK/kW$_p$ (Lindahl, 2020) per year. The inverter was assumed to be replaced at year 15. Hourly electricity spot prices for bidding area SE4 from the year 2018 were obtained from Nord Pool (Nord Pool Group, 2018). The electricity bought from the grid and the electricity that was self-consumed from the PV system production was considered to be 1.4 times higher than the hourly spot prices (Lindahl et al., 2019) to account for the additional grid charges, VAT, trading fees, trading surcharge, and green electricity certificate fees. The selling price from overproduction was considered to be equal to the spot prices. Tax reduction on 30 000 kWh electricity bought from the grid was considered to have a rate of 0.6 SEK/kWh (Öresundskraft 2021).

3.5 Definition assessment

This study aimed to investigate solutions to reach carbon neutrality for the building according to the selected definitions. Firstly, a set of fundamental questions were investigated for each of the definitions as listed below. More information related to these questions is discussed in Chapter 2.

- What is the functional unit?
- What is the calculation period?
- What are the prerequisites?
- What are the system boundaries for energy and LCA calculations?
- What are the threshold values for each category, if any?
- What compensation measures are appraised?
- What are the rules of calculation for balancing with compensation measures?

A comparative input below lists the related information in accordance with these questions. Additional details are provided in the sections below for the respective definitions.

Table 3.4 Input parameters for the definitions

	White	**NollCO$_2$**	**ZEB**	
			ZEB-O/EQ	**ZEB-COMPLETE**
Functional unit	Atemp	BTA	GFA (Same as Atemp)	GFA (Same as Atemp)
Calculation period	50 years	50 years	60 years	60 years
Energy pre-requisite	BBR 29	Energy class B	Low energy class 1	Low energy class 1
Energy measure	No	Heat pump integration	Heat pump integration & DHW demand reduction	Heat pump integration & DHW demand reduction
System boundary LCA				
A1-A5	Yes	Yes	No	Yes
B1-B3	No	No	No	No
B4-B5	No	Yes	No	Yes
B6	Yes	Yes	Yes	Yes
B7	No	Yes	No	Yes
C1-C4	No	Yes	No	Yes
D	No	Yes	Yes	Yes
Emission factors				
Electricity/ tCO$_2$/kWh	22	22	75	75
DH/ tCO$_2$/kWh	60	No	No	No
Limit values				
A1-A3	No	Yes*	No	No
A4-A5	No	Yes**	No	No
B1-B7	No	No	No	No
C1-C4	No	No	No	No
Climate compensation				
PV	Yes	Yes	Yes	Yes
Compensation type	Marginal	Marginal	Average	Average
Biogenic carbon	Yes	No	No	Yes
Carbon purchase	No	Yes	No	No

* A1-A3 limit value reference was taken from an example project from SGBC NollCO$_2$ baseline and limit value June 2021 report (SGBC, 2021)
**A1-A5 limit value from NollCO$_2$ was 55 kgCO$_2$e/m^2 BTA.

For each definition, the following building elements were assessed, shown in Table 3.5. Here BSAB denotes the code for building components from Swedish Construction Service (Svensk Byggtjänst). The numbering for the building components under ZEB was from the recommended list of included materials and components, based on the list of building elements from NS 3451: 2009 (Dokka et al., 2013).

Table 3.5 Comparison of physical system boundaries for each definition

External physical system boundaries for each definition		
White **BSAB**	**NollCO₂** **BSAB**	**ZEB** **NS 3451**
BSAB 15 Basic constructions	BSAB 15 Basic constructions	21 Groundwork and foundations
BSAB 27 Bearing structure in the house frame	BSAB 27 Bearing structure in the house frame	NS 3451 22 Superstructure
BSAB 41 Climate separation components and extensions in roofs and floor joists	BSAB 41 Climate separation components and extensions in roofs and floor joists	NS 3451 23 Outer walls
BSAB 42 Climate separation components and extensions in the outer wall	BSAB 42 Climate separation components and extensions in the outer wall	NS 3451 24 Inner walls
BSAB 43 Internal components for room construction	BSAB 43 Internal components for room construction	NS 3451 25 Floor structure
BSAB 44 Internal surface layers	BSAB 44 Internal surface layers	NS 3451 26 Outer roof
PV System	BSAB 45 House extensions	NS 3451 28 Stairs, balconies, etc.
	BSAB 52 Water supply	NS 3451 30 VVS-installations
	BSAB 53 Wastewater system	NS 3451 32 Heating
	BSAB 54 Fire extinguishing system	NS 3451 33 Firefighting
	BSAB 56 Hot water system	NS 3451 36 Ventilation and Air Conditioning
	BSAB 57 Air handling system	NS 3451 44 Lighting
	BSAB 6 Telecommunication system	NS 3451 62 Passenger and goods transport
	BSAB 7 Lift system	NS 3451 69 Other (PV, other renewable power systems)
	PV System	Equipment & Appliances

Furthermore, compensation from renewable energy, carbon credit purchase, and biogenic carbon storage consideration were assessed based on the demand of each definition. The PV system was considered as an offset measure for any required renewable energy integration. The software System Advisory Model (SAM) was used to size the PV system. The Stockholm weather file was used in all the simulations, and only roof-mounted PV systems were considered for this study. All panel placements were considered to have an inclination of 0° to the roof with virtually no spacing between the modules, and the proposed systems would cover only 90% of the roof. Detailed input of SAM simulations for each definition with their respective scenarios and cases are shown in *Appendix I*. Due to the lack of information on the carbon credit purchase compensation method, yearly credit purchase was considered with Verified Carbon Units (VCU) throughout the calculation period of reaching climate neutrality. The carbon offset value from biogenic carbon storage could be obtained directly from the One Click LCA platform, which differed based on the construction element considerations by the definitions.

3.5.1 White architect's definition of carbon neutrality

White definition bases some of its framework on existing definitions and closely follows calculation methods from the NollCO₂ definition. The energy efficiency of the building should meet the threshold from the latest issue of BBR 29 standards. For the White definition, the LCA calculations were based on the adapted base case study model. This was a timber-frame loadbearing building. Quantities for this project were extracted from the Revit file obtained for the building project and can be seen in *Appendix H*. Following the investigation of the wood-frame building for carbon neutrality, another scenario with a concrete load-bearing building was also examined to determine how this could impact the overall accumulated carbon emissions and the required offsetting measures with this definition.

Climate impact calculation

According to this definition, the functional unit calculates 1 m^2 of heated floor area (A_{temp}) over a service lifetime of 50 years for a building. The calculation included GHG emissions from LCA modules A1-A3, A4-A5, and B6 as the indicated system boundaries defined. The building elements under assessment were selected according to the definition and can be seen in Table 3.5. The calculation method for PV system impact for A1-A3 stages was not stated in White architects' definition, and the analysis was based on a reference study (Müller et al., 2021), estimating that PV modules produced in Europe would account for 420 $kgCO_2e/kW_p$ including production, transportation, and end-of-life treatment.

The emissions from energy use were adopted as indicated by definition. As there were no clear indications for emission factors, assumptions were based on the NollCO₂ definition with the value of 22 $kgCO_2e/MWh$ for purchased electricity from Sweden's electricity mix and 60 $kgCO_2e/MWh$ for energy from district heating (SGBC, 2021). Excel calculations were used to assess the building's operational energy emissions (module B6). Both electricity and district heating emissions are calculated as a linear decrease trend indicating reduced emissions with zero emissions in the year 2050.

Balancing

White Architects' definition considered balancing measures include electricity export and carbon sequestration in biogenic construction materials. As pre-requisite criteria, a PV system was dimensioned that covers a minimum of 10% of the operational energy of the building regardless of its contribution towards carbon neutrality. Electricity generated by the PV system replaces electricity in the electrical grid and therefore requires less production of "dirtier" coal energy. The displacement value is taken as the average coal emissions value in 2018, which equates to -820 g CO_2e/kWh and takes into account a scenario of a fossil-free electricity system by 2045, averaging -410 CO_2e/kWh for buildings lifespan.
Carbon sequestration in the project was accounted for based on EPD values provided by suppliers and was accounted for separately in the project. All results were summarized in an excel calculation as an average value of the impact of the building per square meter of heated floor area (A_{temp}). Table 3.5 shows an illustration of carbon balance adapted from this definition.

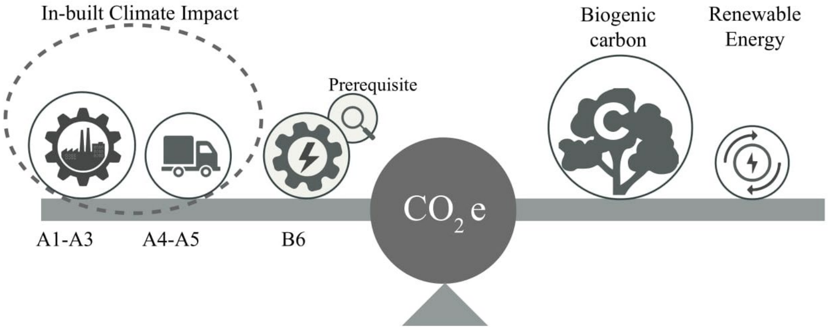

Figure 3.5 An illustration of considered net-zero carbon balance for white definition

Concrete case

To better understand the impact of biogenic carbon sequestration, a scenario was investigated where the wooden load-bearing structure is replaced with a concrete load-bearing structure. A replacement was assumed for the following structural components:

- Roof
- External wall
- Internal walls
- Internal floor slab

An assumption is made that the original Kl-wood structure is replaced with the same volume of concrete with steel reinforcement. Additional insulation is added to each component to account for the difference in thermal conductivity between the two structures. Cost analysis is made between load-bearing structures to assess cost benefits between two structures. All other parameters were kept as they were in the original case. Climate compensation measures from sequestered biogenic carbon in wood products will no longer be present when concrete structures are implemented, consequently, PV system size would have to be increased to achieve a carbon-neutral design. A comparative LCC analysis was carried out considering savings from self-consumption, overproduction sell, and tax reduction for the PV systems for both scenarios.

3.5.2 NollCO₂ definition of carbon neutrality

LCA calculations were based on an adapted case study model. Quantities for the project were taken from an existing building project and can be seen in *Appendix H.* In addition to the initial "White architects" building construction, the building had to fulfill additional prerequisite energy requirements.

Prerequisite criteria

According to the NollCO₂ definition, the energy use of the building has to fulfill energy class B requirements (SGBC, 2021) with a 25% improvement compared to traditional BBR buildings. To fit this requirement, the project has to use a ground source heat pump (GSHP) with a minimum SCOP value of three. The GHG emissions associated with the installation of a heat pump are added in module A1-A3. However, there was a lack of availability of heat pumps with such low SCOP in the market.

Climate impact calculation

The climate impact of the building is calculated for 50 years and includes GHG emissions from LCA modules A1-A3, A4-A5, B1-B7, and C1-C4. Building parts and materials that were taken into consideration can be seen in Table 3.5.

NollCO₂ baseline value calculation method was not available for the study, and the estimated project limit values for the A1-A3 stage are compared to the assumed limit value from the example project in SGBC NollCO₂ baseline and limit values (SGBC, 2021) for apartment buildings. Figure 3.6 indicated impact ($kgCO_2e/m^2BTA$) limit according to (SGBC, 2020b).

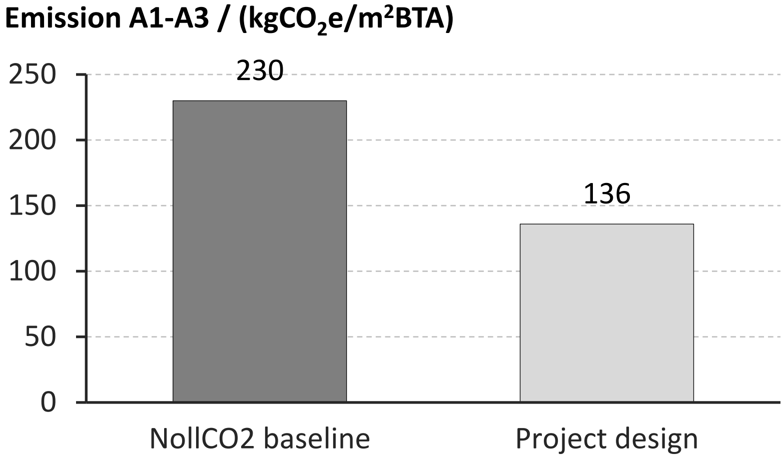

Figure 3.6 Limit value

PV system impact for the LCA A1-A3 module was analyzed as a separate category. Calculations were based on lifetime energy yield based on average performance warranties by module producers and specified carbon footprint (0.042 $kgCO_2e$) per kWh of produced electricity (SGBC, 2020b). In addition, the environmental impact for material transportation (A4) and building site construction (A5) was assessed using the same method as in the 'White architects' case but with a limit value of 55 $kgCO_2e/m^2$ *BTA*.

According to the NollCO₂ definition, B1-B3 stages are assumed to be zero. Estimation of replacement and refurbishment of building parts or materials (B4-B5) were done using excel. The life service period was set according to NollCO₂ specifications (SGBC, 2020a) and can be seen in *Appendix G*. Impact associated with the manufacture (A1-A3), transportation (A4), and installation (A5) was considered and added in each year that the specific replacement was happening. Emissions for manufacturing, transportation, and installation were presumed to follow the linear decrease equation and were reduced to zero by the year 2050.

Module B6 comprises only GHG emissions from electricity demand and is divided into two categories. First, property electricity that considers lights, pumps, and other electrical equipment required to run the building. Property electricity was assigned as a constant value over the year. Second, variable electricity, that with the installation of the heat pump, is used to cover the space heating demand of the building. The variable electricity profile was based on simulation results. Total electricity demand is assessed with PV system production profiles in the later project stages for imported and exported electricity for each hour of the year. The emission factor for electricity followed the same linear decrease "trend" indicated in Figure 3.7.

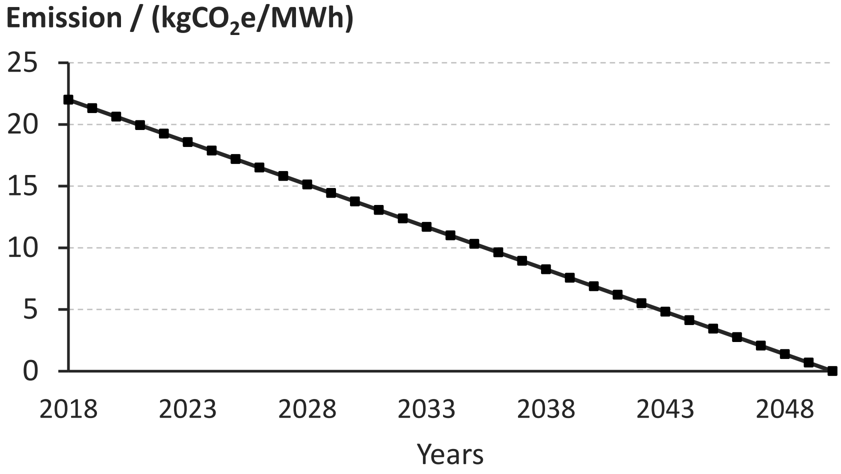

Figure 3.7 Electricity emission factors linear decrease over time

Water use on the property for domestic hot water supply was estimated according to SWEBY recommendation with a value of 18m^3/person/yr and emission factor of 0.3 kgCO$_2$e/m^3 from the One Click LCA database. Emissions factor for water also was following linear decrease function. In calculations, water for ventilation, cooling, or any other processes was not considered. In addition, emission from end-of-life treatment (C1-C4 modules) was set to zero since, according to the definition, by 2050, all waste treatment processes would be carbon neutral and would not impact the environment.

Balancing

According to the NollCO₂ definition, in the given case, two balancing methods could be used to offset initial carbon emissions, selling excess renewable electricity and purchase of carbon credit.

As stated by definition, the selling of excess renewable energy is accounted for replacing more carbon-intensive coal energy in the electricity grid. Figure 3.8 illustrates net carbon balancing with NollCO$_2$. Only electricity exported to the grid is accounted for as displacement for otherwise more emission-intensive coal-produced energy. Photovoltaic (PV) system size and hourly electricity production profiles are generated using SAM software to assess the potential for purchased and sold energy (Scenario 1).

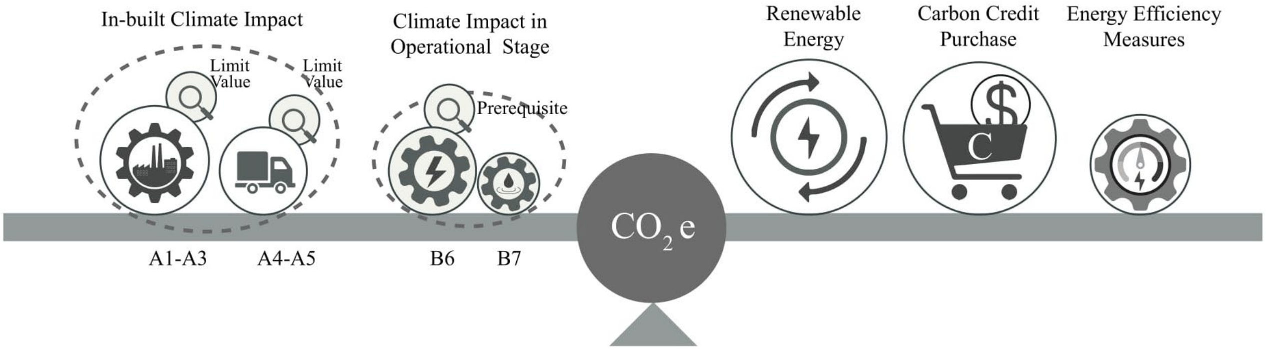

Figure 3.8 An illustration of considered net-zero carbon balance for NollCO$_2$ definition

Total GHG emissions for a given design were used to determine the total price of purchased carbon credits. In scenario 2, all emissions are balanced with carbon credit purchases, the impact of the PV system in module A1-A3 is no longer present, and emissions associated with energy purchase in the B6 stage are no longer influenced by PV systems production. The carbon credit purchase cost range was 50-350 SEK per tCO$_2$e. The size of the PV system and LCC were calculated and compared to the cost of carbon credit purchase.

- Scenario 1. To make the project carbon neutral using only a PV system and assess the cost of the system that would be required to achieve this.
- Scenario 2. Make the project carbon neutrals using only carbon credit purchase and assess life cycle cost.

Sensitivity analysis

Depending on the source, emission factors can vary significantly and account for larger or smaller amounts of total GHG emissions in the project. Therefore, sensitivity analyses were performed to assess how different electricity emission factors would affect the project design. Note that selected emission factors influence only purchased electricity from the grid since DH energy is no longer present in the design, and electricity exported back to the grid displaces marginal emissions from coal energy as stated in the NollCO$_2$ definition. Three different electricity emission factors (with different sources) were analyzed as indicated below:

- NollCO$_2$ specified electricity mix based on EU JRC calculations (22 kgCO$_2$e/mWh)
- OneClickLCA electricity mix for Sweden (51.9 kgCO$_2$e/mWh)
- Average emission factor calculated according to ZEB definition (74.8 kgCO$_2$e/mWh)

Emission factors vary between energy sources depending on the location, databases used for calculation, and selected specific energy sources. Electricity emission intensity in Sweden's electrical grid depends on individual CO_2e intensities of power types that this grid consists of. $NollCO_2$ definition calculation indicated that in 2018 Sweden's electricity grid emissions were 22 $kgCO_2e/mWh$, while using a source from the OneClickLCA database shows that this number can be as high as 51.9 $kgCO_2e/mWh$. The climate impact of using a specific type of energy is evaluated with the following formula:

$$\begin{aligned} &Climate\ impact\ (kgCO_2e) \\ &\qquad = Energy\ consumtion\ (MWh) \\ &\qquad \cdot CO_2e\ intensty\ (kgCO_2/MWh) \end{aligned} \quad \text{Equation 9}$$

3.5.3 Zero Emission Building (ZEB) (Norway)

ZEB certification specifies six ambition levels that the ZEB center laid out. However, only two ambition levels were investigated for this study to achieve climate neutrality for a specific design. One is the lowest ambition level, which is ZEB-O/EQ, and the other is the highest ambition level, ZEB-COMPLETE. The prerequisite for any climate-neutral ZEB certification is to have high energy efficiency with a minimum specification of 'low energy class 1' that corresponds to 40.6 $kWh/\ m^2$ for primary energy (Marszal et al., 2011; Sartori et al., 2012), which includes energy carriers like space heating demand, property electricity, system loss, and domestic hot water. This requirement was achieved by integrating heat pumps with a capacity of 180 kW and a minimum SCOP of 4.5, which would cover all the heating demand from space heating, domestic hot water, and system loss. Heat pump selection and price was taken from the NIBE website (Nibe, 2022). Moreover, the district hot water was assumed to be transferred as individual net metering, reducing the hot water demand from 25 $kWh/\ m^2$ to 20 $kWh/\ m^2$ (Sveby, 2014). These combined measures enabled the building to meet the energy requirement.

Climate impact calculation

The functional unit for ZEB was considered to be 1 m^2 of heated floor area over a service life of 60 years for the building. The ZEB-O/EQ level considers GHG emissions related to all energy use in operation (O) during the lifespan of the building, except energy use for equipment/appliances (EQ). No other modules were included in this ZEB level. Compensation was considered only for using on-site renewable energy generation.

On the other hand, ZEB-COMPLETE considers all of the life-cycle modules and demands a comprehensive study considering all types of energy used in the building and biogenic carbon consideration. The LCA calculations were based on an adapted case study model. The considered building elements were according to the standard NS-3451. These elements have been listed in Table 3.5. Quantities for the project were taken from the existing building project and can be seen in *Appendix H.*

Estimation of replacement and refurbishment of building parts or materials (B4-B5) were done using excel. However, due to lack of information, the life service period was set according to the $NollCO_2$ definition specifications. It can be seen in *Appendix G*, except for components 23, 24, and 26, for which the service life was considered based on market research performed by Prognosesenteret (a Norwegian company working on construction market analysis). According to

EN 15978 (2011), the number of replacements of a product should be calculated with Equation 2 from the example case study in the ZEB Project report (Fufa et al., 2016). The impact for B4-B5 represented 50% of A1-A3 carbon emissions. Hence, the same was considered in this study as well.

The approach for energy emissions from the building during its use stage (B6) was set as an average emission factor calculated for electricity (75 $kgCO_2/mWh$) from 2022 to 2082 (lifetime of the building). The property's estimated water use followed the same calculation as in the $NollCO_2$ method. The calculation for the end-of-life stages for building materials was considered at the end of the building lifespan, although it is worth noting that not all materials have to be treated as waste, and products can still be used for different purposes and have a positive climate value (or can reduce negative climate value).

It was assumed that emissions for module C1 would be equal to the emission generated in the A5 module A5 for the construction and installation process (Fjeldheim et al., 2015). For modules C2-C4, standardized emission values based on current EPDs were used. However, as both processes happen at the end of the lifetime of the building, in the year 2082, it is hard to predict what type of recycling/ reuse/ disposal process will be implemented. As ZEB considers emission-free energy by the year 2055, it would be a reasonable assumption that these emission values would be much lower than those calculated today.

Comparison study for average and marginal emission factor

A comparison study was made to show the differences between the export of average and marginal emission factors for surplus electricity and their effect on the design and total emissions in the building. The average emission factor for electricity export was 75 gCO_2 /kWh, whereas the marginal emission factor was 140 gCO_2 /kWh for the electricity export. For the import of electricity, the emission factor considered was 75 gCO_2/kWh for both scenarios.

Balancing

In ZEB, all the balancing is done only with the export of renewable surplus energy. The renewable energy is primarily to be produced on-site, but there is also an option of evaluating off-site renewable energy for the highest two ambition levels, which was out of the scope of this study. According to Dokka et al., the electricity system will be decarbonized by 2055. From (Graabak & Feilberg, 2011), the simulated emission factor for electricity in 2010 was 360 gCO_2 /kWh. So, the average emission factor for the building was calculated from 2022 to 2082 to be 75 gCO_2 /kW with a linear extrapolation of the mentioned values. The same emission factor of 75 gCO_2 /kWh was used for importing and exporting electricity in the calculation for balancing according to ZEB. The approach is called symmetric weighting and is defined by (Dokka et al., 2013). The lowest level of ZEB only needed to offset emissions from the operation energy use in the building, as seen in Figure 3.9.

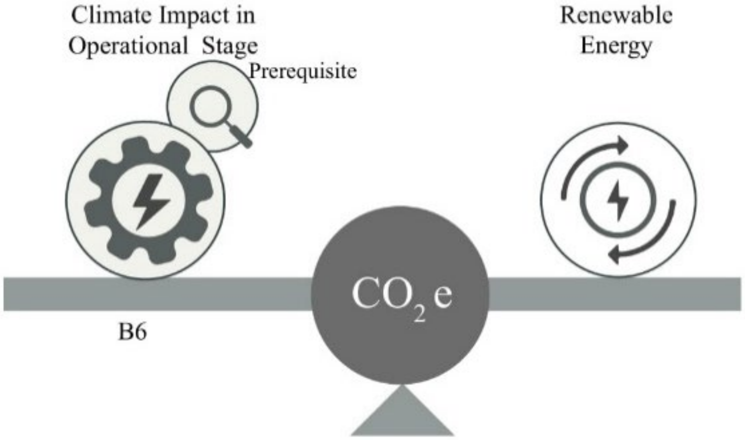

Figure 3.9 An illustration of considered net-zero carbon balance for ZEB-O/EQ definition

The biogenic carbon impact in the design is assessed according to the ZEB ambition level, and only in the highest two ambition levels, it could be considered. The current approach specifies that it should be taken into account only if the end-of-life (module C1-C4) is considered. Balancing requires renewable energy integration on-site and evaluation of off-site production. Figure 3.10 attempts to illustrate net carbon balancing with ZEB-COMPLETE.

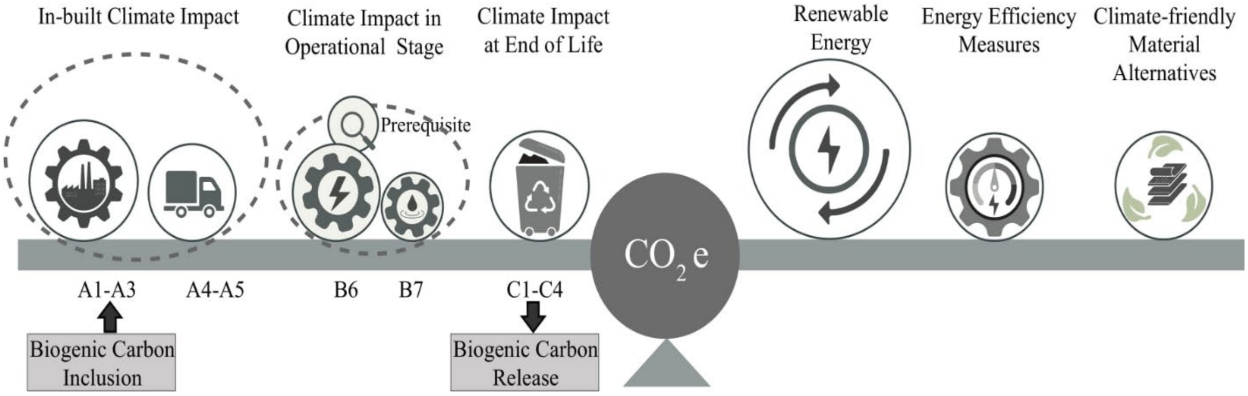

Figure 3.10 An illustration of considered net-zero carbon balance for ZEB-COMPLETE definition

4. Results

4.1 Building Energy

The average U-value for the case study building was calculated to be 0.33 W/m²/K, which was below the limit value of 0.4 W/m²/K according to BBR requirements. The primary and final energy use for the same building for each definition can be seen in Table 4.1. This includes the energy demand from space heating, domestic hot water use, and property electricity. Except for the primary energy result for the White definition, which already met the BBR requirement as demanded by definition, the other two definitions required additional energy measures to meet their energy threshold. The NollCO$_2$ definition required a 25% reduction as a threshold of primary energy defined by BBR 29 to achieve Energy Class B (Boverket, 2020). This resulted in required energy demand of 56.3 kWh/m² for this definition. On the other hand, the primary energy requirement for the ZEB definition was 40.6 kWh/m², according to low energy class 1. While no passive measures were considered to improve the building energy demand for NollCO$_2$, the thresholds from this definition could be met by adapting active measures like implementing a ground source heat pump in the building. On the other hand, the ZEB definition demanded even higher energy efficiency. As a result, measures like domestic hot water demand reduction and a ground source heat pump with a greater seasonal coefficient of performance (SCOP) needed to be adapted, see Table 4.1.

Table 4.1 Energy demand results for each definition

Parameter	**White (Base case)**	**NollCO$_2$**	**ZEB**
Energy prerequisite	75.0	56.3	40.6
Primary energy/ (kWh/m²)	62.2	55.7	40.9
Final energy/(kWh/m²)	73.9	31.0	22.7
Heat Pump SCOP	-	3.5	4.5

4.2 White Architects certification

The total CO_2e emissions, according to White Architect's carbon-neutral definition, for the building with the wooden load-bearing structure was 1459 $tCO_2e/50y$, and the building with a concrete load-bearing structure was 2298 $tCO_2e/50y$. Figure 4.1 indicates that the highest emissions are from module A1-A3 in both designs. A building with concrete load-bearing construction has approximately 57% larger total CO_2 emissions than a wooden load-bearing building. Additionally, biogenic carbon storage potential in a concrete building is only negative 60 $kgCO_2e/m^2A_{temp}$, while in wooden construction, it can account for negative 292 $kgCO_2e/m^2A_{temp}$. Furthermore, emissions from transportation increased by 256% because of the larger weight of concrete construction. Module A5 indicated no change for both cases due to considering the same emission factor ($kgCO_2e/m^2$) and construction area (m^2) for the project.

The PV system size for wooden load-bearing construction was 76 kW_p and was required to increase to 386 kW_p for concrete load-bearing construction. Emissions from module B6 were a combination of emissions from DH and electricity, with DH emissions accounting for approximately 82% and electricity accounting for 18% of the total value.

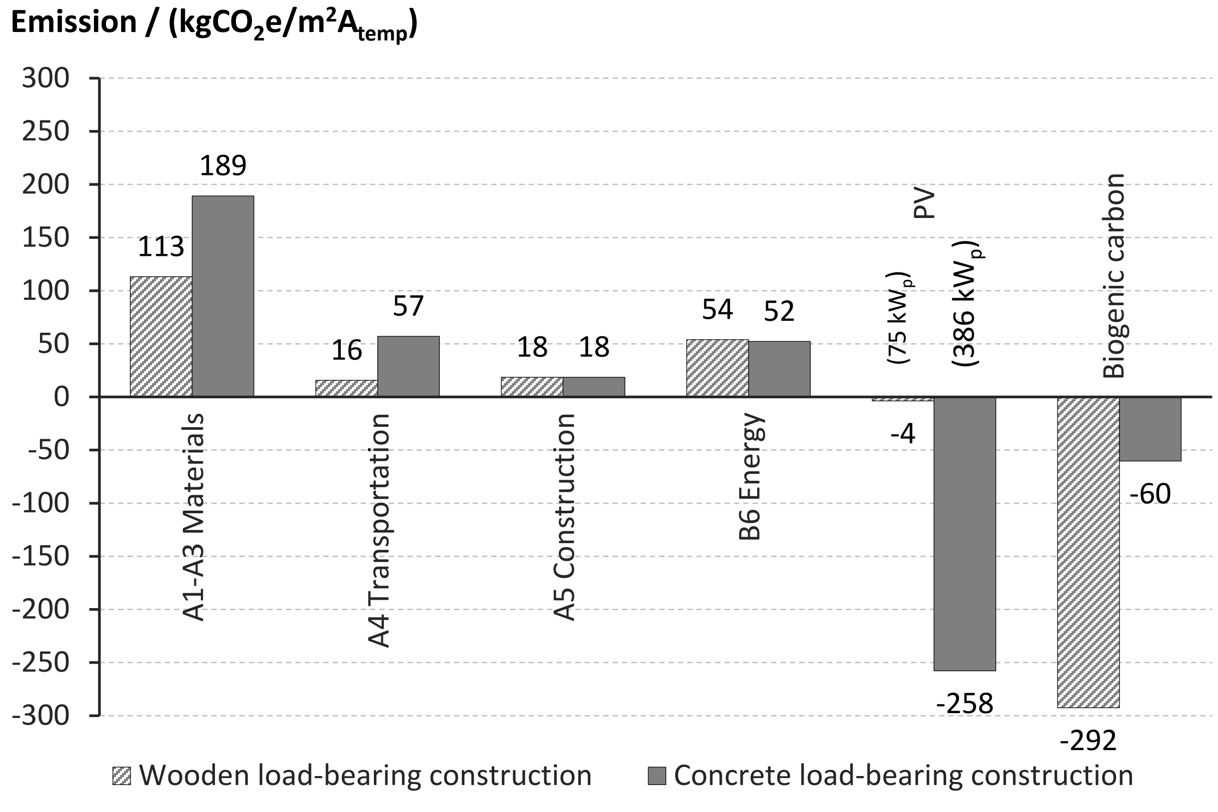

Figure 4.1 Results for life cycle modules and relevant compensatory measures

Further analysis of A1-A5 modules, seen in Figure 4.2, shows which building elements have the most impact in terms of emissions in the considered design. The highest impact from the concrete case was from category BSAB 27 and for wood case category BSAB 41. Elements from all of the categories are specified in *Appendix E*. The highest emission with 217 $tCO_2e/50y$ corresponds to 30 $kgCO_2e/m^{2,}$ and for the concrete case, category BSAB 27 indicated the highest impact with 525 $tCO_2e/50y$, which corresponds to 72 $kgCO_2e/m^2$. BSAB categories and building elements that were considered for these categories can be seen in Figure 4.2 and *Appendix H.*

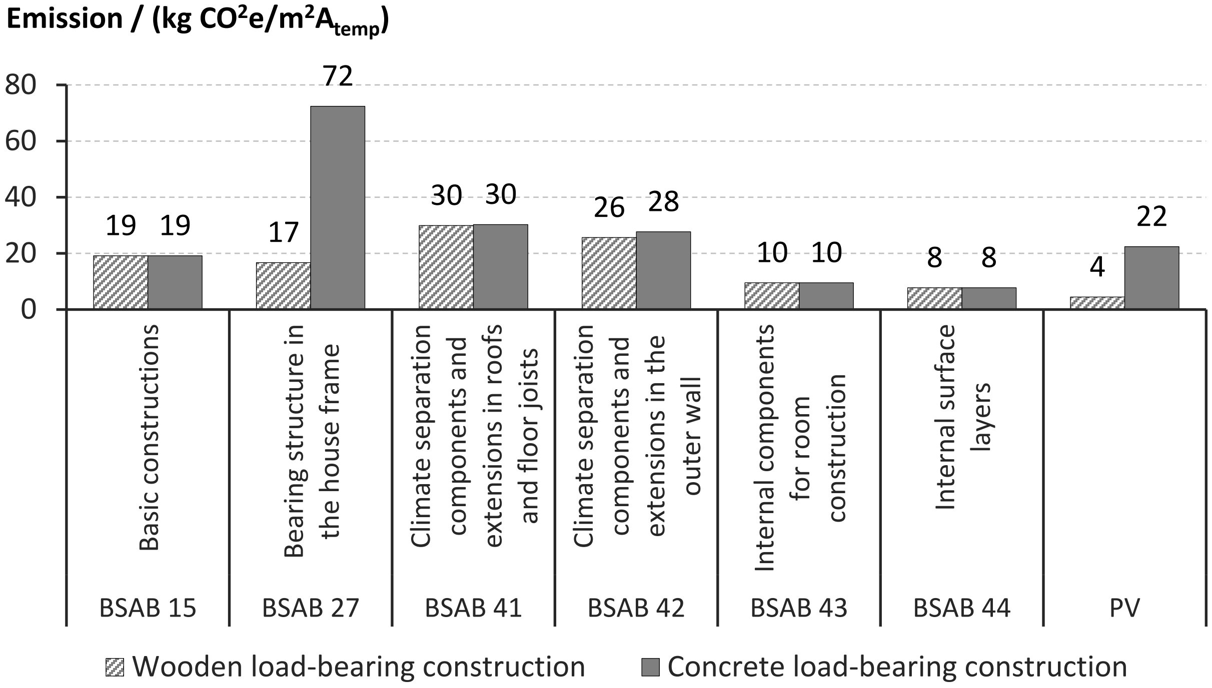

Figure 4.2 Emissions from each BSAB category for two construction types

Additionally, compassion between both cases regarding emissions from each material used in the project can be seen in Figure 4.3. In wooden load-bearing construction, the majority of emissions come from wood 30% and insulation 29%, and concrete accounts only for 9% of total emissions. On the other hand, in concrete load-bearing construction, concrete accounts for 54% of total emissions, and wood and insulation account for 27%.

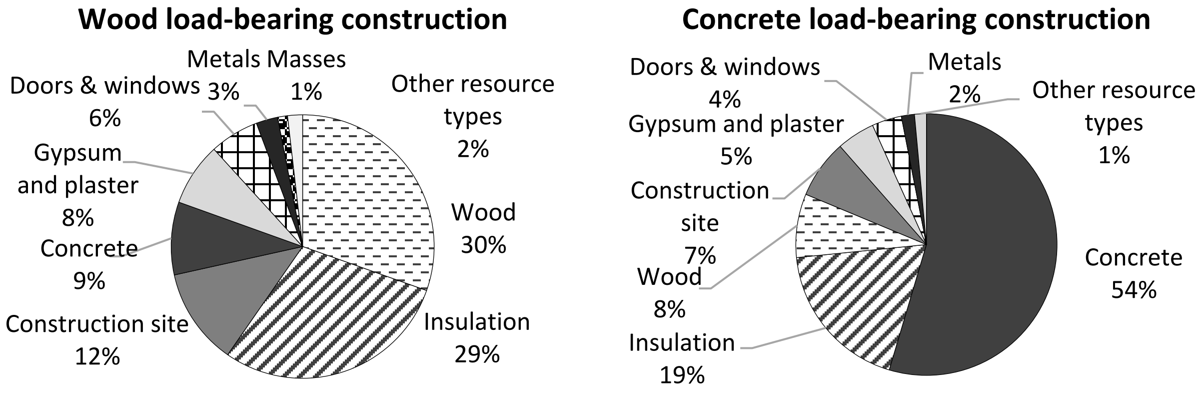

Figure 4.3 Total emissions from materials

The LCC analysis evaluated Net Present Value (NPV) and Life Cycle Profit (LCP) for the specified PV systems for wood and concrete construction. The cost analysis in Figure 4.4 indicates that concrete construction is more expensive than wood construction. The total costs for concrete load-bearing construction are approximately 25 MSEK and are 880 KSEK higher than wooden construction.

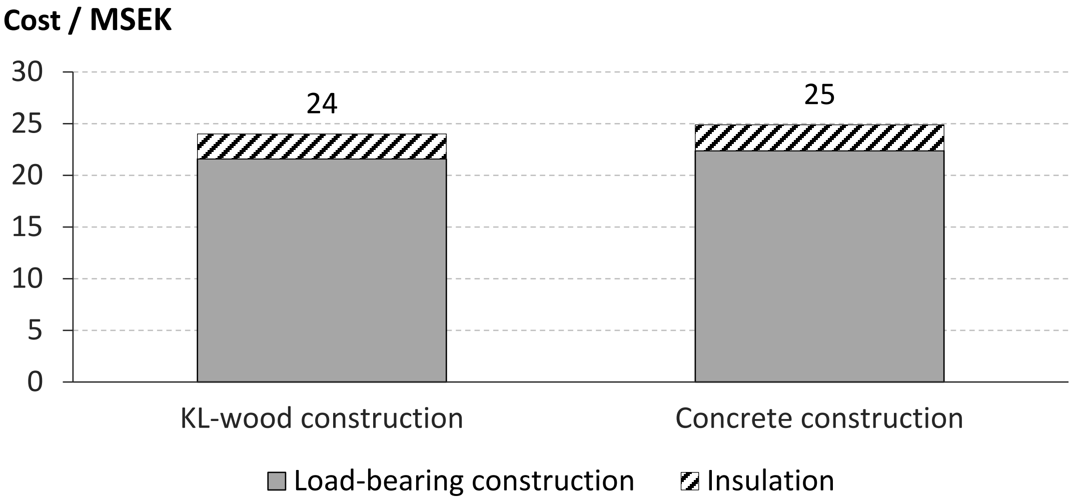

Figure 4.4 Life cycle costing for construction

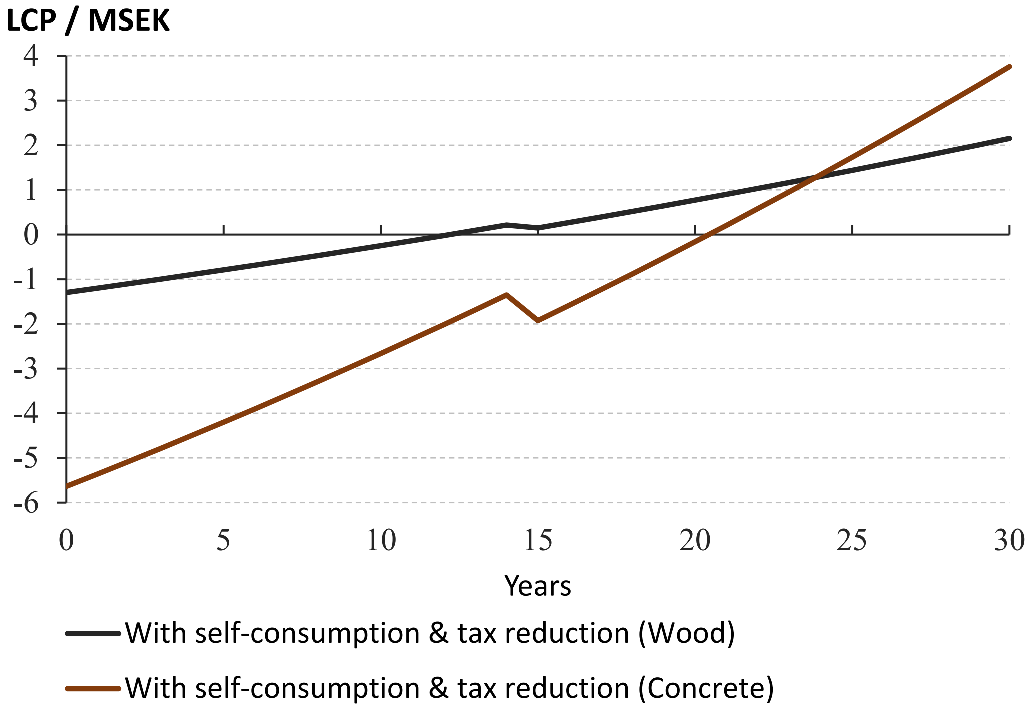

Figure 4.5 LCP with the PV system

With the combined savings from self-consumption and selling with tax reduction, Figure 4.5 shows that the base case (wooden construction) potentially could generate profit from year 13, whereas the concrete construction only obtains profit from year 21. For the wood load-bearing case, the PV system was only sized to provide the minimum required 10% of operational energy and not necessarily sized to achieve climate neutrality since that had already been achieved with biogenic carbon. On the contrary, the concrete case needed to account for the extra emissions and the reduction of sequestered carbon. Subsequently, the area required for renewable energy production was 381 m^2 in the case of the wooden loadbearing construction, which covers approximately 32% of the roof area, whereas, for the concrete, it was approximately 1901 m^2, indicating an insufficient area on the roof. The available roof area was 1087 m^2.

4.3 NollCO₂ certification

In addition to physical system boundaries (building elements included in LCA), heat pump installation (to fulfill energy requirements), and PV systems sizing, the total emission for NollCO₂ design was estimated to be 1813 tCO₂e/50y, an increase of 24% compared to White Architects' definition. It can be concluded that material emissions (A1-A3) account for almost three times more emissions than all other modules put together, see Figure 4.6. Emissions from module B6 no longer consist of DH, and the PV system significantly contributes to energy reduction.

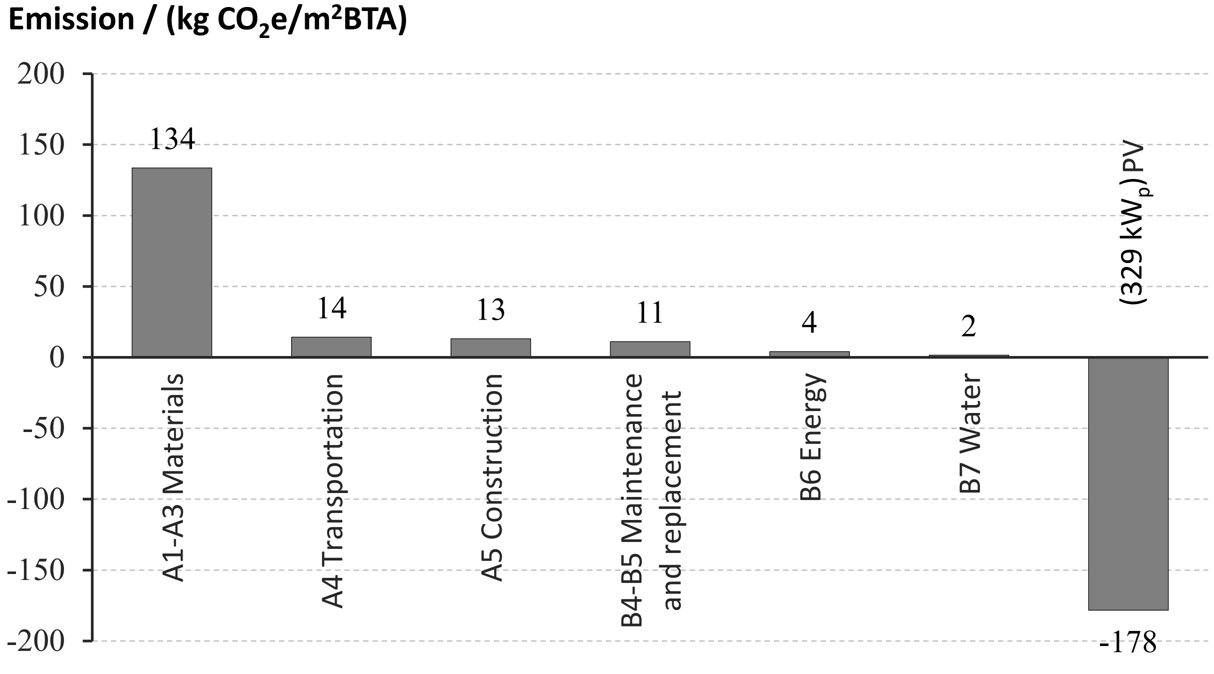

Figure 4.6 Life cycle module and PV system sizing for compensation

A closer examination of the A1-A3 module shows that the PV system has the same emissions as category BSAB 41 (*Appendix E*). The total emissions from PV system components were estimated to be 218 tCO₂e/50y and corresponded to 21 kgCO₂/m^{2}BTA, see Figure 4.7. Categories from BSAB 53 until BSAB 70, which included water supply, wastewater, fire extinguishing, hot water, air handling, telecommunication, and lift systems, indicated a relatively small impact compared with other categories assessed, and total emissions from these categories were 122 $tCO_2e/50y$ representing 12 $kgCO_2e/m^2$.

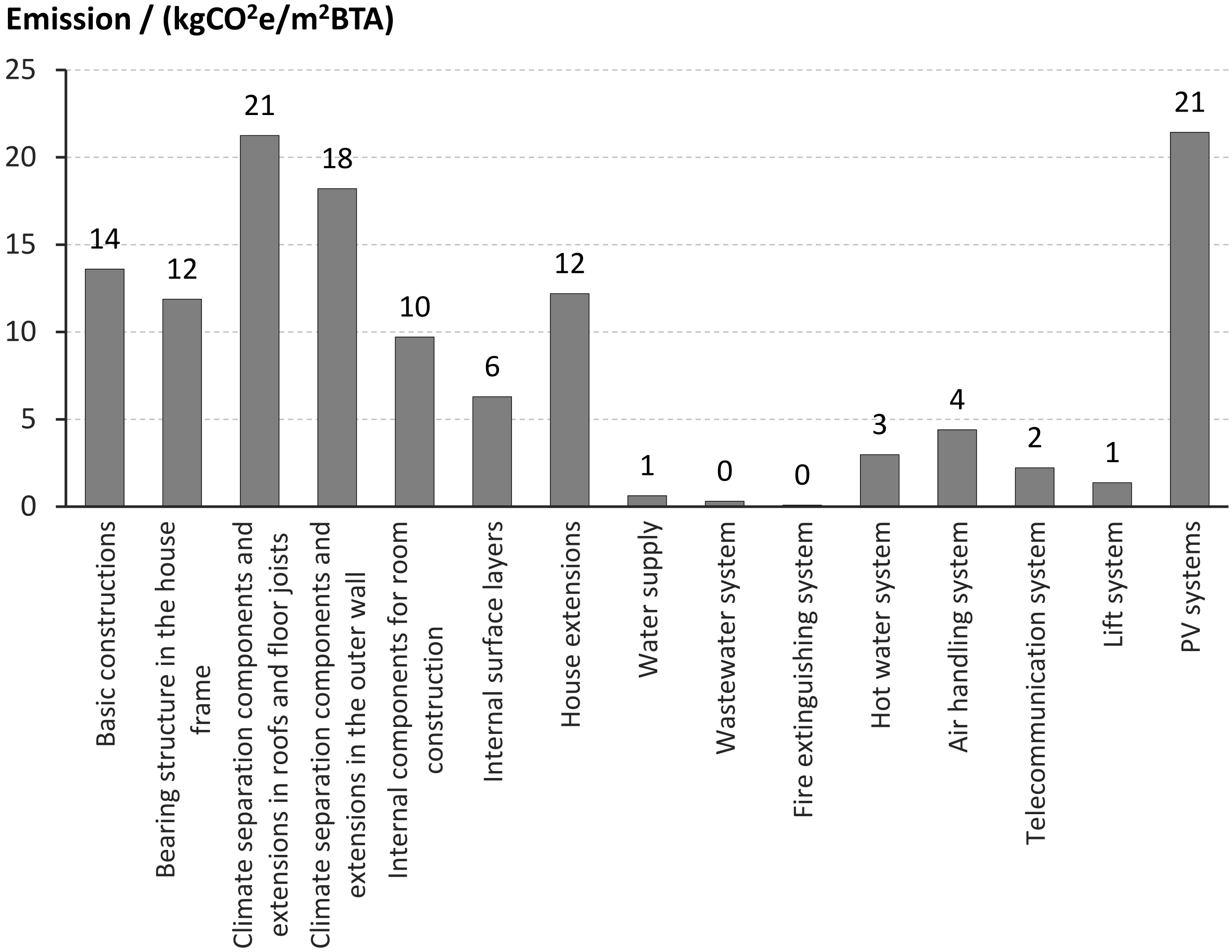

Figure 4.7 Emission from each building element

Total PV system cost analysis shows that with 2.35 MSEK savings, PV systems can be profitable at year 23 when considering the savings with self-consumption and tax reduction combined, see Figure 4.8. Meanwhile, the carbon credit purchases show relatively minor initial costs compared to the PV system. With yearly carbon credit purchases, the average initial price for carbon credits accounts only for 10 KSEK compared to the PV system with an initial investment of approximately 4.8 MSEK. Moreover, the cost difference between electricity purchased from the grid with and without a PV system is also seen in Figure 4.8. Without the PV system, the building needs to buy additional electricity from the grid, which corresponds to 128 KSEK more per year than it needed with the PV system sized for carbon neutrality. Hence, PV system savings are profitable over time, while carbon credit purchases add additional cost on top of this cost from additional electricity purchased from the grid.

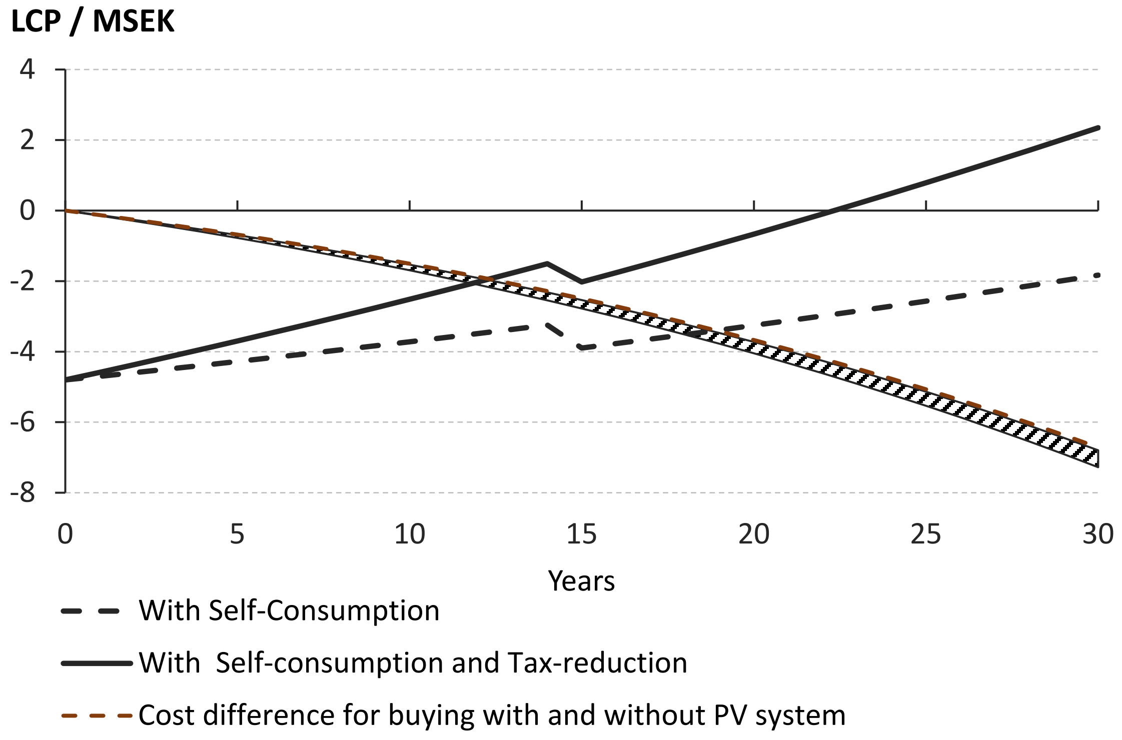

Figure 4.8 PV system LCP vs Carbon credit

The sensitivity analysis indicated in Table 4.2 shows how different emission factors affect the design's total emissions and the associated PV system sizing. For example, when emissions factors from the other two sources (One Click LCA & Nordic mix) are compared with the emission factor used by the NollCO₂ definition, it was seen that the total emission increase was 3% and 14%, respectively. However, the increase in PV systems was 3% and 7%, respectively.

Table 4.2 Different emission factors from various sources

Sources	Emission factor of electricity/ (gCO₂e/kWh)	Total Accumulated emission at Year 50/ (kgCO₂e/ m²)	Total emissions Increase	PV system size/kW$_p$	PV system Increase
NollCO₂	22	245	0%	329	0%
One Click LCA	52	254	3%	339	3%
Nordic mix	139	280	14%	366	7%

As seen in Figure 4.9 from the One Click LCA scenario, with the increased PV system, the selling to the grid has increased from the first scenario, whereas buying from the grid has decreased. A similar case was observed for the Nordic-mix scenario. The selling to the grid is calculated with a marginal emission factor of 820 gCO₂e/kWh starting in the year 2018. Both the emission factors considered for exporting and importing electricity follow a linear decrease to zero by the year 2050. But the consideration for emission factor when selling is significantly higher than any of the emission factors from buying electricity for these selected sources. Hence, the PV system for the Nordic Mix scenario needed less increase in PV sizing even if the total emission was increased comparatively more than the One Click LCA scenario.

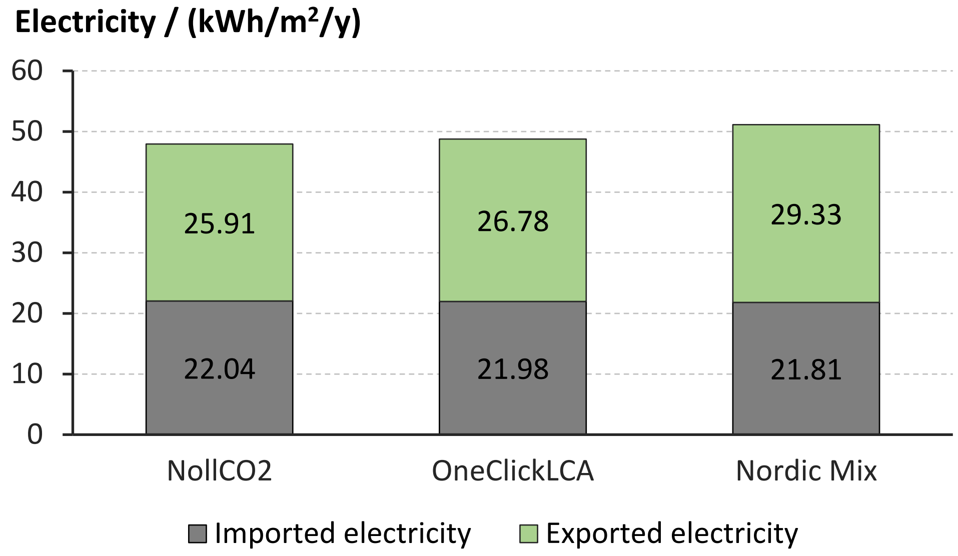

Figure 4.9 Exported and imported electricity amount annually for three different PV system

4.4 ZEB certification

The total emission from the ZEB-O/EQ ambition level corresponded to 527 tCO_2e, whereas ZEB-COMPLETE accounted for 4363 tCO_2e, which is more than eight times higher than the ZEB's lowest level. The result for the lowest ambition level represents emission from the total energy use in the B6 module, excluding any equipment or appliances used for the building. On the other hand, from the highest ambition level of ZEB, the B6 module considered all the energy use and resulted in an approximate amount of 1055 tCO_2e, which is twice the accumulated emission from the lowest ZEB level.

Figure 4.10 shows a comparison between average and marginal emission factors for design. ZEB definition considers average emission factors for electricity in their calculation, unlike the other two definitions, which consider marginal emission factors. Total CO_2 emissions for the ambition level ZEB-COMPLETE with marginal emission factor scenario were 4109 tCO_2e/60y and 4363 tCO_2e/60y with the average emission factor scenario. However, the required compensatory PV system size was almost two times larger for the average emission factor calculation than the marginal emission factor calculations. The PV system sizes corresponded to 1503 kW_p and 816 kW_p with a measured exported emission of -1179 $kgCO_2e/m^2$GFA and -613 $kgCO_2e/m^2$GFA, respectively. Also, differences can be seen in the modules A1-A3, where emissions changed from 260 $kgCO_2e/m^2$GFA to 225 $kgCO_2e/m^2$GFA due to PV system impact.

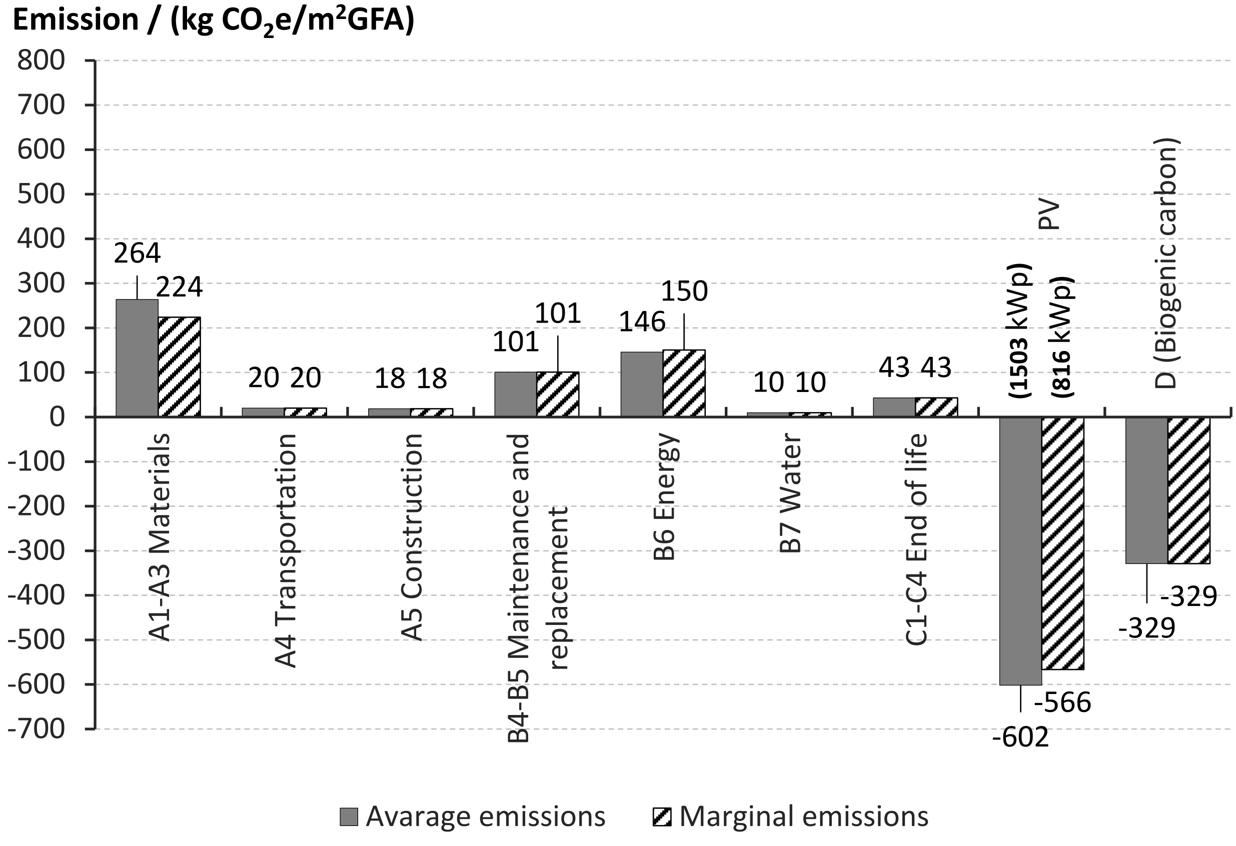

Figure 4.10 Life cycle stages with compensation measure

As the ZEB considers average emission factors in their definition, further analysis of individual building elements from module A1-A3 were shown accordingly and can be seen in Figure 4.11. The figure indicated that the PV system size had the most significant impact compared to the other building elements, similar to the result obtained from NollCO₂. This alone resulted in 601 tCO₂e emissions, which corresponds to 83 kgCO₂e/m^{2}GFA and is almost 17% of the total emission of the whole building. The second highest emission amounted to 348 tCO₂e from the 'Floor Structure', which corresponds to 48 kgCO₂e/m^{2}GFA from the building element under category 25.

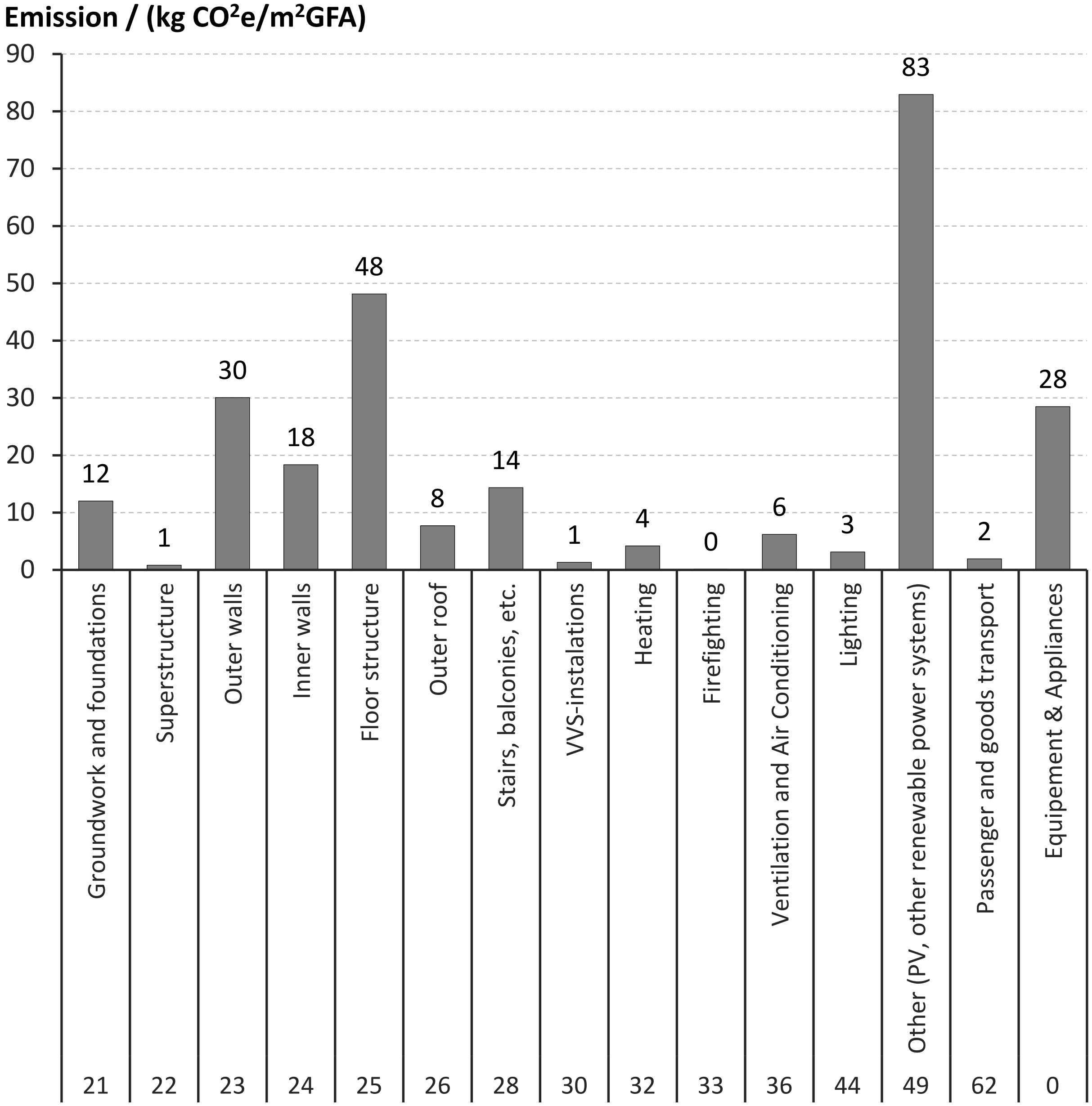

Figure 4.11 Emissions from building elements for A1-A3 stages for ZEB

Furthermore, Figure 4.12 indicated a comparative LCC analysis, which quantified the Life Cycle Profit (LCP) for the required PV systems from ZEB-O/EQ and ZEB-COMPLETE ambition levels. With the savings from self-consumption & selling with tax reduction, Figure 4.4.3 showed that the lowest ambition level could generate a profit from year 21, and the ZEB-COMPLETE level could barely generate a profit from year 30.

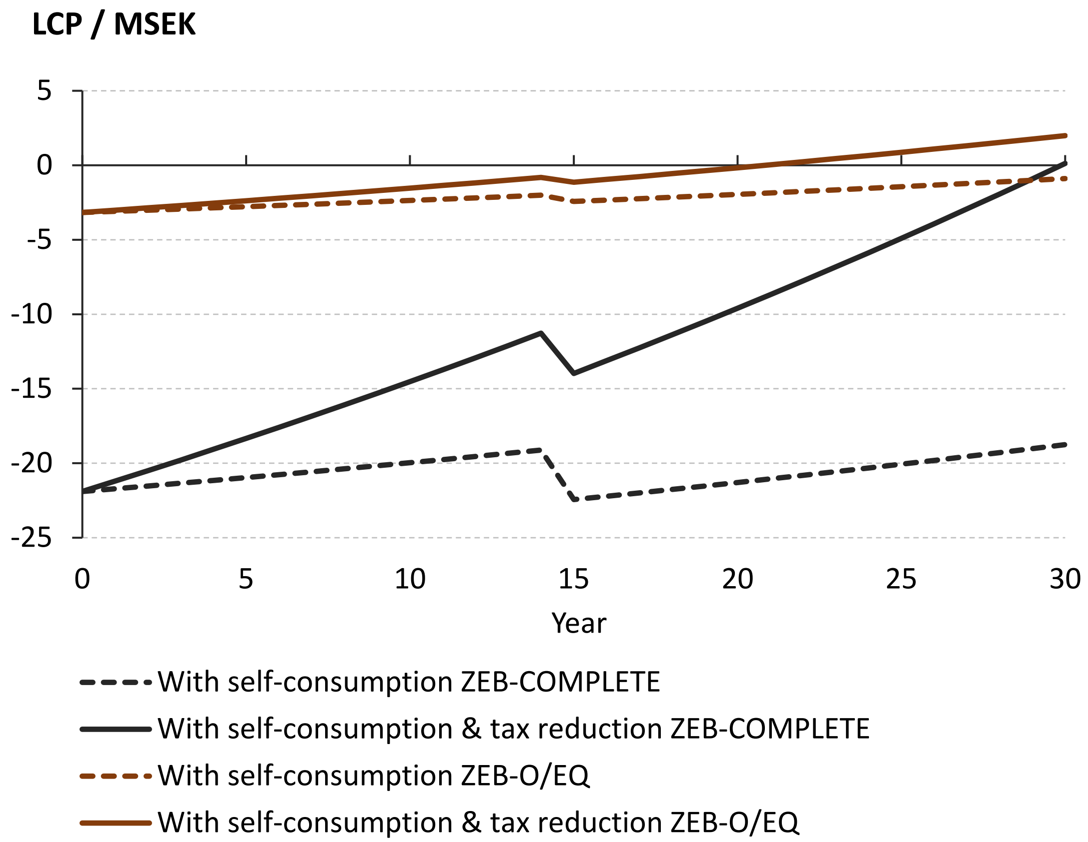

Figure 4.12 PV system LCP for the ZEB ambition levels

4.5 Comparison

Figure 4.13 shows accumulated CO_2e emissions for different definitions for their calculated lifetime. NollCO_2 definition starts as a positive value and gradually decreases to zero by 2050, after which there is no additional impact from the emission. Conversely, the White and ZEB definitions do not follow the same pattern. White Architect's definition starts as a negative value because of the biogenic carbon accounting in the A1-A3 module and goes upward, considering emission from operational energy adds climate impact over time. After 2050, there is no consideration for climate impact, therefore, no additional emissions or emission compensation are seen. The ambition level ZEB-O/EQ shows a straight line indicating that generated emissions are compensated annually. This curve starts from ‘zero’ as there is no other life cycle module consideration except the energy use in the B6 module, which means no embodied carbon emission is considered. And the emission generated from this energy use for year one must be offset with the energy production from the same year. On the other hand, the curve starts with a negative value for the ZEB-COMPLETE level due to its biogenic carbon consideration. Fluctuations related to replacement and refurbishment in module B4-B5 can be seen for the years: 2037, 2042, 2047, 2052, 2062, and 2067. The highest fluctuation is happening in 2052, which considers the replacement of inner walls, outer roof, ventilation, lighting firefighting system and PV systems, stairs, and balconies. A very sharp increase can be seen at the end of the life on account of the release of carbon stored in wood products in module C1-C4. For the NollCO₂ curve, similar fluctuations can be seen in 2032, 2037, 2042, and 2047 due to B4-B5.

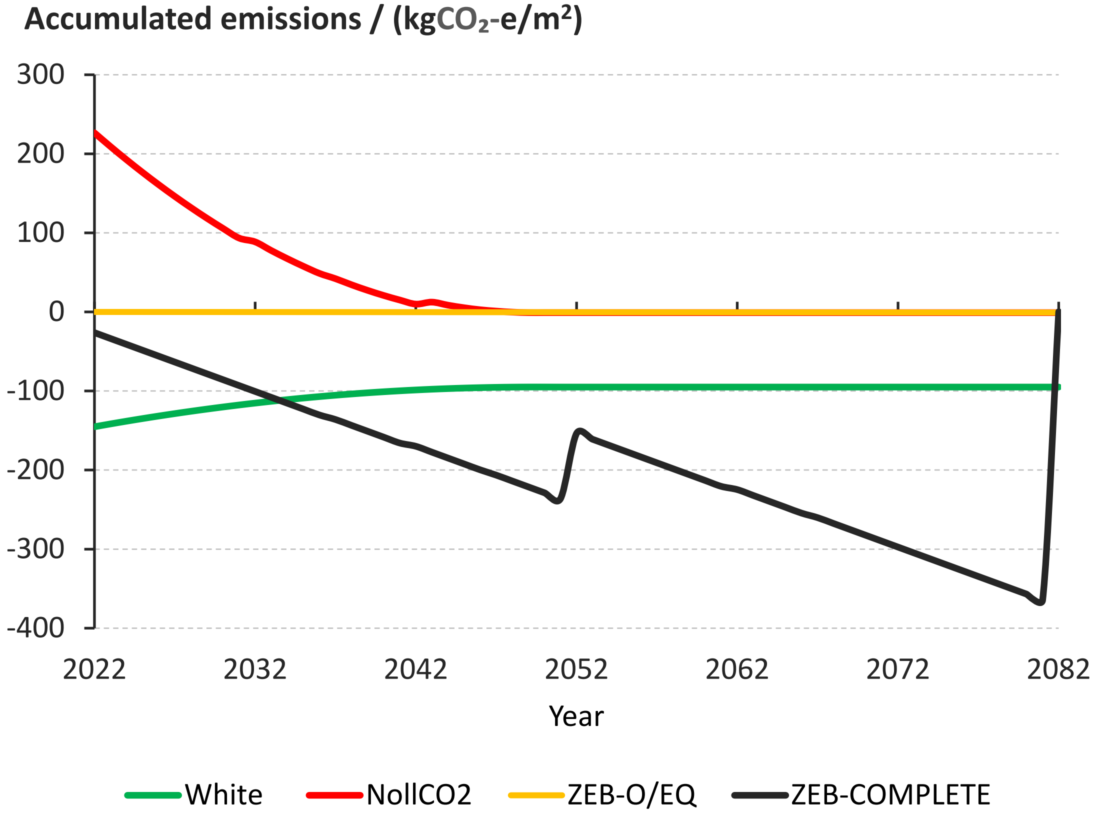

Figure 4.13 Emission over the life span of the building

When comparing total emissions according to each definition, seen in Figure 4.14, module A1-A3 accounted for the highest emissions (except ZEB-O/EQ, A1-A3 is absent). However, a key observation can be made in consideration of what percentage of total emissions does A1-A3 module comprises compared to the rest emissions in the definition. Modules A1-A3 were seen to vary primarily depending on physical system boundaries (how many building elements were included in LCA) and PV system size. Results show that this module accounted for 56%, 75%, and 44% of the total emission for the certification White, NollCO₂, and ZEB, respectively. ZEB had the highest emission in the A1-A3 modules compared to the other definitions. Also, significant differences between emissions generated in NollCO2 and ZEB designs can be seen.

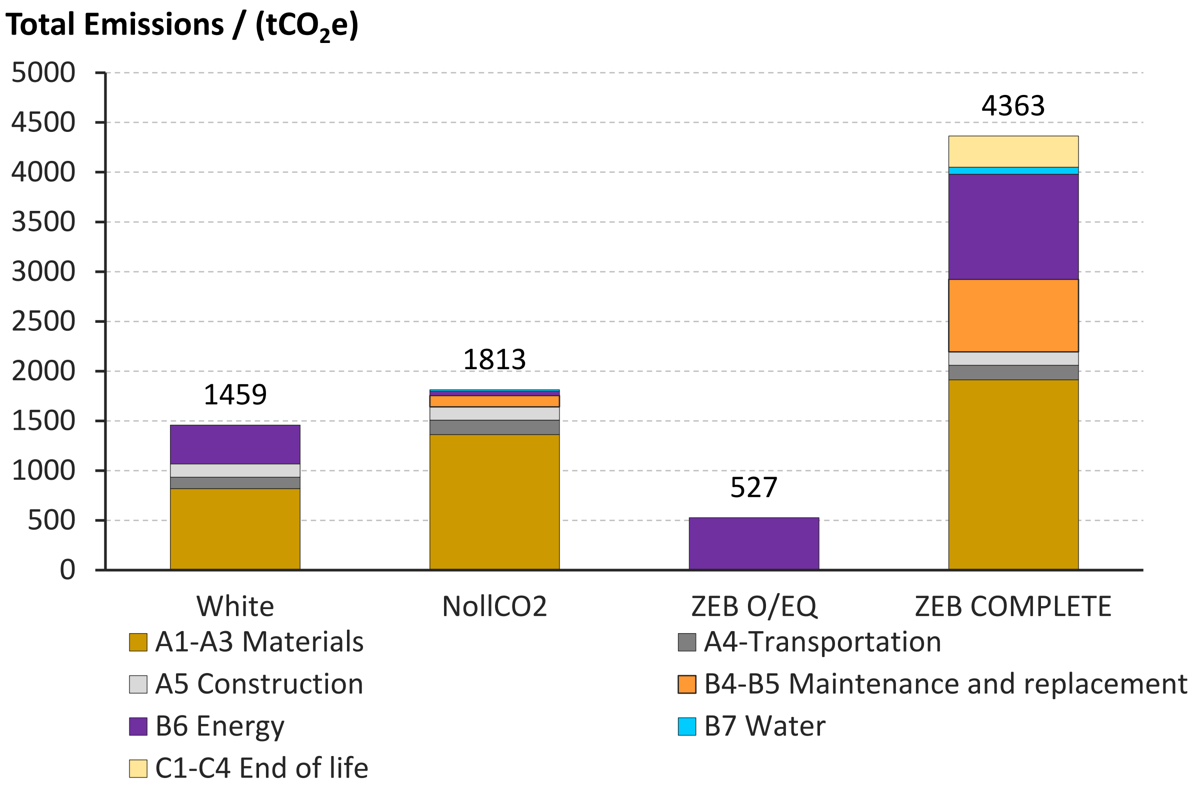

Figure 4.14 Comparison of accumulated emissions throughout the life cycle stages for each definition

Table 4.3 shows the PV system size required for each definition along with their corresponding area requirement. As 90% of the total roof area accounts for 1087 m², it was seen that only White Architects' definition and the lowest ambition level of ZEB could accommodate on-site renewable energy production. The requirement for PV system sizing for ZEB-COMPLETE was the highest, which is almost six times higher than the required PV system of NollCO₂. However, in terms of emission, ZEB-COMPLETE had a 2.4 times higher total emission compared to NollCO₂. Therefore, for these two definitions, PV productions could not be on-site anymore for this building and need to consider alternative methods that may be in terms of a combination of other off-site renewable energy productions. All the definitions showed a profit for their respective PV systems by the end of year 30.

Table 4.3 Comparison of PV systems

Parameters	**White**	**NollCO₂**	**ZEB-O/EQ**	**ZEB-COMPLETE**
PV system size / kW_p	76	329	217	1503
Required area / m² (Available roof area= 1208 m²)	382	1620	1068	7389
Accumulated profit at year 30/MSEK	2.15	2.35	1.99	0.12

5. Discussion

This section aims to discuss and analyze the results and answer the research questions posed in this study. The purpose of the study is to be illustrative of the comparison among different definitions rather than finding the optimal design for each case. Therefore, this study does not claim to be exhaustive, and other building design alternatives could have had a better impact on the results.

It can be said with high certainty that a building's choice of materials and design can significantly contribute to its total operational and embodied emissions. Two primary drivers for this occurrence are the choice of materials in the building design and emissions related to operation energy needs. To simplify LCA calculations, or for the lack of available data, some certifications chose to exclude LCA modules from their calculations, reasoning that the majority of impact arises from the assessment of their defined stages, which leads to differences in results and, in some cases, misleading results altogether.

5.1 White certification

Comparing two load-bearing structure designs indicated significant differences in total accumulated emissions. The concrete loadbearing construction required more renewable energy production since the building no longer accounted for sufficient sequestered carbon in the design to achieve carbon neutrality. The concrete load-bearing construction had higher total GHG emissions due to concrete's higher environmental impact as well as heavier transportation load. For this design, the PV system had to be increased in size almost five times compared to the initial PV system for the wooden load-bearing construction. Additionally, the LCC calculations indicated that wooden load-bearing building construction is cheaper than its concrete counterpart. It is worth noting that there was no consideration for the loadbearing capacities of building elements.

The most controversial aspect of the White Architects' carbon-neutral definition would be the process of accounting for biogenic carbon. It can show a misleading LCA assessment by excluding end-of-life treatment (C1-C4 stages) and not including GHG released back into the atmosphere at the end of buildings' service life. An argument can be made here that end-of-life treatment and GHG emission release depend on how these biogenic materials are disposed of at the end of their service life. Sweden's national climate goals indicate that all waste processing would have zero impact on the environment after the year 2050, and therefore this process should not add any additional emissions to the environment. However, further discussions on this definition showed that the White Architects' carbon-neutral definition is in its early adaption phase, and further changes could be made to account for this factor more precisely.

5.2 NollCO$_2$ certification

As stated by the NollCO$_2$ definition, the calculation process for A1-A3 stages for a PV system impact is based on their lifetime-energy yield. Therefore, the functional unit used for accounting emissions from PV systems is related to this system's energy production during its lifetime. However, this methodology seems inaccurate and raises some questions. For example, according to the calculation method, how the calculation should be made to account for suboptimal PV system designs and would suggest that if a PV system is facing North, for example, it would have less emissions from its production than if it is facing South. Perhaps a more suitable alternative would be to use a functional unit that is based on PV system size, such as $kgCO_2e/kW_p$.

Another unclear process was related to how accounting for climate compensation by exporting surplus electrical energy back to the grid is established. Here, a question arises if exported electrical energy is accounted to displace more emission-intensive coal energy production in the grid, then why energy that is self-consumed with PV systems is not accounted for in a similar manner? Both scenarios limit or reduce energy produced with coal within the energy grid, therefore, they should perhaps have the same effect on the balancing part in the system. Currently, in the $NollCO_2$ definition, self-consumed electricity does not account as a compensatory measure for emissions.

When looking into alternative climate compensatory measures, it was seen that carbon credit purchase accounts for a small fraction of the initial PV system cost. Although, unlike PV systems, purchased carbon credits do not have a payback period, one could question whether buying carbon credits would be the most economical and straightforward way of reaching carbon neutrality for a building. Although it also should consider the extra amount of energy required that needs to be purchased if no PV system is installed. Another issue could arise wherein if everyone starts purchasing carbon credits, what would it mean in terms of having the number of projects that can provide verified carbon units. Moreover, an argument could also be made that, in a scenario where this becomes the most adaptive compensatory measure, then whether the emphasis on climate or energy measures for a building reduces significantly. Conversely, the selected PV system size (329 kW_p) showed a payback period of 30 years with the assumptions, which include the benefit from selling overproduction. This is based on current data, and there is no guarantee that with increased PV system popularity, government subsidies for exported energy will be available at that time.

Additionally, the sensitivity analysis from difference emission factors of electricity showed that increased emission factors correlate with a more extensive PV system to counter the respective emissions.

5.3 ZEB certification

ZEB definition assessed multiple emission levels for carbon neutrality. The contrast in the climate compensation requirements to achieve climate neutrality through the lowest and the highest levels of ZEB exponentially increases in difficulty. One of the core elements in the ZEB definition was that climate neutrality is calculated based on a lifetime of the construction and does not indicate climate neutrality by the year 2050. Also, it was possible to consider all the life cycle modules for the ZEB definition, unlike the other definitions, therefore, potentially deriving a more complete approach to the LCA of a building. Another notable difference from other definitions was seen in the requirement of energy efficiency in building design regardless of the selection of ambition levels. Emissions from the A1-A3 module for the ZEB-COMPLETE ambition level were the highest when compared with the other definitions due to the more demanding inclusion of the building components like appliances and equipment, for example, fridge, oven, washing machine, dishwasher, and electric hobs. Moreover, the PV system installation itself had the most significant impact compared to other materials in this module which was similar to the other two definitions.

Additionally, PV system size itself needs to correlate to climate neutrality for this definition. Exporting surplus electricity back to the grid is a common principle that serves as a climate compensation measure for all three definitions. This process displaces electricity production within the grid, reducing emissions from the electricity that would have to be otherwise produced. As electricity in the grid consists of multiple emission sources, there are two ways to account for what emissions are displaced. One is the average emission factor which indicates average emissions in the electricity grid from all the considered power sources. For example, if 1 kWh of electricity consists of 20% hydro energy and 80% coal energy, the emission factor for this electricity source will correspond to 20% and 80% emission factor from hydro and coal-produced energy, respectively. On the other hand, the marginal emission factor states that when exporting energy back to the grid, not all the emissions in the grid are reduced, but only the most emission-intensive energy is displaced. Therefore, the additional energy displaces the power plants with the "dirtiest" production. As both processes give two different emission factors for compensation measures, two very different PV systems were required to achieve climate neutrality. Moreover, in contrast with the other two definitions, the ZEB definition specifies the average emission factor in their calculation for climate neutrality, which as a result, requires a significantly larger PV system when compared to the required PV system with a marginal emission factor. In addition, the ZEB definition also indicates that the emission factor for imported and exported energy is always the same, therefore, emission compensation has the same impact as purchased energy, contrary to the other two definitions. As a result, the required PV system was remarkably larger for the ZEB levels correlating their respective compensated emissions.

5.4 Combined analysis of all the certifications under this study

It can be pointed out that climate-neutral definitions are quite a recent topic, and more collaboration and research is required to achieve consensus and establish a unified framework that all participants can adapt, which is crucial in the subsequent development phases.

Except for the lowest ambition level of ZEB, all three certifications were in agreement that LCA A1-A5 modules should be included in calculations of a building's climate impact, based on the fact that these life cycle stages have a significant impact on the climate over the course of a building's lifespan. Furthermore, these modules comprise emissions that can be obtained readily and therefore can be confirmed, which is opposed to estimations of future emissions from operational energy, renovation, and waste management, which are assumptions made in an early design stage. Moreover, the certifications under assessment provided consensus on how to account for the emission generated from the operational energy. The contrast here was seen mainly in terms of what type of energy was being accounted for. For example, the White and ZEB definition accounts for all the operational energy, including household electricity, whereas the NollCO_2 definition accounts for energy use, excluding household electricity. In addition to this, the ZEB definition defines the system boundary to be the final delivered energy, however, the White and NollCO_2 definition does not explicitly define if the considered energy in the emission calculation should be primary energy or final delivered energy. On top of that, the standard followed by all the certifications for LCA calculation (EN:15978) does not define the type of energy that should be accounted for in the calculation. Another difference identified is the reporting of results and the use of functional units. Though the ZEB and White certifications use a heated floor area for reporting, in the NollCO_2 case, the functional unit is BTA (total floor area). Therefore, results might be manipulated to achieve limits set for certain stages. For example, more emission-intensive heated areas can be balanced with less emission-intensive outside areas to meet the limits set by definitions.

Because of the difference in system boundaries for building element consideration, energy requirement, and LCA modules by the definitions, the total accumulated climate impact shows an increase in emissions from base case (White) to NollCO$_2$ by 24% and to ZEB by almost 200%. This increased number of emissions required increased compensation measures. In addition to this, though the PV systems from all three certifications have a certain amount of impact in A1-A3, particularly for NollCO$_2$ and ZEB, it can be seen that emissions from the PV system outweigh other emissions in the A1-A3 module, unlike the White certification. This can be explained through how the White certification used biogenic carbon accounting and PV system sizing. The PV system size was only set to the minimum required 10% of the total operational energy and not sized to achieve climate neutrality since that was already obtained with biogenic carbon. Therefore, the PV system did not contribute to a large amount of emissions in A1-A3, as seen for the other two certifications. On the other hand, the ZEB definition also accounts for biogenic carbon, but it also reports the CO$_2$e release at the end-of-life treatment phase, which means the sequestered carbon balance is zero across the lifespan of the building. Therefore, the PV system has to account as a balancing measure for all emissions and is much bigger than the White definitions PV system.

5.5 Author's reflections

According to the three investigated definitions, the following points could be considered when certifying for carbon-neutral buildings.

Firstly, consideration of the biogenic carbon storage in the A1-A3 stages for the building material showed that without reporting, the release back in the C1-C4 stage result could be misguided. Under the current study, it can be perceived that a building evaluated with the White Architects definition would not only be carbon-neutral but would decrease emissions from the atmosphere. This might indicate that increasing building constructions with plenty of biogenic carbon storage material could somehow mitigate carbon from the environment. It can also imply that the increase in construction of buildings could contribute to achieving the goal of offsetting GHG, and in a scenario where no construction is being built, the carbon counting of the environment might be worse. Another issue related to this consideration could be how biogenic carbon is incorporated into the calculation method and whether or not it is considering the static or dynamic approach in relation to its assessment.

Secondly, as the White Architects' and NollCO$_2$ definitions consider a linear decrease of the emissions to zero by 2050, a few conflicting scenarios from this study seem to unfold. One of these would be the unclarity of what happens to the carbon compensation measures after 2050. For example, if emissions from embodied and operational energy are reduced to zero by 2050, does that mean that there would be no need for any compensatory offset measures, and in a scenario where there is a need for these measures, how would they be calculated after 2050?

The purchase of carbon credits is a relatively inexpensive and straightforward alternative for climate-neutral building status. The process of carbon credit purchase seems to divert responsibility from the building owner and constructor, as carbon credit purchases without any limit or threshold could potentially ignore the importance of climate measure considerations for a building. Perhaps it could be a suitable initiative to impose a percentage of renewable energy production on a building to compensate for the emissions. Nevertheless, this would require to have some justification to indicate how the percentage could be determined.

When assessing a carbon-neutral building, all the certification systems seem to follow a common LCA calculation standard (EN: 15978) to account for CO_2e emissions arising from the construction, however, there was no such unified method or joint agreement on what the carbon compensation measures should be, or how these measures should be calculated.

All certifications should address the unclarity and disagreement of energy type (primary energy or delivered energy), energy carriers, and energy quality (emissions) considered in the calculations. Among all three certifications, the ZEB definition provided the most clarity regarding points. Perhaps, it would make more sense if all the definition accounts for delivered energy and emissions involving any energy loss during transportation, regulation, transfer etc., could be compensated by the source of energy itself.

One more objective question from this study would be how the same building can account for different amounts of carbon emission at different points of a lifetime. According to Figure 4.13, it can be seen that the same case study building, at the same time, can be carbon negative and carbon positive according to the results from different definitions. So why is the same building accounting for different amounts of carbon emission at the same point in its lifetime? Perhaps this is a relatively insignificant question concerning the scale of climate neutrality for the building, but it indicates contradictions between the definitions themselves.

Also, the requirement of different statures of compensation measures from each definition could indicate the commercialization of carbon neutrality of a building. Carbon neutral building status can be achieved with just biogenic construction material or by spending a relatively small amount of money to buy carbon credits or spending a relatively high amount for renewable energy production. This leads to an issue as to what order should be considered for compensation measures in a definition. It might be ideal if one aims for the energy efficiency of the building at first. Afterward, emphasis could be put on renewable energy production on the building and locally after that. Carbon credit purchases can be left only as a final resort when the other compensation measures are insufficient.

Lastly, from this study, it could be said that the carbon neutrality of a building should perhaps not be a binary question. Having a different level of carbon neutrality similar to the ZEB ambition levels could be more logical. As described in each of the definitions under this study, the term carbon neutrality does not equate to the same amount of carbon emissions for all definitions. Therefore, a question arises: if two climate-neutral definitions are compared, and one of them only accounts, for instance, only 70% of physical system boundaries compared to the other one or one does not include LCA modules that the other includes, can both definitions claim to be equally climate-neutral?

6. Conclusion

This diploma work evaluated the impact of three definitions of carbon-neutral buildings on the building design of a case study. Results of this study indicated that there are established standard practices that are recognized by all three definitions. However, the definitions indicate contrasting final results for the same building due to the choice of different system boundaries and alternative methods on how to account for climate offset measures. One of the central parts of this study was to assess if a case-study building provided by White architects could be certified as climate neutral according to evaluated definitions.

The A1-A3 module represents very different results depending on which certification is used to assess the building. In addition, the total emission from the same building varied significantly depending on the scope of each certification. Total accumulated emissions, according to White Architect's definition, were 1459 tCO_2e, for NollCO_2, they were 1813 tCO_2e, and for ZEB-COMPLETE, 4363 tCO_2e.

The impact of the building design was different for each of the definitions. The White definition favors biogenic carbon storage and is carbon negative throughout the lifespan without requiring any renewable energy production. NollCO_2 and ZEB definitions required heat pump incorporation only to be qualified to be assessed for climate neutrality. While the NollCO_2 definition requires either a considerably oversized PV system or carbon credit purchases, the ZEB definition is very demanding on energy efficiency and requires on-site renewable energy to achieve carbon neutrality. All the certifications could not reach climate neutrality with only renewable energy production on-site except for the lowest ambition level of ZEB. Hence, evaluation of offsite renewable energy integration or alternative climate compensation measures would be required to achieve climate neutrality for the building.

Additionally, an essential concept for all the climate-neutral definitions associated with carbon emission compensations was PV system size. However, it contributes to the cost required to achieve this neutrality, concluding that there is a difference in cost associated with climate neutrality for all definitions. PV system size required to be certified as a climate-neutral building for White definitions was 76 kW_p, for NollCO_2 329 kWp, and for ZEB 1503 kWp. PV system sizes corresponded to the following area, 382 m^2, 1620 m^2, and 7389 m^2, respectively, with the available roof area on the building of 1087 m^2. NollCO_2 definition climate neutrality could also be achieved with carbon credit purchase.

In summary, although the geometry of the building was the same for all definitions, exactly the same design could not be certified as climate-neutral without incorporating energy measures like heat pump integration. Furthermore, after incorporating energy measures, the building only managed to reach carbon neutrality according to the White Architects, NollCO_2, and ZEB-O/EQ definition, but not ZEB-COMPLETE. It was evident that the different climate-neutral definitions can account for completely different system boundaries for building elements and LCA modules and can claim to be climate-neutral regardless of the contradiction in these considerations with each other.

7. References

Adams, M. , Collin, C. , Burrows, V. , le Den, X. , Richardson, S. , Riemann, L. , Drinkwater, J. , Porteron, S. , Gamboa, C. , & Qvist Secher, A. . ,. (2019). *Bringing embodied carbon upfront. Coordinated action for the building and construction sector to tackle embodied carbon*. www.worldgbc.org/embodied-carbon

Anand, C. K., & Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings: A critical review. In *Renewable and Sustainable Energy Reviews* (Vol. 67, pp. 408–416). Elsevier Ltd. https://doi.org/10.1016/j.rser.2016.09.058

Arehart, J. H., Hart, J., Pomponi, F., & D'Amico, B. (2021). Carbon sequestration and storage in the built environment. In *Sustainable Production and Consumption* (Vol. 27, pp. 1047–1063). Elsevier B.V. https://doi.org/10.1016/j.spc.2021.02.028

Boverket. (2018). *Climate declaration of building*.

Boverket. (2019). *Regulation on climate declarations for buildings proposal for a roadmap and limit values*.

Boverket. (2020). *Konsoliderad version av Boverkets byggregler (2011:6) – föreskrifter och allmänna råd*.

Brandão, M., Levasseur, A., Kirschbaum, M. U. F., Weidema, B. P., Cowie, A. L., Jørgensen, S. V., Hauschild, M. Z., Pennington, D. W., & Chomkhamsri, K. (2013). Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. *International Journal of Life Cycle Assessment*, *18*(1), 230–240. https://doi.org/10.1007/s11367-012-0451-6

Breton, C., Blanchet, P., Amor, B., Beauregard, R., & Chang, W. S. (2018). Assessing the climate change impacts of biogenic carbon in buildings: A critical review of two main dynamic approaches. In *Sustainability (Switzerland)* (Vol. 10, Issue 6). MDPI. https://doi.org/10.3390/su10062020

Callahan, W., James Fava, S. A., Wickwire, S., Sottong, J., Stanway, J., & Ballentine, M. (2011). *Product Life Cycle Accounting and Reporting Standard GHG Protocol Team*.

CFI Team. (2022). *Carbon Credit*. https://corporatefinanceinstitute.com/resources/knowledge/other/carbon-credit/

Corradi, O. (2019, June 13). *Marginal emissions: what they are, and when to use them*. https://electricitymap.org/blog/marginal-emissions-what-they-are-and-when-to-use-them/

de Wolf, C., Pomponi, F., & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings*, *140*, 68–80. https://doi.org/10.1016/j.enbuild.2017.01.075

Dokka, T. H., Sartori, I., Skanska, M. T., Lien, K., & Byskov Lindberg, K. (2013). *A Norwegian Zero Emission Building Definition*.

EN 16449. (2014). *Wood and wood-based products - Calculation of the biogenic carbon content of wood and conversion to carbon dioxide*. www.sis.se.

EPA, E. P. A. (2007). *Emissions Factor Uncertainty Assessment*.

EPA, E. P. Agency. ,. (2020). *Sources of Greenhouse Gas Emissions*.

Erb, K. H., Kastner, T., Plutzar, C., Bais, A. L. S., Carvalhais, N., Fetzel, T., Gingrich, S., Haberl, H., Lauk, C., Niedertscheider, M., Pongratz, J., Thurner, M., & Luyssaert, S. (2018). Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature*, *553*(7686), 73–76. https://doi.org/10.1038/nature25138

European Commission. (2019). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE*

EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS.

Ezcurra, E., Barrios, E., Ezcurra, P., Ezcurra, A., Vanderplank, S., Vidal, O., Villanueva-Almanza, L., & Aburto-Oropeza, O. (2019). A natural experiment reveals the impact of hydroelectric dams on the estuaries of tropical rivers. In *Sci. Adv* (Vol. 5). https://www.science.org

Fjeldheim, H., Kristjansdottir, T., & Sørnes, K. (2015). *Passivhus Norden | Sustainable Cities and Buildings Brings practitioners and researchers together ESTABLISHING THE LIFE CYCLE PRIMARY ENERGY BALANCE FOR POWERHOUSE KJØRBO*. www.7phn.org

Fouquet, M., Levasseur, A., Margni, M., Lebert, A., Lasvaux, S., Souyri, B., Buhé, C., & Woloszyn, M. (2015a). Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. *Building and Environment*, *90*, 51–59. https://doi.org/10.1016/j.buildenv.2015.03.022

Fouquet, M., Levasseur, A., Margni, M., Lebert, A., Lasvaux, S., Souyri, B., Buhé, C., & Woloszyn, M. (2015b). Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. *Building and Environment*, *90*, 51–59. https://doi.org/10.1016/j.buildenv.2015.03.022

Fufa, S. Mamo., Dahl Schlanbusch, Reidun., Sørnes, Kari., Inman, Marianne., Andresen, Inger., & Research Centre on Zero Emission Buildings. (2016). *A Norwegian ZEB definition guideline*.

Graabak, I., & Feilberg, N. (2011). *CO2 emissions in a different scenarios of electricity generation in Europe*.

Green Power Alliance, . (2010). *Establishing the Ground Rules for Property: Industry-wide Sustainability Metrics*.

Harris, Z. M., Milner, S., & Taylor, G. (2018). Biogenic Carbon-Capture and Sequestration. In *Greenhouse Gas Balances of Bioenergy Systems* (pp. 55–76). Elsevier Inc. https://doi.org/10.1016/B978-0-08-101036-5.00005-7

Hestnes, A. Grete. , & Eik-Nes, N. Lea. ,. (2017). *Zero Emission Buildings*. https://www.researchgate.net/publication/313056647_Zero_Emission_Buildings

Historic inflation Sweden. (2022). *Historic CPI inflation Sweden*.

Hoxha, E., Passer, A., Saade, M. R. M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., & Habert, G. (2020). Biogenic carbon in buildings: a critical overview of LCA methods. *Buildings and Cities*, *1*(1), 504–524. https://doi.org/10.5334/bc.46

Hwargård, L. (2020). *Swedish companies' current use of carbon offsetting-underlying ethical view and preparedness for post-2020 carbon market conditions*. www.geo.uu.se

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings - A review of current trends. In *Energy and Buildings* (Vol. 66, pp. 232–245). https://doi.org/10.1016/j.enbuild.2013.07.026

IEA. (2022). *Distribution of solar photovoltaic module production worldwide in 2020, by country*. IEA-PVPS - Trends in Photovoltaic Applications 2021, page 46

IEA, I. E. A. (2018). *2018 Global Status Report, Towards a zero-emission, efficient and resilient buildings and construction sector*. www.iea.org

IPCC, ., Schlömer, S., Bruckner, T., Fulton, L., Hertwich Austria, E., McKinnon, A. U., Perczyk, D., Roy, J., Schaeffer, R., Hänsel, G., de Jager, D., Bruckner, T., Fulton, L., Hertwich, E., McKinnon, A., Perczyk, D., Roy, J., Schaeffer, R., Sims, R., … Minx, J. (2014). *Technology-specific Cost and Performance Parameters*.

IPCC, W. G. I. (2022). *Climate Change 2022, Mitigation of Climate Change*. https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf.

ISO 14021. (2017). *Environmental labels and declarations – Self-declared environmental claims (Type II environmental labelling) (ISO 14021:2016)*. www.sis.se

ISO/TS 14067. (2013). *Greenhouse Gases — Carbon Footprint of Products — Requirementsand Guidelines for Quantification and Communication.* www.sis.se.Buytheentirestandardviahttps://www.sis.se/std-916234Webwww.iso.orgThispreviewisdownloadedfromwww.sis.se.Buytheentirestandardviahttps://www.sis.se/std-916234

IVL, S. E. R. I. (n.d.). *Independent advice for effective climate compensation*. Retrieved May 13, 2022, from https://www.ivl.se/english/ivl/our-offer/our-services/independent-advice-for-effective-climate-compensation.html

Karlsson, Emma. , Espert, Sara. , Österdahl, Å. Ekberg. , Glader, Karin. , Andersson, Kajsa. , & Wahlström, Åsa. ,. (2019). *Förstudie om Klimatkrav i Byggprocessen Erfarenheter från BeBo och Belok Version: 1.1*. www.belok.se

KRD. (2017). *Forskrift om tekniske krav til byggverk (Byggteknisk forskrift)*. https://lovdata.no/dokument/SFO/forskrift/2010-03-26-489

Kristjansdottir, F. Torhildur. , Selvig, Eivind. , Risholt, B., & Time, B. (2014). *A Norwegian ZEB-definition embodied emission*. https://www.researchgate.net/publication/266858163

Lehne, J., & Preston, F. (2018). *Making Concrete Change Innovation in Low-carbon Cement and Concrete*. www.chathamhouse.org

Lindahl, J. (2020). *National Survey Report of PV Power Applications in Sweden 2020 Task 1 Strategic PV Analysis and Outreach PVPS*. www.iea-pvps.org

Lindahl, J., Dahlberg Rosell, M., & Oller Westerberg, A. (2019). *National Survey Report of PV Power Applications in Sweden 2019 Task 1 Strategic PV Analysis and Outreach*. www.iea-pvps.org

Liu, H. Y. (2019). Building a dwelling that remains carbon-neutral over its lifetime – A case study in Kinmen. *Journal of Cleaner Production*, *208*, 522–529. https://doi.org/10.1016/j.jclepro.2018.10.101

Lützkendorf, T., & Frischknecht, R. (2020). (Net-) zero-emission buildings: a typology of terms and definitions. *Buildings and Cities*, *1*(1), 662–675. https://doi.org/10.5334/bc.66

Manders, T. N., Höffken, J. I., & van der Vleuten, E. B. A. (2016). Small-scale hydropower in the Netherlands: Problems and strategies of system builders. In *Renewable and Sustainable Energy Reviews* (Vol. 59, pp. 1493–1503). Elsevier Ltd. https://doi.org/10.1016/j.rser.2015.12.100

Meex, E., Hollberg, A., Knapen, E., Hildebrand, L., & Verbeeck, G. (2018). Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. *Building and Environment*, *133*, 228–236. https://doi.org/10.1016/j.buildenv.2018.02.016

Miller, S. A., & Moore, F. C. (2020). Climate and health damages from global concrete production. *Nature Climate Change*, *10*(5), 439–443. https://doi.org/10.1038/s41558-020-0733-0

Müller, A., Friedrich, L., Reichel, C., Herceg, S., Mittag, M., & Neuhaus, D. H. (2021). A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory. *Solar Energy Materials and Solar Cells*, *230*. https://doi.org/10.1016/j.solmat.2021.111277

Nibe. (2022). *Nibe*. https://www.nibe.eu/sv-se/produkter/produkter-for-storre-fastigheter/f1345

Nord Pool Group. (2018). *Nord Pool*. https://www.nordpoolgroup.com/en/

Pittau, F., Krause, F., Lumia, G., & Habert, G. (2018). Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. *Building and Environment*, *129*, 117–129. https://doi.org/10.1016/j.buildenv.2017.12.006

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. In *Energy and Buildings* (Vol. 42, Issue 10, pp. 1592–1600). Elsevier Ltd. https://doi.org/10.1016/j.enbuild.2010.05.007

REN21. (2021). *RENEWABLES 2021 GLOBAL STATUS REPORT*.

Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings*, *39*(3), 249–257. https://doi.org/10.1016/j.enbuild.2006.07.001

Sartori, I., Napolitano, A., & Voss, K. (2012). Net zero energy buildings: A consistent definition framework. *Energy and Buildings*, *48*, 220–232. https://doi.org/10.1016/j.enbuild.2012.01.032

Second Nature. (2022). *Offset Procurement Resources*. https://secondnature.org/climate-action-guidance/offset-procurement-resources/

SGBC. (2020a). *NollCO2 A NET ZERO CARBON FUTURE, Manual 1.0*.

SGBC. (2020b). *NollCO2, Nybyggnad-1.0-Ramverk*.

SGBC, S. G. B. Council. ,. (2021). *NollCO2 BASELINE OCH GRÄNSVÄRDEN JUNI 2021*.

Sharma, A., Saxena, A., Sethi, M., Shree, V., & Varun. (2011). Life cycle assessment of buildings: A review. In *Renewable and Sustainable Energy Reviews* (Vol. 15, Issue 1, pp. 871–875). https://doi.org/10.1016/j.rser.2010.09.008

Siler-Evans, K., Azevedo, I. L., & Morgan, M. G. (2012). Marginal emissions factors for the U.S. electricity system. *Environmental Science and Technology*, *46*(9), 4742–4748. https://doi.org/10.1021/es300145v

SSB. (2011). *Waste from building and construction.* https://www.ssb.no/statistikkbanken/SelectVarVal/saveselections.asp.

Statens Fastighetsverk. (2020). *Projekteringsanvisningar Livscykelkostnad*.

Sveby. (2014). *Sveby Standard for the Energy use in buildings*. www.swedishenergyagency.se

Swedish Tenant Association. (2022). *Gott om plats för ensamboende i villa*. https://hurvibor.se/hur-vi-bor/bostadsyta/

Taverna R, Hofer P, Werner, F. , Kaufmann, E. , & Thürig, E. (2007). *The CO2 effects of the Swiss forestry and timber industry. Scenarios of future potential for climate-change mitigation.*

UNEP, U. N. E. P. (2020). *2020 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION, Towards a zero-emissions, efficient and resilient buildings and construction sector*. http://www.un.org/Depts/

UNFCCC. (2015). *ADOPTION OF THE PARIS AGREEMENT*.

United Nations Environment Programme. (2020). *Emissions Gap Report*. United Nations. https://www.unep.org/emissions-gap-report-2020

VERRA. (n.d.). *Verified Carbon Units (VCUs)*. Retrieved May 13, 2022, from https://verra.org/project/vcs-program/verified-carbon-units-vcus/

What Next. (2020). *NOT ZERO: How "net zero" targets disguise climate inaction*. www.nickpurserdesign.com

White Arkitekter. (n.d.). *Carbon Neutral Buildings CREATING VALUE THROUGH ARCHITECTURE*.

Wiik, M. K., Fufa, S. M., Kristjansdottir, T., & Andresen, I. (2018). Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB research centre. *Energy and Buildings*, *165*, 25–34. https://doi.org/10.1016/j.enbuild.2018.01.025

Wikells Sektionsfakta. (2022). *Wikells*. https://wikells.se/

WMO. (2020). *State of the global climate 2020*.

ZEB. (2017). *ZEB Final Report 2009–2017*. www.zeb.no

Zheng, Z., Han, F., Li, F., & Zhu, J. (2016). Assessment of marginal emissions factor in power systems under ramp-rate constraints. *CSEE Journal of Power and Energy Systems*, *1*(4), 37–49. https://doi.org/10.17775/cseejpes.2015.00049

Ziegler, R. (2016). Climate Neutrality – Towards An Ethical Conception of Climate Neutrality. *Ethics, Policy and Environment*, *19*(3), 256–272. https://doi.org/10.1080/21550085.2016.1226241

Zuo, J., Read, B., Pullen, S., & Shi, Q. (2012). Achieving carbon neutrality in commercial building developments - Perceptions of the construction industry. *Habitat International*, *36*(2), 278–286. https://doi.org/10.1016/j.habitatint.2011.10.010

Appendix

Appendix A

Appendix Figure 1: Typical floor plan of the building (White Arkitekter, n.d.)

Appendix B

Appendix Table 1: The occupancy schedule with a household hourly electricity consumption profile

Hourly Profile (weekdays)		
Hours	**Occupancy schedule/ %**	**Electricity consumption profile/ kWh**
1	50	20.02
2	44	17.52
3	38	15.02
4	31	12.52
5	31	12.52
6	31	12.52
7	38	15.02
8	44	17.52
9	50	20.02
10	56	22.53
11	56	22.53
12	63	25.03
13	63	25.03
14	69	27.53
15	75	30.04
16	69	27.53
17	81	32.54
18	94	37.55
19	100	40.05
20	100	40.05
21	94	37.55
22	88	35.04
23	69	27.53
24	56	22.53

Appendix C

Appendix Table 2: Material properties for heat loss calculation

Constructions	Material	λ-value / (W/(m·K))	Thickness / m	ρ / (kg/m³)	Cp / (Wh/(kg·K))
Wall	Wood cladding	0.130	0.022	553	0.694
	Air Gap	0.667	0.028	1.280	0.278
	Mineral Wool	0.042	0.080	43	0.336
	Mineral Wo₂₂ol	0.042	0.170	43	0.336
	KL wood	0.100	0.120	905	0.694
	Gypsum	0.160	0.015	800	0.303
Roof	Membrane	0.160	0.010	1120	0.406
	Air Gap	0.667	0.180	1.280	0.278
	Insulation (Roof)	0.037	0.360	43	0.336
	KL. wood	0.100	0.145	905	0.694
	Gypsum	0.160	0.025	800	0.303
Ground	Concrete (Reinforced)	2.000	0.100	2400	0.260
	Insulation (Polystyrene)	0.047	0.150	115	0.314
	Gravel	1.950	0.300	2240	0.264

Appendix D

Control method for energy simulation

At first, a simple shoebox building of 5 m width, 10 m length, and 3 m height was modeled in Rhino and Excel, considering an exposed (floating) ground floor. From Rhino, the model was assessed through two different EnergyPlus scripts, using Climate Studio and Ladybug-Honeybee tools. The model's graphic was studied carefully where the considered surfaces, openings, roof, ceiling, floors etc., were visualized. Afterward, the control was carried out with seven different steps. For the initial steps, a customized weather file for Copenhagen, which considers the absence of the sun was used, and for the last step, a typical EnergyPlus Weather (epw) file was used. The reason behind the consideration of the ground floor as the exterior floor was the discrepancy between the initial results obtained for energy use intensity (EUI) from both excel calculation and the Rhino model. Where in Excel, to obtain the ground floor U-value, a steady ground soil conductivity $\boldsymbol{\lambda}$ is considered in the U-value ground calculation formula from Equation 4, which corresponds to SS-EN ISO 13370:2007 standard. But from the EnergyPlus script, the ground conductivity was seen to be considered dynamic, and only if Excel's ground soil conductivity was adjusted with a range from 0.05 to 25 W/m^2·K, only then similar results for the EUI parameter could be achieved with a lower marginal difference. To have better control of the model, a floating exterior ground was considered in the model. Initially, the Rhino model was set up as adiabatic to ensure no heat transfer from the indoor to the outdoor and vice versa.

For the first step, each model was kept in a "steady state" with a constant temperature difference between indoors and outdoors. The outdoor temperature was set to 0 °C, considering the absence of sun, whereas the indoor temperature was 20 °C. This step considered no internal loads, ventilation, or infiltration. Construction for the roof, wall, and the exterior floor was considered to have a U-value of 0.2 W/m^2·K with the following input used in Excel for the material layer 'insulation' and 'concrete'.

Appendix Table 3: Material properties of the construction

Material	**λ-value / (W/(m·K))**	**Thickness / (m)**	**ρ / (kg/m³)**	**mass / (kg)**	**Cp / (Wh/(kg·K))**	**R (1/U)**
Rse						0.04
Insulation	0.041	0.194	115	1924	0.314	4.73
concrete	2	0.200	2400	41400	0.264	0.10
Rsi						0.13

For the second step, infiltration was added to the excel calculation with a q 50 of 0.0003 $m^3/m^2/s$, where q 50 is the leakage at 50 Pa overpressure (SS-EN 13829). According to SS 24300-1, p 13-14, a K factor of 20 that represents natural and balanced ventilation. The q_leakage was calculated as q_50/K = 0,000015 $m^3/m^2/s$. The leakage result was then obtained 0.0029 m^3/s by multiplying the q_leakage value by the total surface area of the building, which was 190 m^2. In the climate studio, the input used was the converted value of the leakage of 0.0029 m_3/s to 0,684 ACH. In Honeybee, the typical building pressure is considered 4 pa by default, hence it was changed to a lower pressure of 0.5 pa, which resulted in a similar energy requirement as excel and climate studio.

For the third step, mechanical ventilation / intentional ventilation was introduced in the excel calculation and on the Rhino model. The q_{vent}, was set to meet the Swedish standard, 0.35 liter/s/m^2Atemp. The intentional ventilation loss result was 21 W/K. No heat recovery was considered at this step.

For step four, a heat recovery system with a temperature efficiency (η) of 75% was considered. The intentional ventilation loss was reduced to 5.3 W/K with the heat recovery.

For step five, a window with 25% glazing was added to the south façade, which accounted for 3.65 m^2 area both in excel calculation and from the Rhino model. A U-value of 1.21 W/m^2-k was used to calculate the transmission loss. In the CS from the window library, 'solarban 72' with a U- value of 1.21 was used. Here, the operable area ratio was set to 0 with a discharge coefficient of 0. Furthermore, the window frame consideration was enabled in order to have a lower marginal difference from the excel calculation (Step 5.1).

For step six, the internal loads were set to 3 W/m2. The power calculated from excel was 150 W, and the heat gain through internal load was calculated as Power /(time*1000), resulting in a total energy gain of 1314 kWh/year. In CS, the internal loads were set to 3 W/m2 in the 'loads' tab for equipment.

In the final step, irradiation was added. Hence, in the excel calculation, the Copenhagen's annual average temperature of 8 °C was considered. The effective indoor temperature was kept to be 17 °C, considering the heat gain from the loads. In the energy scripts, epw file for Copenhagen was assigned. Furthermore, the effective indoor temperature was lowered to 15 °C to have a lower marginal difference from the excel calculation (Step 7.1).

Appendix Table 4: Results from shoebox simulation for space heating demand

Step	EXCEL	CS	HB	Difference CS	Difference HB
	kWh/m^2/Y	kWh/m^2/Y	kWh/m$^{2/}$Y	kWh/m^2/Y	kWh/m^2/Y
Step 1	133	134.3	134.3	1.02%	1.03%
Step 2	145	147.3	147.4	1.60%	1.64%
Step 3	218.7	221.7	221.8	1.35%	1.40%
Step 4	163.5	165.9	165.9	1.48%	1.45%
Step 5	176.7	171.1	176.2	3.22%	0.26%
Step 5.1	176.7	172.2		2.61%	
Step 6	150.2	146.4	149.9	2.63%	0.19%
Step 7	79.5	53.7		48.04%	
Step 7.1	61.8	55.7	55.6	15.21%	15.41%

The comparison among the three sets of obtained energy use intensity showed very similar values, especially the energy script from Climate Studio is almost in line with the result obtained from the Ladybug-Honeybee script. The highest relative difference between the two was in the final step, which is understandable since this is where the EnergyPlus weather data came into play.

Instead of the shoebox model, the simulations were run on the main building model following the same steps, and a similar difference in result was observed. Later on, the input for the simulations were added in several different orders to check for any discrepancies. The input order that showed a discrepancy in the results is described below for the simulation run with the HB script:

The first step was to add all the input respective to the building under study. Subsequently, with the new assigned material for wall, roof, and ground according to the case study building material, the simulation showed a new result of 26 kWh/m^2/Y. Afterwards, when simulating with the new infiltration (0.058 l/m^2·s) and ventilation load (0.43 l/s·m^2) from the obtained building information, the simulation heating demand showed 87 kWh/m^2/Y. The internal heat gains like lighting load (2.3 W/m^2) and equipment load (4.5 W/m^2) were added in the simulation, which resulted in 37 kWh/m^2/Y. Lastly, when the heat recovery system was added to the simulation, the result showed a decrease to 4 kWh/m^2/Y. It was assumed that this "low" heating demand resulted due to the lack of a detailed HVAC system in the simulation script and the Ideal HVAC air load most likely dimensioned all the heating demand from the building with the assigned heat recovery in the simulation.

Appendix E

Appendix Table 5: Building elements that are included and excluded in the NollCO$_2$ calculations (SGBC, 2020a)

BSAB 15 Basic constructions	15.S/11/SB/SC/SE/SF/SG/SH/SJ/SK/SL/ST/SU Basic constructions for houses For example: foundations, piles, pile plinths, pile slabs, pillar sockets, foundation soles, foundation beams, foundation walls, pile decks, and production of crushed rock	15.SZ Other basic constructions for houses
BSAB 27 Bearing structure in the house frame	Above and below ground: 27.A Composite bearing structure in the house frame (can have two main functions at the same time), 27.B Frame interior walls 27.C Frame exterior walls 27.D Pillar frames 27.E Beam frames 27.F Frame floor 27.G Roof and outer joist frames 27.H Supplementary bearing structure in the house frame For example, Horizontal and vertical load-bearing parts, cast and prefabricated inner and outer frame walls, reinforcement, beams, columns, perforated decks, tensile steel, slit plates, press plates, high-profile plates, beam shoes, screws, bolts, and other fittings/forging required for steel and wooden frame strength	27.Z Other bearing structures in the house frame
BSAB 41 Climate separation components and extensions in roofs and floor joists	41.A Composite climate-separating components and extensions in roofs and floor joists (can have two main functions at the same time) 41.C Exterior climate screens in roofs and floor joists 41.D Indoor climate screens in roofs and floor joists 41.E Opening extensions in roofs and floor joists 41.F/FB/FC Exterior and interior drainage systems from roofs and floor joists For example, waterproofing moisture barrier, insulation, joists, fittings, and profiles	**41.FD/FE/FY** Extensions for roofs and floor joists **41.Z** Other climate-separating components and extensions in roofs and floor joists nails, screws, and staples
BSAB 42 Climate separation components and extensions in the outer wall	Above and below ground: 42.A Composite climate-separating components and extensions in the outer wall (can have two main functions at the same time) 42.B Exterior climate screens in outer wall 42.C Interior climate screens in outer wall 42.D Opening additions in outer wall 42.E Exterior wall additions For example, façade cladding, surface layers, fittings, joint materials, sealing strips, windows, doors, sections, and gates	**42.Z** Other climate-separating components and additions in the outer wall Nails, screws, and staples
BSAB 43 Internal components for room construction	Above and below ground: 43.B Complementary wall structures 43.C Interior walls (other than frame interior walls) and opening additions 43.D Floors and floor openings 43.E Ceilings For example, non-load-bearing walls, subfloors, interior doors and glass sections, interior and suspended ceilings, cast-in-place concrete, joists, fittings, profiles, insulation, putty,	**43.Z** Other components for room construction Nails, screws, and staples

	plasterboard, other board materials, acoustic boards, joint materials, frames, and suspended ceiling structures	
BSAB 44 Internal surface layers	Above and below ground: 44.B Surface layers on floors and stairs 44.C Surface layers on walls 44.D Surface layers on the ceiling For example, parquet, wooden floors, plastic carpets, fabric textile carpets, textile tiles, tiles, wallpaper, paint, waterproofing, glue, grout, and putty	**44.Z** Other inner surface layers Nails, screws, and staples.
BSAB 45 House extensions	Above and below ground: 45.BB Balconies 45.BC Walkways 45.BE Entrance stairs 45.CB Internal stairs, including stair material, stair cladding, fittings, and railings	**45.A** Composite house extensions **45.BD** Canopy **45.BF** Façade ladders **45.BG** Windshields **45.BH** Ramps **45.Z** Other house extensions
BSAB 49 Other components for room construction etc.	Above and below ground: 49.B Shaft in house Includes any additional fire discs	
BSAB 52 Water supply	Above and below ground: 52.B Tap water system	
BSAB 53 Wastewater system	Above and below ground: 53.B Sewerage system	**53.C** Waste collection and vacuuming system **53.D** Suction systems for industrial processes **53.E** Laundry system
BSAB 54 Fire extinguishing system	Above and below ground: 54.B Water extinguishing system > 54.B/1 Sprinkler system	**54.B/2** Water extinguishing System - water mist system **54.B/3** Fire hydrant systems and risers **54.C** Foam extinguishing system **54.D** Gas extinguishing system
BSAB 55 Cooling system	Above and below ground: 55.B Refrigerant system 55.C Cool media system 55.D Coolant system 55.E Heat transfer system 55.F Recycling system	
BSAB 56 Heating system	Above and below ground: 56.B Hot water system	**56.C** Steam heating system **56.D** Hot oil heating system
BSAB 57 Air handling system	Above and below ground: 57.B General ventilation system 57.C Process ventilation system 57.F Air heating system	**57.D** Fire gas control system
BSAB 6 Electricity and telecommunications systems	Above and below ground: 61/2 Sewerage system - electrical pipes, cable ladders, electrical ducts, cable culverts 63.B Electricity distribution networks 63.F/FE/FF/FH Lighting and illumination systems 63.H/1/21 Electric heating system	**61/1/3/4/5**, **63.F/FB/FC/FD/FG/FJ/FK/FL/FM**, **63.G** Light distribution system **63.H/22/3/4/HB/HG**, **64** Telecommunication system
BSAB 7 Transport system	Above and below ground: 71 Lift system 73 Escalator and roller ramp systems	**74** Crane system **75** Tube mail systems **76** System with machine-driven gate, gate, door, etc. **78** Other transport systems

Appendix F

Appendix Table 6: Building elements included for ZEB definition, based on (NS 3451: 2009), (Fufa et al., 2016)

Building parts	Building Components
2 Building Structure	
21 Groundwork and foundations	211 Clearing of land 212 Excavation 213 Ground Reinforcement 214 Support structures 215 Pile foundations 216 Direct foundations 217 Drainage 218 Equipment and completion 219 Other elements
22 Superstructure	221 Frames 222 Columns 223 Beams 224 Bracings 225 Fire protection of load bearing construction 226 Cladding and surfaces 228 Equipment and completion 229 Other
23 Outer walls	231 Load bearing wall 232 Non-load bearing wall 233 Glass Façade 234 Windows and doors 235 Outer cladding and surfaces 236 Internal surfaces 237 Solar shading 238 Equipment and completion 239 Other
24 Inner walls	241 Load bearing wall 242 Non-load bearing wall 243 System walls 244 Windows, doors, folding walls 245 Skirting 246 Cladding and surfaces 247 N/A 248 Equipment and completion 249 Other
25 Floor structure	251 Load bearing deck 252 Slab on ground 253 Raised/Built-up Floor, screed 254 Floor System 255 Floor Surfaces 256 Fixed Ceiling and Surface 257 Suspended Ceiling 258 Equipment and completion 259 Other
26 Outer roof	261 Primary construction 262 Roof covering 263 Glass Roof, Roof light, Roof Opening 265 Cornice, Flashings, Gutters and Downpipes

	266 Ceiling and Internal Surfaces 267 Prefabricated Roof Elements 268 Equipment and Completion 269 Other
28 Stairs, balconies, etc.	281 Internal Stairs 282 External Stairs 283 Ramps 284 Balconies and Verandas 285 Grandstands and Amphitheaters 286 Marquees and Canopies 287 Railings, Handrails, and Fenders 288 Equipment and Completion 289 Other
3 Heating, Ventilation, and Air Conditioning	
32 Heating	325 Equipment for heating installations e.g. heat pumps, heaters, domestic hot water tanks and exchangers and boilers which are not electrical (see 45). 329 Other heat installations e.g. Solar thermal collector system
36 Ventilation and Air Conditioning	362 Duct System for Air Conditioning 364 Equipment for Air Distribution 365 Equipment for Air Treatment 366 Insulation for Air Treatment 369 Other
4. Electric Power Supply	
44 Lighting	442 Light fixtures and fittings, cables, cable trays, plug sockets
45 Electric heating	452 Electric heaters to be installed in the floor, on walls or roofs 453 Underfloor heating 454 Electrical domestic hot water tanks and electrical boilers 459 Other electrical heating system equipment
49 Other	Photovoltaic system Other renewable power systems
6. Other installations	
61 Prefabricated unit	611-619 Prefabricated rooms/modules, excluding technical equipment and fixed inventory that is otherwise excluded from the minimum requirements in this table.
62 Passenger and goods transport	621 Lifts/elevator

Appendix G

Appendix Table 7: The expected service life of building elements for NollCO₂ certification (SGBC, 2020a)

Building elements, construction products, and building service systems	**Expected service life**
BSAB 15.S Basic constructions for houses BSAB 27 Bearing structure in house frame BSAB 49.B House shaft	60 years
BSAB 43 Internal components for room construction (non-load bearing) BSAB 45 House extensions (non-load-bearing stairs)	30 years
BSAB 41 Climate-separating components and extensions in roofs and floor joists BSAB 42 Climate-separation components and extensions in the outer wall (non-load bearing) BSAB 45 Exterior house additions (balconies, walkways)	30 years (35 years for glass façade elements, 10 years for outer paint layers)
BSAB 44 Internal surface layers	10 years
BSAB 46 Room extensions (permanently installed)	10 years
BSAB 52.B Tap water system	25 years
BSAB 53.B Wastewater system	25 years
BSAB 54.B Water extinguishing system	30 years
BSAB 55 Cooling system	15 years
BSAB 56.B Hot water system	20 years
BSAB 57 Air handling system (air handling unit/AHU)	20 years
BSAB 57 Air handling system (other)	30 years
BSAB 61 Sewer system	30 years
BSAB 63 Electric power system (except for BSAB 63. FF/FE/FG/FH)	30 years
BSAB 63 FF/FE/FG/FH Lighting and illumination systems	15 years
BSAB 64 Telecommunication system	15 years
BSAB 71 Lift system BSAB 73 Escalator system and roller ramp system	20 years

Appendix H

Appendix Table 8: Table of input data for the project

Material	Thickness	Area	Volume	Weight	EPD number	GWP	BSAB	NS 3451
	(m)	(m^2)	(m^3)	(kg)				
Foundation								
1. Concrete (footing)	0.55	0.055	19.8		NEPD-2707-1408-SE	234 kgCO$_2$e/m^3	15	216
2. Concrete (foundation)	0.35	0.7	252		NEPD-2707-1408-SE	234 kgCO$_2$e/m^3	15	216
3. Reinforcement				35334	S-P-02040	0.5 kgCO$_2$e/kg	15	216
4. Polyester insulation	0.1	720	72		MD-16005-EN	52 kgCO$_2$e/m^3	15	216
Ground Slab								
1. Parquet	0.02	1209	24.2		MD-19009-EN	387 kgCO$_2$e/m^3	44	255
2. Concrete	0.1	1209	120.9		NEPD-1296-419-SE	251 kgCO$_2$e/m^3	15	251
3. Reinforcement				15712	S-P-02040	0.5 kgCO$_2$e/kg	15	254
4. Polyester insulation	0.2	1209	241.7		EPD-IVH-20140140-IBB1-DE	52.5kgCO$_2$e/m^3	15	254
5. Gravel	0.2	1209	241.7			4 kgCO$_2$e/m^3	15	216
Floor Slab								
1. Parquet	0.02	6043	120.9		MD-19009-EN	387 kgCO$_2$e/m^3	44	255
2. Plywood x2	0.025	6043	151.1		NEPD-1579-604-EN	192 kgCO$_2$e/m^3	41	254
3. KL - wood	0.145	6043	876.2		NEPD-345-236-NO	45 kgCO$_2$e/m^3	27	254
4. Insulation	0.07	6043	423.0		NEPD00267E	71 kgCO$_2$e/m^3	41	254
4. Wood structure			22.2		S-P-01325	31 kg CO$_2$e/m^3	27	254
5. Insulation	0.22	6043	1329.5		NEPD00267E	71 kg CO$_2$e/m^3	41	254
5. Wood structure			69.8		S-P-01325	31 kg CO$_2$e/m^3	27	254
6. Installation layer (air)	0.028	6043	169.2			-	-	-
6. Wood structure			13.8		S-P-01325	31 kg CO$_2$e/m^3	27	254
7. Gypsum x2	0.025	6043	151.1		S-P-02001	124 kg CO$_2$e/m^3	41	256
8. Paint (x1)		6043		1462	RTS_156_21	1.3 kg CO$_2$e/kg	44	256
External Wall								
1. Tree facade	0.022	5113	112.5		NEPD-3303-1942-NO	166 kgCO$_2$e/m^3	42	235
2. Air layer	0.028	5113				-	-	-
2. Wood structure			11.7		S-P-01325	31 kgCO$_2$e/m^3	27	232
3. Insulation	0.08	5113	409.1		NEPD00267E	71 kgCO$_2$e/m^3	42	232
3. Wood structure			21.5		S-P-01325	31 kgCO$_2$e/m^3	27	232
4. Insulation	0.17	5113	869.3		NEPD00267E	71 kgCO$_2$e/m^3	42	232
4. Wood structure			45.6		S-P-01325	31 kgCO$_2$e/m^3	27	232
5. KL - wood	0.12	5113	613.6		NEPD-345-236-NO	45 kgCO$_2$e/m^3	27	231
6. Membrane	0.00015	5113	0.77		NEPD-341-230-NO	2.2 kg CO$_2$e/kg	42	239
7. Gypsum (x1)	0.015	5113	76.7		S-P-02001	124 kgCO$_2$e/m^3	42	236
8. Paint (x1)		5113		1237	RTS_156_21	1.3 kg CO$_2$e/kg	44	239

Material	**Thickness**	**Area**	**Volume**	**Weight**	**EPD number**	**GWP**		
	(m)	**(m^2)**	**(m^3)**	**(kg)**		**(kgCO$_2$e/m^3)**		
Columns								
1. Columns (concrete)		4.9	14.6		S-P-02985	408 kgCO$_2$e/m^3	27	222
Interior separating wall								
1. Gypsum (x2)	0.022	2512	55.3		S-P-02001	124 kgCO$_2$e/m^3	43	246
2. Kl-wood	0.12	2512	301.5		NEPD-345-236-NO	45 kgCO2e/m^3	27	241
3. Insulation	0.045	2512	113.1		NEPD00267E	71 kgCO$_2$e/m^3	43	242
3. Wood structure			29		S-P-01325	31 kgCO$_2$e/m^3	27	242
4. Wood structure			29		S-P-01325	31 kgCO$_2$e/m^3	27	242
4. Insulation	0.045	2512	113.1		NEPD00267E	71 kgCO$_2$e/m^3	43	242
5. Kl-wood	0.12	2512	301.5		NEPD-345-236-NO	45 kgCO2e/m^3	27	241
6. Gypsum (x2)	0.022	2512	55.3		S-P-02001	124 kgCO$_2$e/m^3	43	246
7. Paint (x2)		2512		1216	RTS_156_21	1.3 kg CO$_2$e/kg	44	249
Interior wall								
1. Gypsum (x1)	0.125	3581	44.8		S-P-02001	124 kgCO$_2$e/m^3	43	246
2. Wood structure		3581	20.7		S-P-01325	31 kgCO$_2$e/m^3	27	242
3. Insulation	0.11	3581	394		NEPD00267E	71 kgCO$_2$e/m^3	43	242
4. Gypsum (x1)	0.125	3581	44.8		S-P-02001	124 kgCO$_2$e/m^3	43	246
5. Paint (x2)		3581		1732	RTS_156_21	1.3 kg CO$_2$e/kg	44	249
Roof								
1. XEROFLOR MOSS-SEDUM	0.03	1726	51.8		INIES_ISUB20200921_ 161831, 26182	0.4 kgCO$_2$e/m^2	41	262
2. NOPHDRAIN 5+1	0.025	1726	43.2		INIES_ISUB20200921_ 090434, 23951	0.7 kgCO$_2$e/m^2	41	262
3. ICOPAL MONO	0.0069	1726	11.9		NEPD00269E	737 kgCO$_2$e/m^3	45	251
4. Unknown layer (air)	0.18	1726	310.8			-	-	-
5. Insulation	0.36	1726	621.5		NEPD-2227-1020-EN	38 kgCO$_2$e/m^3	41	261
6. Kl-wood	0.145	1726	250.3		NEPD-345-236-NO	45 kgCO2e/m^3	27	267
7. Membrane	0.00015	1726			NEPD-341-230-NO	2.2 kg CO$_2$e/kg	41	269
8. Gypsum (x2)	0.025	1726	43.2		S-P-02001	124 kgCO$_2$e/m^3	41	266
9. Paint (x1)		1726		417	RTS_156_21	1.3 kg CO$_2$e/kg	44	269
Hallway								
1. TRÄTRALL AV KISELBEHANDLAD FURU	0.028	1834				33 kgCO$_2$e/ m^3	45	251
2. REGEL	0.045		4.3		S-P-01325	31 kgCO$_2$e/m^3	45	251
3. TÄTSKIKT		1834			NEPD00268E	806 kgCO$_2$e/m^3	45	251
4. KL-wood	0.145	1834	266		NEPD-345-236-NO	45 kgCO$_2$e/m^3	45	251

Material	**Thickness**	**Area**	**Volume**	**Weight**	**EPD number**	**GWP**		
	(m)	**(m^2)**	**(m^3)**	**(kg)**		**(kgCO$_2$e/m^3)**		
Structures and materials								
1. External doors		281			External wood door - One Click LCA	82 kgCO$_2$e/kg	42	234
2. Windows		1254			S-P-01969. v.2020	1.3 kg CO$_2$e/kg	42	234
3. Internal doors		757			EPD-VHI-20130063-IBG1-DE	0.9 kgCO$_2$e/kg	43	244
Material	**Units**	**Area**	**Power**	**Weight**	**EPD number**	**GWP**		
	(pcs)	**(m2)**	**(kW)**	**(kg)**				
Building technology								
1. Ventilation system	-	7248	-	4600	-	6.2 kgCO$_2$e/m^2	57	36
2. Precast stairs	-	-	-	648000	-	0.16 kgCO$_2$e/kg	45	281
3. Heating system	-	7248	-	19932	-	2.8 kgCO$_2$e/m^2	56	32
4. Fresh water system	-	7248	-	1900	-	0.8 kgCO$_2$e/m^2	52	30
5. Wastewater system	-	7248	-	1300	-	0.4 kgCO$_2$e/m^2	53	30
6. Electrical systems	-	7248	-	16000	-	3.1 kgCO$_2$e/m^2	60	442
7. Elevators	2	-	-	5278	-	2.6 kgCO$_2$e/kg	70	621
8. Fire systems	200	-	-	-	-	4.5 kgCO$_2$e/unit	54	33
9. Heat pump			1	-		59 kgCO$_2$e/kW	56	32
10. PV systems	-	-	-	-	-	-	-	49
11. Appliances								
11.1 Fridge	132	-	-	15000	-	4.5 kgCO$_2$e/kg	-	-
11.2 El. hobs	132	-	-	11000	-	5.0 kgCO$_2$e/kg	-	-
11.3 El. Oven	132	-	-	3800	-	2.6 kgCO$_2$e/kg	-	-
11.4 Washing machine	132	-	-	8800	-	2.5 kgCO$_2$e/kg	-	-
11.5 Dishwasher	132	-	-	9300	-	6.5 kgCO$_2$e/kg	-	-

Appendix I

Appendix Table 9: Input for SAM simulations

Parameters	**White (Base Case)**	**White Concrete case**	**NollCO$_2$ Original case**	**One-Click LCA Scenario**	**Nordic Mix Scenario**	**ZEB-O/EQ**	**ZEB-COMPLETE (Average Emission Factor)**	**ZEB-COMPLETE (Marginal Emission Factor)**
Module Per String	8	11	12	11	12	11	48	36
Strings in Parallel	29	105	82	92	91	59	374	203
Number of modules	232	1155	984	1012	1092	649	4488	2484
Module Length/m	1.63	1.63	1.63	1.63	1.63	1.63	1.63	1.63
Module Width/m	1	1	1	1	1	1	1	1
Total Module area/m^2	378	1882	1604	1650	1780	1057	7315	4048
Ground Coverage Ratio	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Total area/m^2	382	1901	1620	1666	1798	1068	7389	4089
Total Land Area/Acre	0.1	0.5	0.4	0.4	0.4	0.60	1.80	1.00
Tilt/^{0}	0	0	0	0	0	0	0	0
Azimuth/ ^{0}	192	192	192	192	192	192	192	192
DC to AC ratio	1.92	1.38	1.6	1.6	1.7	1.21	1.72	1.63
Inverter Nos	2	10	7	7	7	5	7	15
Inverter Model	SunPower: SPR-20000m-3-H [480V]	Yaskawa Solectria Solar: PVI 28TL-480	Huawei Technologies Co - Ltd : SUN2000-30KTL-US	Huawei Technologies Co - Ltd : SUN2000-30KTL-US [480V]	Huawei Technologies Co - Ltd : SUN2000-30KTL-US [480V]	Huawei Technologies Co - Ltd : SUN2000-36KTL-US [480V]	INGETEAM POWER TECHNOLOGY S A : INGECON SUN 125 TL U 208 Outdoor [208V]	Huawei Technologies Co - Ltd : SUN2000-40KTL-US [480V]
Max MPPT DC voltage	800	800	800	800	800	850	750	720
Max AC power	20000	28000	30000	30000	30000	36000	125000	40000
Module Nominal efficiency	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
Capacity factor	8.5	8.7	8.7	8.7	8.7	8.7	8.5	8.8
Energy yield kWh/kW	745	765	766	764	762	762	744	769
Performance ratio	0.81	0.83	0.83	0.83	0.83	0.83	0.81	0.83

LUND UNIVERSITY

Divisions of Energy and Building Design, Building Physics and Building Services
Department of Building and Environmental Technology