Department of Built Environment

How green building certificates fulfill the environmental goals in the buildings' life cycle

Ali Amiri

Aalto University

DOCTORAL
DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 147/2021

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Ali Amiri

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall 213a (Konetekniikka 1) of the school on 11 November 2021 at 16.

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Aalto University publication series
DOCTORAL DISSERTATIONS 147/2021

ISBN 978-952-64-0562-9 (printed)
ISBN 978-952-64-0563-6 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-64-0563-6

Unigrafia Oy
Helsinki 2021

Finland

NORDIC SWAN ECOLABEL
Printed matter
4041-0619

Aalto University
Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

Author
Ali Amiri

Name of the doctoral dissertation
How green building certificates fulfill the environmental goals in the buildings' life cycle

Publisher School of Engineering

Unit Department of Built Environment

Series Aalto University publication series DOCTORAL DISSERTATIONS 147/2021

Field of research Engineering

Manuscript submitted 16 June 2021 **Date of the defence** 11 November 2021

Permission for public defence granted (date) 27 September 2021 **Language** English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

Abstract
While buildings are responsible for the consumption of nearly 40% of the total energy usage and a large amount of material, they are considered as one of the potential solutions for climate change mitigation. The emissions caused by energy and material use are produced during the life cycle of buildings including pre-use and use stages as the main ones followed by end of life (EoL) stage. The consideration of sustainability and the concern regarding limited natural resources has brought about in the preparation of green building certificates during the last three decades. Among different green building certificates, Building Research Establishment Environmental Assessment Method (BREEAM) is the most widely used while Leadership in Energy and Environmental Design (LEED) is most internationally adopted.

This dissertation is going to evaluate green building certificates regarding their fulfillment of reduction in energy and material use via LEED as a reference. Two main stages of pre-use and use are considered while the EoL stage is ignored because of its low contribution. The dissertation is based on four journal articles, and a mixture of qualitative and quantitative methods including literature review, case studies, and statistical data analysis has been used.

It was found that, in the use stage, green building certificates have fulfilled the goal of decreasing energy use and emission cut especially at higher levels of certificates but at lower levels the decline in energy consumption is questionable. Regarding the pre-use stage, green building certificates have poorly allocated the points to the materials that have lower environmental impacts like wood. The scenarios of different material selection confirm the lower environmental impacts of wooden buildings based on life-cycle assessment (LCA) as a sustainability evaluation method meaning that it is noteworthy to put more emphasis on material selection in green building certificates. Wooden buildings construction as a recommended solution not only yield fewer emissions during their production compared to concrete and steel ones but also have a significant potential of storing carbon.

The study shows that the future environmental plans and regulations by policymakers need continuous updates and modifications in order to find the best solution for climate change mitigation in different locations and times, this applies to green building certificates as well. While the body of research in green buildings has mainly focused on the use stage, there needs to be more attention on the pre-use stage. Besides the motivation for the production of future energy from renewable and clean sources, the embodied emissions which occur in a short time play a significant role in climate change mitigation.

Keywords Green building certificate, wooden building, LEED, BREEAM, sustainable construction

ISBN (printed) 978-952-64-0562-9 **ISBN (pdf)** 978-952-64-0563-6

ISSN (printed) 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2021

Pages 114 **urn** http://urn.fi/URN:ISBN:978-952-64-0563-6

Acknowledgements

My journey as a doctoral candidate at Aalto University started when I met my first supervisor, Jaana Sorvari, in her office. Her warm welcome gave me the confidence to pursue my goal. She also invited Juudit Ottelin, a postdoc researcher, to be my thesis advisor, which made my team one of the best to start a PhD while going through my first early article publication. The detailed and helpful advice from Jaana and constructive comments from Juudit allowed me to go forward smoothly.

My main career in academia started when I met my new supervisor, Seppo Junnila, after Jaana left Aalto and joined Finnish Environment Institute (SYKE). He and Juudit formed a great team. Seppo acted as the leader and made it possible for me to target higher goals. His original and up-to-date advice regarding the research made publication in leading journals possible. With his knowledge, he made me aware of what was occurring in academia and how I could succeed in my future plans. Thank you for your motivation and help, Seppo, Jaana and Juudit.

I also want to express my gratitude to my pre-examiners, Professor Melissa Bilec from the University of Pittsburgh and Professor Francesco Pittau from Politecnico di Milano, for their deep and insightful feedback on my dissertation. Special thanks go to Melissa, who agreed to act as the opponent.

Next, I want to thank my colleagues and co-authors. Thank you Jussi, Jani, Petri, Eerika, Annina, Antti, Ilmari and Vitalija. My time with you in Finland was wonderful. And thank you Jukka and Narges from the University of Iceland.

My gratitude goes to all organizations and their representatives that have financially or otherwise supported my work, including Aalto University, Carbon-SinkCity (310283), Co-Carbon (13336238) and the city of Helsinki. I also thank my research travel funders, including the Walter Ahlström Foundation via Tutkijat Maailmalle and the Foundation for Aalto University Science and Technology.

Finally, I thank my family, who gave me energy and motivation in addition to support. I also thank my friends and relatives.

Espoo, October 2021

Ali Amiri

Contents

List of Abbreviations and Symbols

BREEAM	Building Research Establishment Environmental Assessment Method
C	carbon
CO_2	carbon dioxide
Con	concrete
EoL	end of life
GHG	greenhouse gas
IO	input output
LEED	Leadership in Energy and Environmental Design
LCA	life-cycle assessment
LCEA	life-cycle energy assessment
MR	material and resources
OptCon	optimised concrete
USGBC	US Green Building Council
V	version

List of Publications

This doctoral dissertation consists of a summary and the following publications, which are referred to in the text by their numerals

1. Amiri, Ali; Ottelin, Juudit; Sorvari, Jaana. 2019. Are LEED-Certified Buildings Energy-Efficient in Practice? MDPI. Sustainability, volume 11, issue 6, article number 1672. https://doi.org/10.3390/su11061672.

2. Amiri, Ali; Ottelin, Juudit; Sorvari, Jaana; Junnila, Seppo. 2020. Economic and Technical Considerations in Pursuing Green Building Certification: A Case Study from Iran. MDPI. Sustainability, volume 12, issue 2, article number 719. https://doi.org/10.3390/su12020719.

3. Amiri, Ali; Emami, Nargessadat; Ottelin, Juudit; Sorvari, Jaana; Marteinsson, Bjorn; Heinonen, Jukka; Junnila, Seppo. 2021. Embodied Emissions of Buildings—A Forgotten Factor in Green Building Certificates. Elsevier, Energy and Buildings, volume 241, article number 110962. https://doi.org/10.1016/j.enbuild.2021.110962.

4. Amiri, Ali; Ottelin, Juudit; Sorvari, Jaana; Junnila, Seppo. 2020. Cities as Carbon Sinks—Classification of Wooden Buildings. IOP Science. Environmental Research Letters. volume 15, article number 9. https://doi.org/10.1088/1748-9326/aba134.

Author's Contribution

Publication 1: Are LEED-Certified Buildings Energy-efficient in Practice?

Amiri was the main author of this publication. As the primary author, Amiri initiated the study, performed the major proportion of the analysis, and wrote the main body of this paper. Sorvari supervised the study, contributed to the process of data collection, and provided advice on the research scope. Ottelin contributed to editing and structuring the paper and advising on data analysis.

Publication 2: Economic and Technical Considerations in Pursuing Green Building Certification: A Case Study from Iran

Amiri was the main author of this publication. He did the conceptualization, validation, and formal analysis of the study. He also prepared the original draft. Junnila did the supervision and structuring of the paper. Sorvari did the administration of the project and cooperated with Ottelin for the editing and reviewing of the manuscript.

Publication 3: Embodied Emissions of Buildings—A Forgotten Factor in Green Building Certificates

Amiri was the main author of this publication. He conducted the main analysis and prepared the list of building materials used in the case study that were used for the design of material replacement scenarios. He also conducted the assessment and the impact of material change on green building certificates. Emami conducted the life-cycle assessment study. Junnila and Heinonen supervised the project. Ottelin, Sorvari, Marteinsson, Heinonen, and Junnila contributed to the brainstorming, structuring, and editing of the paper.

Publication 4: Cities as Carbon Sinks—Classification of Wooden Buildings

Amiri was the main author of this publication. He conducted the literature review of the cases used for the classification of wooden buildings. He also designed the future scenarios for new building construction in Europe to be greener. Junnila supervised the study, contributed to the process of data collection and provided advice on the research scope. Ottelin and Sorvari contributed to editing and structuring the paper.

1. Introduction

During the last few decades, there has been an increase in the willingness to consider sustainability in the construction of buildings [1-4]. According to the last report by the Intergovernmental Panel on Climate Change (IPCC), it is challenging to restrict climate change to 1.5°C, as there has been no downturn in greenhouse gas (GHG) emissions globally [5]. In addition, the consumption of global material for building construction keeps increasing [6-11].

It is considered that buildings are one of the main consumers of energy and material [12-16]. For example, buildings in the UK and US use 42% and 45% of the entire energy consumption countrywide; the corresponding share is 31% in OECD countries [17]. In addition to the energy, different kinds of material are used for the purpose of building construction. Thus, it is important to establish rules and make plans to minimize the utilization of energy and material and the emission production by buildings [18-21].

Buildings consume energy and produce emissions during their life cycle, which includes two main stages of pre-use (construction) and use (operation), apart from the end of life (EoL) stage (Figure 1). Compared to the pre-use and use stages, the EoL stage is often excluded because of its low contribution in energy use and emissions production during the building's life cycle. In the pre-use stage, emissions result from material extraction, transport to manufacturing company, production, transport to the site for the purpose of construction, and construction; these are broadly termed as initial embodied emissions that require short-term mitigation. In addition, emissions during the use stage result from energy use for the purpose of space cooling and heating, refrigeration, hot water preparation, lighting, cooking, and equipment operation.

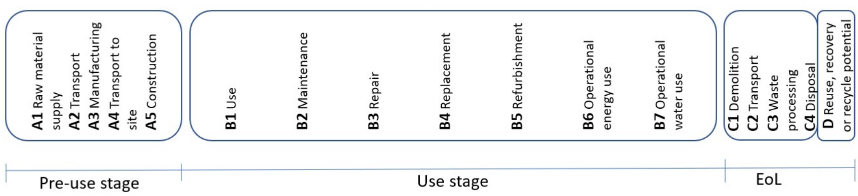


Figure 1. Life cycle stages of a building based on ISO 14040 and 14044.

The focus on buildings as a potential for emissions reduction both in pre-use and use stages has resulted in the creation of green buildings. However, in practice, the implication of green buildings might vary in different countries. For example, a building might be considered as green in a country if there is onsite energy production. In another location, using recycled material which results in lower environmental impact of a building might be considered as green construction. It is also possible to name a building green based on the amount of carbon emitted. For example, in Europe buildings are suggested to be zero-carbon building in order to call them green [22]. Habert et al. [22] defined a carbon limit for a new building and called it “carbon budget”. In their study they declared the importance of global chosen target and how this target is shared among the countries and people.

Globally, different definitions are used for green buildings. For example, Yudelson [23] describes a green building as “A high-performance property that considers and reduces its impact on the environment and human health.” Kibert [24] defines green buildings as “Healthy facilities designed and built in a resource-efficient manner, using ecologically based principles.” Therefore, it is necessary to have a clear and uniform definition for green buildings globally. This has resulted in the preparation of green building certificates during the last 25 years.

The first green building certificate system which is used most frequently is the British Building Research Establishment Environmental Assessment Method (BREEAM). The other one that is most internationally used is the American Leadership in the Energy and Environmental Design (LEED) created by the US Green Building Council (USGBC) in 1998. Currently, there are a large number of green building certificates and a few examples of these are the Green Star (Australia), the Green Standard for Energy & Environmental Design (G-SEED, Korea), and Comprehensive Assessment System for Built Environment Efficiency (CASBEE, Japan) [25]. Further, there are different voluntary standards of energy efficiency in buildings like Energy Star [26] or Passivhaus [27-29].

There are numerous economic benefits for buildings which are green certified. According to the literature, these benefits can be categorized into four types: 1) Lower maintenance costs that are the result of functional testing of all energy systems before use stage. 2) Lower costs at use stage on account of energy saving, for example, electricity. 3) Tax profits offered by local authorities or the government. 4) Increased value of buildings [30].

In addition, higher-quality places for living and working are considered as social benefits of green-certified buildings [31]. The maximum use of natural light in green buildings makes them more attractive than traditional buildings [19]. Further, in green buildings, reuse and recycle strategies are targeted instead of using new materials; such buildings also attempt to decrease the use of fossil fuels and replace them with renewable and low-emitting sources of energy [32,33].

In order to assess the reliability of green building certificates, there has been research on pre-use and use stages of buildings (see e.g. [34-44] or [45-47]). According to extant literature, there has been more focus on the use stage, while new studies using life cycle assessment (LCA) as a sustainability evaluation tool have been conducted to evaluate the environmental impacts in the pre-use stage.

Considering the use stage, the New Buildings Institute (NBI) conducted a study on the energy use of green buildings certified by LEED and confirmed 25%–30% less energy consumption by certified buildings compared to conventional ones [34,37]. Further, Newsham et al. [37] re-analysed the study by NBI and confirmed that green certified buildings consume 18%–39% less energy compared to traditional ones; however, almost one-third of certified buildings used more energy than conventional ones in practice.

On the other hand, Scofield [34] reduplicated the study conducted by Newsham et al. [37] and found the difference in energy consumption—that is, site energy—of certified and non-certified buildings as being half of that found by NBI. He divided the energy used by buildings as source energy (the energy considering the emissions from production to hand-in) and site energy (fuel or electricity consumed within a property). His results showed no difference in certified and non-certified buildings in terms of source energy consumption. In addition, Scofield and Doane [36] used the data of 1521 commercial buildings offered by USGBC and focused on 132 certified ones. They found no difference in the use of source energy between certified and non-certified buildings, while the use of site energy use was slightly lower.

With regard to the pre-use stage, Suh et al. [45] conducted an LCA study of green certified buildings for their life cycle stages in which the focus was the pre-use stage. They compared the adverse environmental impacts of green certified buildings with traditional ones. The inputs were energy, material, service, and water while the outputs were greenhouse gas (GHG) emissions and toxic pollutant emissions. The study revealed lower production of emissions in certified buildings.

Further, Hu et al. [46] conducted an LCA study apart from the life cycle energy assessment (LCEA) on school buildings in order to assess the reliability of green building certificates in practice. They aimed to ascertain if the green certified buildings have lower environmental impacts. Moreover, Lessard et al. [47] used LCA and focused on two categories of the LEED system, one of them being material and resources (MR). They designed six scenarios of different LEED levels with dissimilar material selection and compared the environmental impacts of scenarios with the base case building.

In addition, there are other studies which have used LCA as an evaluation tool for the comparison of low-carbon materials like wood with other ones such as concrete, steel, or masonry. It is necessary to mention that they have not included the assessment of green building certificates in their study. For example, Pierbon et al. [48] compared two wooden scenarios for an office building with a concrete one. They found the GHG emissions for the concrete scenario to be 450 kg m^{-2}, while the amount was 328 kg m^{-2} and 334 kg m^{-2} for wooden scenarios. Takano et al. [49] performed an LCA comparison of six case buildings of timber, cross-laminated timber (CLT), brick, steel, and two buildings of concrete. The timber building had the lowest GHG emissions, while the highest one was the brick building, followed by concrete ones. Most studies in the literature have introduced wooden buildings as buildings that have lower emissions during their pre-use stage [50-56].

1.1 Research aim

A large number of studies have been conducted for the use stage of green certified buildings over the last decade and this is a trend that is being continued. These studies have been focused on the efficiency of green buildings in terms of energy and emission reduction. The findings have been inconclusive, as certain studies concluded lower energy consumption by certified buildings while certain others concluded no difference between green certified and traditional ones or even more energy use by certified ones. It is not clear why the results and conclusions by different researchers differ from each other.

With regard to the pre-use stage, it must be noted that there is limited research that has been conducted recently. Most researchers have used LCA as a sustainability tool, with a focus on material use in the building construction. It is worthwhile to conduct more research on the pre-use stage, as the emissions in this stage occur dramatically faster compared to those in the use stage. Short-term reactions are required for the issue of climate change in the current period.

In addition, the future energy sources are continuously changing and there might be more renewable sources which affect the ratio of emissions in the use and pre-use stages. This implies that the advantages of low-energy buildings might become inflated over time and this makes the pre-use stage even more important. There has been an increase in renewable energy sources in Europe from 8.5% to 17.55% from 2004 to 2017 and these are expected to increase to 32% by the year 2030 [57,58]. The short time release of emissions in the pre-use stage requires a quick reaction. The short-term target of CO2 reduction by the Intergovernmental Panel on Climate Change requires investigation in the pre-use stage of buildings [59-62]. There is a need for research on how green building certificates fulfil these requirements in order to attain this goal.

Moreover, there have been updates and changes to the green building certificates that affect the future certification of buildings, which is not possible to judge based on past research; thus, a detailed evaluation of the certificates is necessary. In addition, there are only a few studies that have evaluated the impact of low-carbon materials like wood on green building certificates. There might be an additional cost for the construction of green certified buildings and, thus, the assessment of these certificates has advantages for greener building constructions worldwide.

Therefore, this study utilizes extant literature and case study buildings to provide a thorough evaluation of green building certificates in both the pre-use and use stages and answer the following main question:

How do green buildings perform in lowering energy use and emissions production in the pre-use and use stages?

As there has been sufficient research on energy efficiency and emission production of green buildings during the use stage, the part of the question regarding use stage assessment is answered by the literature review. On the other hand, the part regarding the pre-use stage is analysed in detail using case studies, LCA, and global level estimations. In addition, we conduct an impact assessment of low-carbon material, like wood, on climate change in its possible use in future European building construction. A few feasible scenarios are designed for future new buildings in Europe which use low-carbon materials like wood. This is useful for both policymakers and building certification developers for the purpose of climate change mitigation, short-term reaction, and green certification development.

1.2 The research structure and role of papers

This dissertation is built upon four articles, all of which have been peer-reviewed and published in academic journals. The compilation part of the dissertation links all four articles together and discusses its contribution, demonstrating how the individual papers contribute to the research question of the dissertation and their mutual conclusion.

The compilation is divided into four parts: chapter one describes the motivation, aim, and research question of the dissertation. Chapter two details the research methods, data collection techniques, and the overall analytical process of the dissertation. Chapter three summarizes the key contents of each paper in order to highlight their contribution to the dissertation. The compilation ends with a discussion and conclusions chapter.

The thesis consists of the journal papers and the compilation. Each of the papers contributes to answering the research question of the thesis. Paper 1 is a literature review and evaluates the energy efficiency of green-certified buildings. It evaluates if LEED as a green building certificate has been successful in decreasing energy use and emissions production during use stage. Paper 2 is an original research paper that details the LEED regarding points allocation using a case study. It discovers how LEED points can be obtained with technical changes while introducing the least costly options. Paper 3 is a thorough assessment of green building certificates—that is, LEED and BREEAM—for the allocation of points to embodied emissions in the pre-use phase. It employs a case study in which different combinations of material selection with special interest on wood have been evaluated using LCA. Finally, paper 4 finds out the Europe level impact on climate change if wood as a low-emitting building construction material (found in paper 3), possessing the carbon storage potential, will be used in new building construction for a period of 20 years. Table 1 presents the purpose of each paper.

Table 1. Aim of papers.

Research question: How green buildings perform in mitigating climate change in pre-use and use stages?				
	Paper 1	**Paper 2**	**Paper 3**	**Paper 4**
Title	*Are LEED-Certified Buildings Energy-Efficient in Practice?*	*Economic and Technical Considerations in Pursuing Green Building Certification: A Case Study from Iran*	*Embodied Emissions of Buildings—A Forgotten Factor in Green Building Certificates*	*Cities as Carbon sinks—Classification of Wooden Buildings*

Perspectives (Aim)	Evaluating if green certified buildings are reducing energy use and emissions cut in the use stage	Detailed evaluation of the criteria for green building certificates for giving points and certifying the building with focus on both use and pre-use stages	Assessment on how green certificates consider pre-use stage (i.e., materials and construction) emissions reduction	An estimation of big-scale change in pre-use stage material transformation into low-carbon material, that is, wood

2. Methodology

This chapter presents the design and the methodology of dissertation. The study assesses the efficiency of green buildings in terms of emission reduction in terms of two main stages—the use and pre-use stages. The study is based on four journal articles. While one of the papers, paper 2, includes both use and pre-use assessment, paper 1 focuses on the use stage through a literature review. The other papers—that is, papers 3 and 4—present a detailed description of the pre-use stage using case study, life cycle assessment (LCA), and numerical analysis. In the following sections, the research design has been presented with some general information regarding the methods used for each paper. Then the methodology for each article is explained in detail.

2.1 Research design

Generally, there are two main methodological choices—that is, qualitative and quantitative—while the third option is combining these two as mixed methods. The qualitative method consists of observations, interviews, qualitative documents, or audio and visual materials; the quantitative method is an approach of testing theories by studying the relationship among variables [63,64]. Although the processes for both qualitative and quantitative methods are the same, qualitative methods mainly rely on image data and text, while quantitative methods have unique steps in data analysis [65].

In order to answer the research question for this dissertation, a mixed of method strategy has been employed. A strong mixed method must include a qualitative question, quantitative question, or hypothesis and attempt to benefit from both in order to conduct the research [63]. In addition, a review of literature is necessary, as it provides information on what has been done by other researchers and provides insight into means to narrow or widen the scope of research.

In addition to paper 2, the use stage evaluation was assessed in paper 1 using previous studies in addition to paper 2 (Figure 2). In order to answer the questions regarding the pre-use stage, original research was conducted. For papers 2 and 3, case studies were used, while paper 4 was based on multiple case buildings and used numerical scenario analysis for a global evaluation. Next, the methods of each paper are described in detail in sections 2.1–2.4.

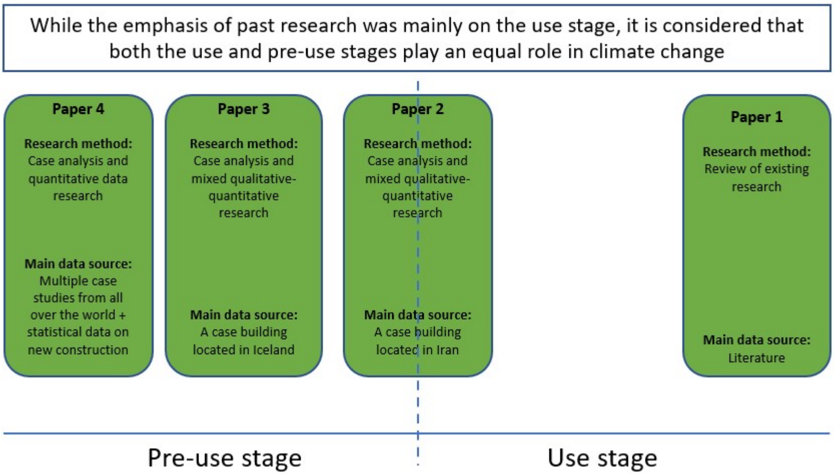


Figure 2. Life cycle stages of a building.

2.1 Use stage evaluation in extant literature

Paper 1. Are LEED-Certified Buildings Energy-efficient in Practice?
Paper 1 is a literature review focused on the use stage. Generally, a review article is a constructive and critical analysis of the literature through classification, analysis, summary, or comparison. The goal of a review paper is the organization or evaluation of literature, identify trends or patterns, synthesizing literature, identifying research gaps, providing recommendations for future research, and searching for answers for a specific question [66]. The aim of the review here was to find the answer to the question of whether green buildings use lesser energy in the use stage than other buildings, thereby resulting in lower GHG emissions.

For this review paper, a search for the resources was planned to answer the question of whether green-certified buildings are practically energy efficient in the use stage. The search was conducted in the year 2019 among scientific journal papers and Web of Science was selected as the search engine. As the LEED certificate is used for this purpose (among all green building certificates), the words 'LEED' and 'Energy' were searched for in the first stage, yielding 160 hits. Next, letters, conference proceedings, and meeting abstracts were excluded. In the last stage, full papers were assessed for eligibility of review after record scanning of the remaining sources.

2.2 Use and pre-use evaluation by case study (a)

Economic and Technical Considerations in Pursuing Green Building Certification: A Case Study from Iran
Case studies have become a useful method of conducting research not only in social sciences such as psychology, political sciences, and history but also in practice-oriented fields such as education, engineering, and urban planning.

Compared to surveys or questionnaires, which need more bureaucratic processes, case studies are easier to conduct and are a preferred method for detailed evaluation.

In general, case studies are a preferred strategy when 'why' and 'how' questions are targeted, and a certain real-life context is under investigation [67]. The case studies can be exploratory or descriptive based on the aim and objective of the study [68]. For this dissertation, both exploratory and descriptive strategies are required. The case must be selected to be a representative of a big area of research in order to produce the most reliable results.

For paper 2, a case study of a building located in Iran (Table 2) was used in order to obtain a deep understanding of the criteria of awarding points for green building certificates and identify if the system fulfils the target of low energy use in the use stage in addition to the material efficiency in the pre-use stage.

The case building was carefully and purposely selected so that it represents a customary building in the selected country. Buildings are typically five to six floors in most cities of Iran. Reinforced concrete is used for the structural components of these buildings, as the use of steel for this purpose results in extra cost. The city where the case building is located is Karaj, which is very close to the capital (Tehran), where costs are slightly lower compared to the capital because of different conditions—for example, lower salaries.

Table 2. Case study information

Type of building	Residential
Type of ownership	Private
Status	New construction
Number of floors	5+1
Number of units	15
Construction start date	October 2017
Construction end date	March 2019
Land area	660 m2
Building coverage	451 m2
Gross area (Total construction)	2740 m2
Height	21 m

LEED is a point-based system certificate, and if a building gets 40 points out of 110 points, it can get the Certified level of the certificate. For other levels, more points are needed—that is, 50 for Silver, 60 for Gold, and 80 points for Platinum as the highest level.

For this paper, we first evaluated the building in its current format (scenario 1) and found out the number of points that it obtained. Next, we conducted a thorough evaluation of all available points and identified which ones are eligible for the studied case building. Finally, we designed two other scenarios in which we targeted to receive the number of points needed for obtaining the Certified and Silver levels. While the points in categories that were easier to obtain were discovered, the cost of any change for this purpose was estimated.

With this process, it was possible to identify the possible reasons that some green certified buildings were not practically energy efficient, as discussed in paper 1. In addition, an evaluation of points allocation in the pre-use stage of building with regard to material selection was done.

2.3 Pre-use evaluation by case study (b)

Paper 3. Embodied Emissions of Buildings—A Forgotten Factor in Green Building Certificates

Similar to paper 2, this study was based on a case study. In this paper, LCA was used as a sustainability assessment tool using a case building in Iceland as the base scenario. LCA is used for the direct and indirect environmental evaluation of a product, service, or process related to production, transport, use, and end-of-life [69-71]. For conducting LCA, the main guidance is ISO 14040:2006 standard, which was employed in this study.

LCA can be conducted in three main approaches including process LCA, input-output (IO) LCA, and the combination of process and IO LCA that is called hybrid LCA [71,72]. Among these, process LCA has a more accurate approach for the quality of tracking actual processes apart from material and energy flows, which are related to the production and delivery chain [73]. On the other hand, IO LCA operates with a more comprehensive system boundary and monetary flows compared to process LCA [72]. Therefore, hybrid LCA—as a combination of other approaches—possesses both properties, that is, comprehensive coverage and high accuracy [71,74-76]. Process LCA is considered as the most widely selected approach for buildings and, thus, was selected for this paper.

The case building for this study is located in Reykjavik (Iceland) and is a modern educational facility. Most buildings in Iceland are concrete buildings and the cement for concrete production is imported. The idea was to design a few scenarios with different combination of material use in order to identify the best option with the lowest environmental impacts (Figure 3). On the other hand, it was targeted to assess the change in obtaining points in LEED and BREEAM green certificates. Therefore, it was evaluated how LEED and BREEAM, being the most frequently used green certificates, have considered the environmental impacts in the pre-use stage in accordance with the selection of material.

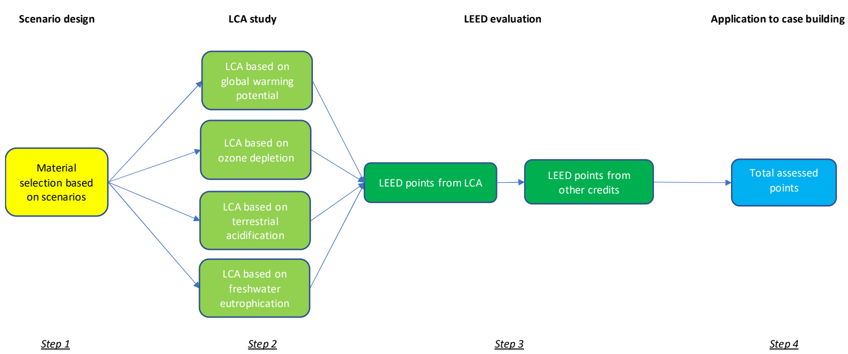


Figure 3. The stages of the study.

Three scenarios were designed in addition to the base case building. There was a step-by-step change in the material used for the construction of a building, which resulted in different environmental impacts and achievable points in LEED and BREEAM. The alternative scenarios were designed carefully so that the U-values were equivalent between the scenarios and base case in order to have the same energy usage in the use stage. The structural design of the scenarios is made according to the Nordic building regulations meaning that the structure of building for the scenarios has the same structural strength and behaviour as the base case building.

The base case, Con, is a concrete building made up of concrete in all the main components such as beams and columns, structural and non-structural walls, and slabs. Scenario 1, OptCon, was designed to use lower-strength concrete for non-structural components and, thus, so two kinds of concrete, C30 and C20, were used. In scenario 3, ConWood, all components that were non-structural were replaced by wood. Finally, scenario 3 (Wood) was a complete change to wooden components for both structural and non-structural components. The only components that remained concrete were the walls that were underground for the Wood scenario. The materials are presented in the following table.

Table 3. The change in material in various scenarios.

	Con	OptCon	ConWood	Wood
Foundation	C30 concrete	C30 concrete	C30 concrete	C30 concrete
External walls	C30 concrete	C30 concrete	C30 concrete	CLT
Structural internal walls	C30 concrete	C30 concrete	C30 concrete	CLT
Non-structural internal walls	C30 concrete	C20 concrete	CLT	CLT
Floor slabs	C30 concrete	C30 concrete	C30 concrete	CLT
Roof slab	C30 concrete	C30 concrete	C30 concrete	CLT
Internal windows	Aluminium	Current	Wooden	Wooden
External windows	Aluminium	Current	Current	Wooden
Doors	Aluminium	Current	Wooden	Wooden
Custom floor finish	Terrazzo	Terrazzo	Hardwood	Hardwood
Private floor finish	Linoleum	Linoleum	Parquet	Parquet

In order to answer the research question, the LCA study was conducted for all three scenarios and the base case scenario. Then, it was evaluated how the number of earned points are changing with the change in material selection. In the last step, the total number of points for each scenario was calculated and the best selection of materials was identified.

2.4 Future construction design of low-carbon material by numerical scenario analysis

Paper 4. Cities as Carbon Sinks—Classification of Wooden Buildings
In continuation of paper 3 to evaluate the overall significance of low-carbon building materials in the built environment—that is, wood—this article was

based on two main steps. In the first step, the target was to ascertain the potential carbon storge of wood as a sustainable building material in the unit of CO2 kg m^{-2}. According to a review based on 50 different case buildings from all over the world, wooden buildings were categorized into three levels based on their carbon storage capability. All the 50 cases included the structural components for the purpose of carbon storage potential while some others included the non-structural components as well. Regarding the structural analysis, the case buildings have used their location's regulations in order to prepare the wooden replacement for steel, concrete or masonry. Most of them have compared currently constructed buildings with wood, steel, concrete or masonry. The next step was to apply this data to the predicted building construction volumes in Europe.

Four different scenarios were designed. Here, the variable parameters were the level of wooden buildings and the percentage of wooden buildings compared to others—that is, concrete or steel—for future construction. In Europe, the annual GA construction of residential building was 185.71 million m^2 in 2015 of which 4.9% were wooden; The annual increase rate of construction was equal to 0.87% [77].

Scenario one assumed that the proportion of wooden buildings compared to others remains the same as in 2015 which is equal to 5%. The second scenario assumed a 10% portion that is close to the scenario defined by Hildebrandt et al. [77]. The third scenario is a value between the second and last scenarios—that is, 45%. Finally, the last scenario was selected as 80%, which is close to the 84% value used for North American residential wooden buildings in the year 2017 [78].

In addition to the mentioned scenarios, a feasible scenario which aimed at the gradual change to wooden buildings was designed. While considering the current situation in Europe regarding different types of buildings by material, it was assessed and planned that the change to a low-carbon material—that is, wood—is possible. Then, the impact of this change on climate change was evaluated and included an estimation of potential carbon storage in implementing this scenario.

3. Results

This chapter presents the findings of the four papers. The main findings and contribution of papers are presented and there will be detailed presentation of results for both the use and pre-use stages of a building life cycle. As mentioned in the previous chapter, paper 1 answers the part of the question related to the use stage, while paper 2 encompasses both the use and pre-use stages. Two main case studies are used: one (a) in paper 2 and the other (b) in paper 3. With a focus on the pre-use stage, paper 3 utilizes a few replacement scenarios of materials in order to have lower environmental impacts compared to the base case. The research continues to paper 4 with the provision of a few scenarios for the future new buildings in Europe for a period of 20 years, using wood as a low-carbon building material.

3.1 Key findings

To answer the research question, we divided it into two categories. First, to answer if green buildings are efficient in terms of the energy use and emissions reduction in their use stage. Second, the evaluation of green buildings in the pre-use stage. In addition, we assessed the long-term potential of replacing building materials with low-carbon materials like wood. The contribution of paper is presented in the following table.

Table 4. Contribution of papers.

Research question: How green buildings perform in mitigating climate change in pre-use and use stages?				
	Paper 1	**Paper 2**	**Paper 3**	**Paper 4**
Title	*Are LEED-Certified Buildings Energy-Efficient in Practice?*	*Economic and Technical Considerations in Pursuing Green Building Certification: A Case Study from Iran*	*Embodied Emissions of Buildings—A Forgotten Factor in Green Building Certificates*	*Cities as Carbon Sinks—Classification of Wooden Buildings*
Perspectives (Aim)	Evaluating if green certified buildings are reducing energy use and emissions reduction in the use stage	Detailed evaluation of green building criteria for giving points and certifying the building	Assessment on how green certificates consider pre-use stage (construction) emissions reduction	An estimation of big-scale change in material changes into low-carbon material like wood for the purpose of lower pre-use stage emissions

Main contribution	Green certified buildings, particularly at higher levels of certificate, such as Platinum or Gold, use less energy in their use stage but in lower levels like Certified it is questionable	Fewer environmental impacts in use and pre-use stages of green certified buildings are confirmed in higher levels like Platinum or Gold, but this cannot be confirmed for lower levels like Certified	LCA showed clear impact difference between optional building materials in the pre-use stage, while green certificates evaluation had shorter periods of showing the difference	There is a large potential for temporary carbon storage in built environment if the primary building material is switched to wood
Conclusions: With regard to the use stage, green building certificates—specifically LEED—work rather well in indicating lower emissions of the buildings at higher levels of the certificate (Gold or Platinum); however, in lower levels (Certified or Silver), the suitability remains questionable. In the pre-use stage, the certificates do not allocate too many points and, thus, this plays poorly for this stage of the building life cycle, while the pre-use stage emissions are shown to be significant for climate change mitigation, as they are produced in a short time. This also applies to the body of research, as the focus in buildings has been mainly on the use stage in the past but pre-use stage has become more important in recent years. It appears that new research is influencing green building certificates to pay more attention to the emissions that occur in the pre-use stage.				

3.1 Literature findings regarding green-certified buildings in the use stage

Contribution of paper 1
Are LEED-Certified Buildings Energy-efficient in Practice?

Applying LEED as a green building certificate will result in the reduction of energy use and environmental impacts in the use stage, but this happens mainly in higher levels of certificate—that is, Platinum or Gold (Table 5). The energy consumption at the lowest level, Certified, appears to be the same as that in non-certified buildings. There is lack of adequate data to provide a clear answer, which requires research to be conducted all over the world.

Table 5. The most important reviewed articles and their findings.

Author	Country	Main Findings
Scofield [34]	USA	• The same amount of source energy is used by LEED-certified and non-certified buildings • Site energy use by LEED-certified buildings is 10%–17% less than non-certified ones, which is half of the amount reported by NBI
Newsham et al. [37]	USA	• The energy consumption by LEED-certified buildings is 18%–39% less than non-certified ones on average • Considering the average saving, some LEED-certified buildings use 28%–35% more energy compared to non-certified ones.
Scofield [35]	USA	• Silver and Certified level buildings in the NYC use more energy than non-LEED certified ones. • The energy consumption by Gold LEED-certified buildings is 20% less than non-certified ones.
Issa et al. [38]	Canada	• The energy consumption by LEED-certified schools was 37% more than non-certified ones. • The gas consumption by LEED-certified buildings was 56% less than non-certified ones.
Scofield et al. [36]	USA	• LEED-certified and non-certified buildings in Chicago used the same source energy.

		• Site energy use by LEED-certified buildings was 10%–12% less than non-certified ones in Chicago.
Chen et al. [39]	China	• The energy consumption by three LEED-certified office buildings in China was 2%–5% compared to non-certified ones.
Sabapathy et al. [40]	India	• LEED-certified buildings in Bangalore (India) use 34% less energy compared to non-certified ones, thereby resulting in a cost reduction of 8%, on average, in energy use
Uğur and Leblebici [41]	Turkey	• The energy consumption by two LEED-certified buildings with Gold and Platinum level certificate was 31% and 40% less than non-certified ones, while their construction cost was 4.43% and 9.43% more, respectively, compared to non-certified buildings.
Cubi and Keithet [42]	-	• In case if green certificates like LEED distinguish the carbon footprint from energy (considering site and source energy), there will be a reduction in emissions. • The actual performance e of green-certified buildings regarding energy use must be claimed by certificate systems
Kern et al. [43]	Brazil	• The actual energy and water consumption of an LEED-certified building during its first year of occupation was higher than the expected values in the design phase. • LEED-certified occupants are satisfied with indoor lighting and temperature.
Michael et al. [79]	South Africa	• Carbon footprint and operating costs by a LEED-certified building in South Africa was reduced, while the indoor air quality was improved.
Fuerst and McAllister [80]	USA	• Lower operating cost, higher productivity, and reputational benefits were achieved by LEED-certified buildings in addition to the rent and sale premiums.
Jeong et al. [81]	South Korea	• Buildings certified by G-SEED (A South Korean green building certificate) and LEED have no significant energy saving compared to non-certified ones; this result is contradictory to the assumption of energy saving of 10%–15%.
Al-Ghamdi and Bilec [82]	-	• Modelling of an office building (3995 m^2) in relation to LEED in 400 different locations of the world resulted in the emission of energy use range between 394 ton and 911 ton-CO2 equivalent
Heidarinejad et al. [83]	USA	• The energy use for heating ranked maximum and lighting as minimum in 134 US office buildings certified by LEED
Fuertes and Schiavon [84]	USA	• 40% of 429 LEED New Construction (NC) and 660 LEED Commercial Interiors (CI) used 16.1 W/m^2 and 10.8 W/m^2 of plug load energy in the peak load, respectively • The regular plug loads energy use was 10.8 W/m^2 in 68% of LEED-certified buildings.
Chen et al. [39]	China	• Three LEED-certified buildings in China, one in Beijing and two in Shanghai, used 2%–5% less energy compared to non-certified buildings. • The energy consumption by three LEED-certified buildings located in China, one in Beijing and two in Shanghai, was 2%–5% less than the non-certified ones.
Chokor and Asmar [85]	USA	• The actual (use stage) energy consumption by LEED-certified and non-certified buildings is the same.
Menassa et al. [21]	USA	• The goal of 30% reduction in electricity use was not achieved in 9 out of 11 LEED-certified buildings for the US Navy.
Wedding and Crawford-Brown [86]	USA	• Inconsistency was seen between the predicted and actual energy use of LEED-certified buildings.

One of the main issues here is the difference in the definition of energy used by the buildings. Researchers have different results in which the source energy (includes all emissions for the production and transportation) or site energy play a role. This issue is connected with the location of the project. It is possible to select the source of energy in certain developed countries, which implies that it is acceptable to use source energy for the evaluation of LEED-certified buildings in these countries. This is an incorrect consideration in the countries that there is no possibility of selecting the energy source to buy and, thus, only site energy must be selected. In these countries, the source energy is based on the policies of the government or city council. Imagine that a city is receiving its energy from different sources, such as nuclear power or natural gas, but the northern part of the city just has the option of selecting natural gas. This implies that the buildings' selection of energy type is based on the governmental or city policies but not on the constructor or owners.

Further, most articles studying the efficiency of LEED-certified buildings in the use stage are from the US, which has a long history of adopting LEED certificates. LEED has been recently adopted in different countries, particularly in China. However, the studies from other countries are still limited and, thus, it can be focused upon in the future. There is a need for continuous improvements in the process of awarding green building certificates in order to decrease energy use and emissions production in the use stage.

3.2 The findings from case study (a) regarding green-certified buildings for both the use and pre-use stages

Contribution of paper 2

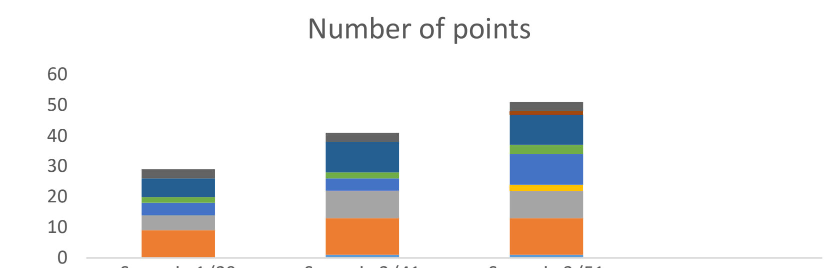
Economic and Technical Considerations in Pursuing Green Building Certification: A Case Study from Iran

LEED gives 110 points to 9 categories (Table 6). Each category has different credits and certain credits might have prerequisites. Generally, the location of the project, level of public awareness, available technology, and green building regulations in the location of the project play a significant role in obtaining and targeting points. Among these, the location of the project appears to be the easiest but not necessarily the cheapest option because of different prices of land for the purpose of constructing buildings.

Table 6. LEED information.

Categories of LEED	Share %	Points	Credits	Prerequisites
Integrative Process (IP)	0.9	1	1	-
Sustainable Sites (SS)	9.1	10	6	1
Location and Transportation (LT)	14.6	16	7	-
Water Efficiency (WE)	10	11	4	3
Energy and Atmosphere (EA)	30	33	7	4
Materials and Resources (MR)	11.8	13	5	2
Indoor Environmental Quality (IQ)	14.5	16	9	2
Innovation (IN)	5.5	6	2	-
Regional Priority (RP)	3.6	4	4	-
Total	**100**	**110**	**45**	**12**

It was planned to ascertain the total points that the case building could obtain in its current format without any changes. At the next stages, two lowest level of the certificates—that is, Certified and Silver—were targeted, thereby implying that the number of points must be over 40 and 50. A total of 29 points were obtained for the case study and some other available points that required smaller changes and investment were identified (Figure 4).



	Scenario 1 (29 points)	Scenario 2 (41 points)	Scenario 3 (51 points)
RP	3	3	3
IN	0	0	1
IQ	6	10	10
WE	2	2	3
EA	4	4	10
MR	0	0	2
SS	5	9	9
LT	9	12	12
IP	0	1	1

Figure 4. Obtained and planned points to achieve certificate (case building = scenario 1).

The results from paper 2 clarify why LEED green certified buildings might not completely fulfil energy and emissions reduction during the use stage. While the goal is fulfilled in higher levels such as Gold or Platinum, lower levels might not decrease energy use. LEED does not require the receipt of points from all categories. This implies that a building might focus on location, sustainable site, and indoor quality, all of which result in adequate points to get certified without a focus on energy efficiency. On the other hand, there must be an evaluation during the use stage of the building showing the energy use in practice. Some buildings might be designed as low energy use buildings, but the energy consumption might differ in practice.

As indicated in Table 7, the case building has got the maximum points from the category of Location and Transportation (LT), which needs the project to be located in a favourite location defined by LEED. On the other hand, the case has got no points in the Material and Resources (MR) category, thereby implying that the case cannot be considered as material-efficient for its pre-use stage. In conclusion, the lower certificates' beneficial environmental impacts—that is, Certified or Solver—might be questionable but depends on the detail of points obtained in different categories.

Table 7. Eligible aspects for the case study with small change or low cost (S = should).

Symbol	***Points***	***Credit***	***Already earned***	***Eligible to earn***
		Category: Integrative Process		
IP	1	Integrative Process		1
		Category: Location and Transportation		
LT1	1	Sensitive Land Protection	1	
LT2	2	High Priority Site	-	-
LT3	5	Surrounding Density and Diverse Uses	5	
LT4	5	Access to Quality Transit	3	2
LT5	1	Bicycle Facilities	-	-
LT6	1	Reduced Parking Footprint		1
LT7	1	Green Vehicles	-	-
		Category: Sustainable Sites		
SS_p	Prerequisite	Construction Activity Pollution Prevention		S fulfil
SS1	1	Site Assessment		1
SS2	2	Site Development—Protect or Restore Habitat	-	1
SS3	1	Open Space		1
SS4	3	Rainwater Management	3	
SS5	2	Heat Island Reduction	2	
SS6	1	Light Pollution Reduction		1
		Category: Materials and Resources		
MR_{p1}	Prerequisite	Storage and Collection of Recyclables		S fulfil
MR_{p2}	Prerequisite	Construction & Demolition Waste Management Planning		S fulfil
MR1	5	Building Life-Cycle Impact Reduction	-	-
MR2	2	Environmental Product Declarations	-	-
MR3	2	Sourcing of Raw Materials	-	-
MR4	2	Material Ingredients	-	-
MR5	2	Construction & Demolition Waste Management		2
		Category: Energy and Atmosphere		
EA_{p1}	Prerequisite	Fundamental Commissioning and Verification		S fulfil
EA_{p2}	Prerequisite	Minimum Energy Performance		S fulfil
EA_{p3}	Prerequisite	Building-Level Energy Metering	Fulfilled	
EA_{p4}	Prerequisite	Fundamental Refrigerant Management	Fulfilled	
EA1	6	Enhanced Commissioning		6
EA2	18	Optimize Energy Performance	-	-
EA3	1	Advanced Energy Metering	1	
EA4	2	Demand Response	2	
EA5	3	Renewable Energy Production	-	-
EA6	1	Enhanced Refrigerant Management	1	
EA7	2	Green Power and Carbon Offsets	-	-
		Category: Water Efficiency		
WEp1	Prerequisite	Outdoor Water Use Reduction	Fulfilled	
WEp2	Prerequisite	Indoor Water Use Reduction	Fulfilled	
WE_{p3}	Prerequisite	Building-Level Water Metering	Fulfilled	
WE1	2	Outdoor Water Use Reduction	2	
WE2	6	Indoor Water Use Reduction	-	-

WE3	2	Cooling Tower Water Use	-	-
WE4	1	Water Metering		1
Category: Indoor Environmental Quality				
IQ_{p1}	Prerequisite	Minimum Indoor Air Quality Performance	Fulfilled	
IQ_{p2}	Prerequisite	Environmental Tobacco Smoke Control		S fulfil
IQ1	2	Enhanced Indoor Air Quality Strategies	-	-
IQ2	3	Low-Emitting Materials	2	-
IQ3	1	Construction Indoor Air Quality Management Plan		1
IQ4	2	Indoor Air Quality Assessment	-	-
IQ5	1	Thermal Comfort	1	
IQ6	2	Interior Lighting	1	1
IQ7	3	Daylight	-	2
IQ8	1	Quality Views	1	
IQ9	1	Acoustic Performance	1	
Category: Innovation				
IN1	5	Innovation	-	-
IN2	1	LEED Accredited Professional		1
Category: Regional Priority				
RP	4	Regional Priority: Specific Credit	3	-
	110	***Total***	***29***	***22***

3.3 Case study (b) findings regarding green-certified buildings in pre-use stage

Contribution of paper 3
Embodied emissions of buildings—a forgotten factor in green building certificates

The purpose of this paper was to evaluate the suitability of green buildings—that is, LEED and BREEAM—in supporting the embodied emission reductions of buildings in the pre-use stage. More specifically, it was estimated if and how well the green building certificate's points support the selection of building materials with low embodied emissions. Three scenarios with different building materials in addition to the case building were defined for comparison. An LCA study was conducted for all four cases with an emphasis on four indicators: climate change, ozone depletion, terrestrial acidification, and freshwater eutrophication. This was to allow the determination of LEED and BREEAM certifications score in each scenario. In addition, transportation emissions were evaluated to assess the possibility of using the findings globally for the challenge of climate change.

As indicated in Table 8, 14 out of 110 points were related to material selection for the case study, in which five points require substantial changes (e.g., LCA). The number of points for embodied emissions which occur in the pre-use stage are few in LEED compared to the points allocated for the energy and atmosphere category that are focused on energy reduction in the use stage. The short-term reaction regarding climate change reduction requires short-term planning, thereby implying that green building certificates must pay more attention to the pre-use stage, which is related to embodied emissions.

Table 8. Requirements related to obtaining LEED in different scenarios.

Credits in LEED	MR 1	MR 2	MR 3	MR 4	EQ	IN	Total	Action taken
Wood	3	2	2	2	3	2	14	• Lower environmental impact (-10%) according to building LCA study (MR_1). • Used over 20 different permanently installed products that have EPD, sourcing of raw materials, and material ingredients information (MR_{2-4}). • Increased amount of used wood as low-emitting material (EQ). • Achieved triple the credit requirements (-30%) for building LCA study (IN).
Con-Wood	0	1	2	2	3	0	8	• Used over 20 different permanently installed products that have EPD, sourcing of raw materials, and material ingredients information (MR_{2-4}). • Increased amount of used wood as low-emitting material (EQ).
OptCon	0	1	1	1	2	0	5	• Used over 20 different permanently installed products that have EPD, sourcing of raw materials, and material ingredients information (MR2-4). • Used low-emitting materials that increase the air quality, human health, productivity, and the environment (EQ).
Con	0	1	1	1	2	0	5	• Used over 20 different permanently installed products that have EPD, sourcing of raw materials, and material ingredients information (MR_{2-4}). • Used low-emitting materials that increase the air quality, human health, productivity, and the environment (EQ).

(Con = concrete, OptCon: optimized concrete, ConWood: concrete wood)

The wood building had the lowest environmental impact followed by Con-Wood, OptCon, and Con buildings according to LCA (Figure 5). In the case of the most important indicator, climate change, the Con building had an emission estimate of 664.5 kg CO2 eq/m^2. This is in line with previous results by Ng and Kwok [87] and Dong and Ng [88] but relatively high compared to the general building LCAs [73], which does not support the sustainable design need. The issue is because the use of concrete as a local building material. As foreseen, the structure was the main contributor of emissions production. The replacement of aluminium windows significantly declined the emissions in all four scenarios.

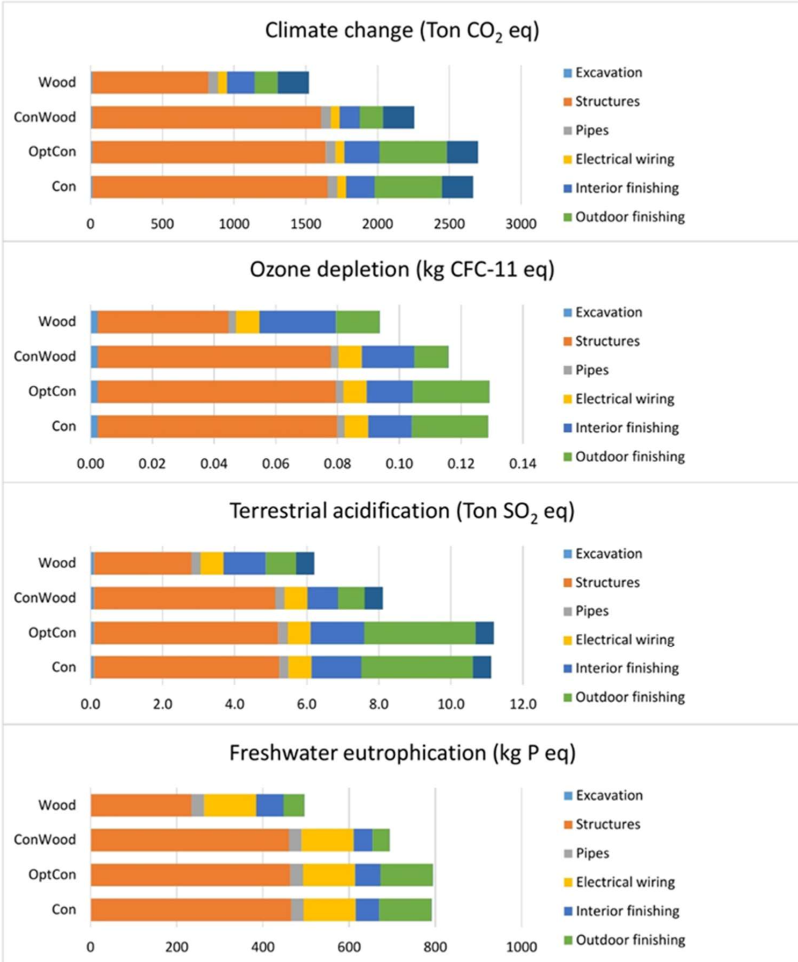


Figure 5. Emissions in different scenarios

From paper 3, it was found that wood can be a potential low-carbon material and help in achieving the goal of emissions reduction during the pre-use stage. Therefore, the research was continued to paper 4 with a large-scale estimation of carbon storage potential if new construction in Europe gradually switches to wooden materials.

In order to make this study useful for other countries similar to Iceland, which are mainly importing construction material and other countries that are willing to have faster reaction regarding climate change mitigation, we assessed the emissions resulting from transportation separately. The mentioned countries can import wooden products after considering the transportation emissions. Here, only a one-way transportation was considered, as the vessels need to go for the back route because of exports from Iceland. The share of transportation varies significantly among four scenarios (Figure 6). In the wood scenario, transportation emissions equal 15% for climate change indicator. It is 20%–45% of the total terrestrial acidification and ozone depletion for all four scenarios.

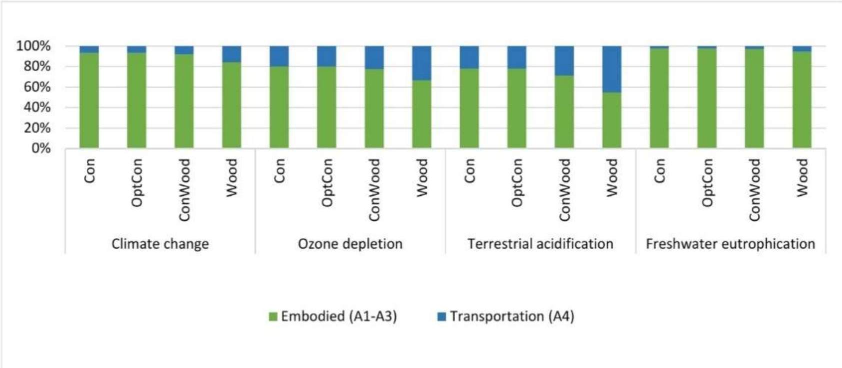


Figure 6. Transportation emissions for the scenarios.

3.4 Low-carbon material impact on future construction in Europe

Contribution of paper 4

Cities as carbon sinks—classification of wooden buildings

From paper 3, it was found that wood can be a potential low-carbon material in order to achieve the goal of emissions reduction during the pre-use stage. Therefore, the research was continued in paper 4 with a large-scale estimation of carbon storage potential if new construction in Europe gradually switches to wooden materials.

For this paper, we first went through 50 wooden building cases from extant literature and calculated their potential carbon storage, which was based on the amount of wood used in their construction (Figure 7). All the reviewed case buildings included structural components in order to do the LCA study and assess the potential carbon storage because the structural components had significant role. The comparison was mainly between already constructed buildings with wood, concrete, steel or masonry. In case if some replacement scenarios were designed, the building construction regulations from the location of the building were considered for the structural components.

The findings were used for the definition and categorization of wooden buildings. Some constructors might claim for benefits and motivation plans from the municipalities for wooden building construction, but the number of wooden components or the amount of wood use in the constructed building was not clear. We categorized the wooden buildings as 100 (low), 200 (mid), and 300 (high) levels based on their carbon storage potential (CO2 kg m^{-2}). The next step was the design of future scenarios based on these levels apart from the number of wooden buildings compared to concrete or steel ones.

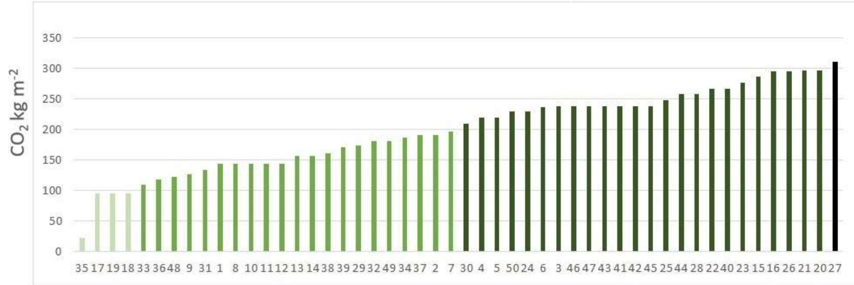


Figure 7. Transportation emissions for the scenarios.

For future scenarios, different types of wooden buildings based on their carbon storage capacity (100 CO2 kg m-2, 200 CO2 kg m-2, and 300 CO2 kg m-2) and different percentages of wooden buildings compared to others were considered. The annual captured CO2 varied between 1 Mt and 55 Mt for the period between 2020 and 2040, which is equivalent to 1% and 47% of emissions produced by European cement production in the year 2018 [57]. The cumulative values are 0.356Gt–1.067 Gt for the 80% scenario, 0.2 Gt–0.6 Gt for the 45% scenario, 0.044 Gt–0.133 Gt for the 10% scenario, and 0.022 Gt–0.067 Gt for the 5% scenario (Figure 8).

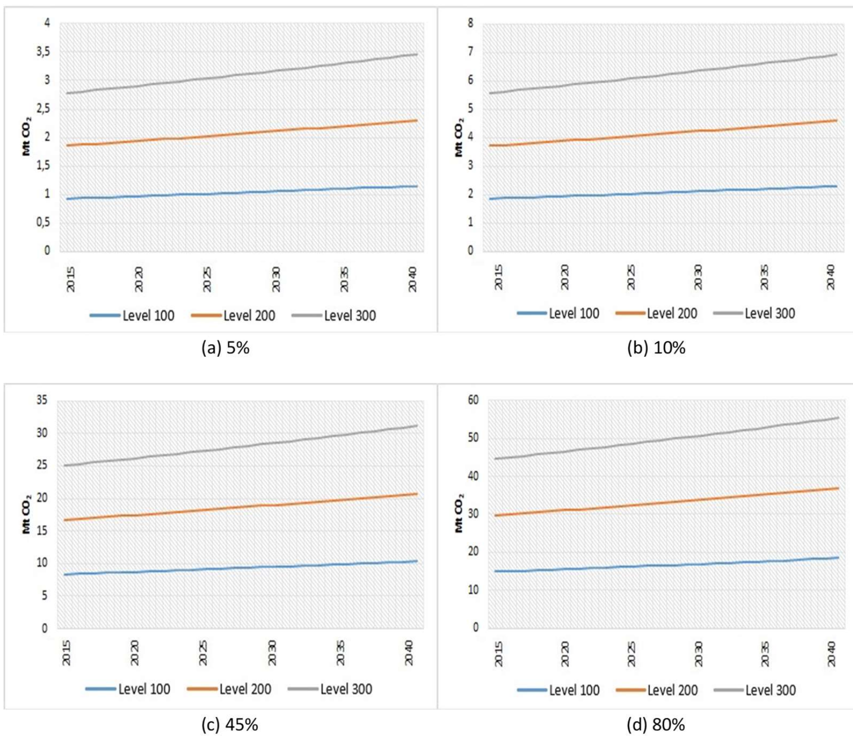


Figure 8. Carbon storage in different scenarios.

In addition, a feasible scenario was designed for decision-makers in which two variables—that is, wooden building levels and percentage of wooden buildings were applied. The scenario was recommended for the increase in the carbon storage of European built environment. It was assumed that the proportion of wooden buildings would be 10% of all buildings in the year 2020 and this is set to increase to 80% by 2040. For this purpose, there was a division of five years for the 20-year period. From the year 2020 to 2025, the share increase will be 2% annually, with a target of 20% for 2025. The share increase will be 3% annually for the period 2025–2030, 4% for 2030–2035, and 5% for 2035–2040. On the other hand, it was planned to gradually upgrade the level of wooden buildings from 100 CO2 kg m^{-2} to 300 CO2 kg m^{-2}. It began from 100 CO2 kg m^{-2} in 2020 and is set to increase to 200 CO2 kg m^{-2} in 2030, reaching the maximum of 300 CO2 kg m^{-2} in 2040. For this recommended scenario, the annual captured CO2 will be 55 Mt for 2040, 15 Mt for 2030, and 2 Mt for 2020. The cumulative amount for the 20-year period will be 0.42 Gt.

In general, there are two main ways of mitigating climate change and protecting the environment. One is to produce less greenhouse gas emissions, while the other one is to capture carbon. Even replacing fossil fuels with renewable sources will not reduce CO2 emissions of materials, such as cement or steel, to zero, as producing these materials involves chemical reactions which result in emissions [13]. In the past, building regulations and incentives have focused on the energy efficiency of buildings. Recently, there has been some development to also target the emissions embodied in construction materials. In the future, it will be increasingly important to also encompass the potential for storing carbon in the built environment. Voluntary green building certificates, like LEED, could play an important role in incentivizing such development globally.

4. Discussion and conclusion

This chapter discusses the findings of the study and evaluates their importance. First, we present the important findings and provide explanations for these. Then, we validate our findings with the findings of other researchers and explain if the findings are expected; in case these are unexpected, we provide the possible reasons for such findings. Further, in order to answer the research question thoroughly, we have separated the use stage with pre-use stage here and provide a detailed presentation for these. In addition, the chapter provides useful and feasible recommendations for policymakers based on our findings as well as the shortages in the industry. Any piece of research might have a few limitations, while there are gaps in the body of research; therefore, we include future research recommendations which may be helpful for other researchers who are interested in continuing research on this topic.

4.1 Interpretation, explanation, and validation of the results

Buildings are one of the main consumers of energy and material and their construction and use produces a large amount of emissions. The emissions from both material and energy use in buildings play a significant role in climate change. On the other hand, buildings are considered as a potential for climate change mitigation if appropriate plans and instructions are applied. This has motivated the construction of greener and more sustainable buildings. However, the definition of a green building varies, for example, in different locations as per the environmental situation in that location. The need for a common standard has resulted in the preparation of green building certificates. The first and most frequently used one is BREEAM, while the most internationally used one is LEED. Recently, there has been improvement in the introduction of additional green certificates worldwide based on the varied requirements of countries.

The idea of a green building certificate was brilliant and is appreciated because of its guideline and motivation for constructing greener buildings. However, there is uncertainty if the goals regarding the reduction of energy and material use are actually met, bearing in mind that green certified buildings might cost more in certain countries based on environmental issues and regulations. Therefore, this study aimed to assess green building certificates regarding the reduction in environmental impacts of buildings in the use and pre-use stages of their life cycle.

4.1.1 How green building certificates do in use stage

For the use stage, a review of the literature was used, as the number of studies on the use stage of green certified buildings were reasonable. A few studies have concluded that green certified buildings use less energy during their use stage and, thus, emit less, while some others concluded that certified and non-certified buildings use the same amount of energy or that even more energy is used by certified buildings; there are several reasons for this conflict.

The first reason is related to the level of certificate. Most green building certificates are point-based, thereby implying that a greater number of points result in obtaining a higher-level certificate. For example, LEED has four levels: Certified, Silver, Gold, and Platinum. The buildings that obtain higher levels,—that is, Gold or Platinum—are considered as being efficient with regard to energy use and emission cuts, while those with lower-level certifications—that is, Certified or Silver—might use equal energy compared to the traditional ones [26,34-36,39,41,43,44,80,81].

The location of the project in the world is the next aspect that affects the differences in results [89,90]. The regulations in countries, cities, or municipalities are different. In addition, environmental concerns play a significant role which is set by policy makers in the location of the project. A building might be constructed in a cold climate where there are tight regulations in order to save energy as much as possible. This implies that, in certain locations, recommendations and regulations might make a traditional building as energy efficient as green certified buildings or even better. Therefore, it is important to consider the local context.

Next is the boundary and similarity of buildings for comparison [91]. Usually, the comparison is between certified and non-certified buildings that are not quite the same. For example, there might be a comparison of a 30-year-old traditional building with a 10-year-old green certified building. It is evident that the technology, material access, regulation, and environmental concerns differ at the time of construction of these buildings. Or it is also plausible that a new non-certified building with current environmental concerns might use less energy than a certified building that was constructed a decade ago.

The other reason is the definition of energy that certain researchers have used for their research—that is, the source or site energy [34,35,37]. The site energy (can also be called billed energy) is the energy received by the building at its entrance regardless of its source or transport emissions, while the source energy includes all the emissions that occurred during its production until the hand in to the users. The researchers that have considered source energy have concluded that green certified buildings are not using less energy compared to non-certified ones during their use stage.

One other factor that is responsible for the diverse findings by researchers is the difference between the building that has been designed for using a certain level of energy and its actual energy use in practice [43,91,92]. The judgment of most green building certificates is based on building energy modelling and points are given to the building that utilizes less energy compared to a reference model building. There might be a few errors with the modelling, or the modelling might not be completely the same as the building which is going to be constructed. In addition, there might be a few changes in material selection because of the situation at the time of construction time or there might be a change requested by the owners—all these aspects may result in some level of difference between the designed and constructed buildings.

The last aspect is the consideration of occupants' behaviour [38,91,93]. The occupants of green certified buildings might use more energy compared to non-certified ones because they may believe that the building is completely energy efficient. In addition, the price of energy is different in different countries, which will also affect the occupants' behaviour. Further, higher indoor quality of certified buildings might result in more energy use during the use stage.

The information in the review paper (Paper 1) was mostly obtained from cited papers and the paper attempted to go through the detail of their methodology and boundary setting in order to increase the reliability of its findings and identify any conflict between their results. Although most case buildings of the studies have been located in the US, an attempt was made to include other locations as well. Certain studies, such as Scofield or Newsham, include more than a hundred case buildings, which makes the validity of the results high. The review paper is co-authored by two other researchers, one postdoc and one professor, thereby resulting in an assessment from different perspectives.

Paper 2 covered both the use and pre-use stages. A constructed case study was evaluated technically and economically in case it was planned to obtain a green certificate. This was an opportunity to go in depth into how points are awarded, which increased the value of the study and its validity. Paper 2 was a continuation of paper 1 and, thus, a few doubts regarding the energy efficiency of green certified buildings were investigated and the potential answers to questions were evaluated for confirmation.

4.1.2 How do green building certificates function in the pre-use stage?

According to the findings of the thesis, embodied emissions are poorly incorporated in green building certificates, which is in line with the focus of previous research, which has previously been mainly on the use stage [48-51,56,94,95]. Although LCA has been included in LEED version 4, the material efficiency and low-carbon material use requires more attention [96-98]. In a green building certificate such as LEED or BREEAM, the priority of material selection is given to certain labelled material that might not be available everywhere in the world while there might be different low-carbon material in that location. A renewable and carbon storing material like wood cannot obtain a high number of points, which makes the revision of the certificates necessary.

With regard to material selection for different scenarios, the wooden building option was shown to be the best option, which is in line with some previous findings [48,56,99,100]. As foreseen, the structure played the main role regarding the emissions based on LCA. Wood as a sustainable material has two benefits: one is lower GHG emissions compared to other options such as concrete or steel, and the other is the potential of carbon storage. The carbon storage capacity can be considered as a quick reaction to climate change mitigation.

An important finding was related to how the points are awarded in green building certificates such as LEED or BREEAM. The categories have certain prerequisites, which implies that for obtaining any points in that category, fulfilling the prerequisites is obligatory. This is an appreciated policy, but there is no restriction from which category the points must be obtained. To clarify more, the number of points is important to get certified, but it is open for selection from any targeted category. This implies that the constructor might select the points from certain easier categories based on the situation and ignore obtaining points from certain categories such as energy or material. When points from these categories are not targeted, it will result in an inefficient building in terms of energy and material consumption. This is very probable, particularly in lower-level certificates, like Certified, in which the number of points to obtain a certification is low.

Overall, 13% (14 points out of 110) are directly related to the material selection in LEED and 5% (5 points) are based on LCA study results. These values are 8% (12 points out of 150) for material-related points and 3% (5 points) for LCA-related points in BREEAM. There are also a few points available in the category of innovation which are open to be obtained by focusing on material selection. Compared to the points allocated to the energy efficiency in the use stage by these green building certificates, lesser attention has been paid to pre-use and material efficiency, which plays an important role in climate change.

When focusing on wood as a replacement material for steel or concrete, a few interesting results were found. Based on the evaluation of over 50 wooden case buildings from different locations of the world with diverse characteristics, a new definition was determined for these buildings according to their carbon storage potential. These were level 100 (low), level 200 (mid), and level 300 (high) with a certain potential of carbon storage ($CO2$ kg m^{-2}). This categorization is helpful for decision-makers in order to establish their motivation plans and prevent any inequality. Certain constructors might claim that their building is wooden and wish to benefit from the motivation plans, while they might merely have a wooden façade for their building. This is not fair, as some other constructors might have used a large amount of wood per m^2, including building components such as structure, load bearing and partition walls, flooring and ceiling, and façade, all of which play a significant role on the amount of carbon storage of a building.

For the potential carbon storage of wooden buildings scenarios, two variables were considered: the wooden building level already found in this study and the number (percentage) of wooden buildings compared to other buildings such as those made of concrete or steel. If a period of 20 years is planned, the amount of stored carbon varied between 1 Mt to 55 Mt which is equivalent to 1% to 47% of European cement production emission in 2018 [58]. The finding is in line with Heräjävi [101] or Churkina [102] if just one of the levels—that is, level 300—is applied. The results of paper 4 are thorough, as different levels of wooden buildings have been included.

As mentioned earlier, paper 2 encompasses both the use and pre-use stages. It provides a deep understanding of green building certificate and shows how they work. While it goes through detailed cost differences among different options to become green certified, it also provides the technical changes required for this purpose. Using the paper, it is possible to find the best and least expensive solution in order to obtain the requisite points. The findings of the paper are in line with the findings of other researchers [39,81,83,85,86], while it adds some extra data which is useful for constructors who are interested in obtaining a green certificate. The unique thing about this paper compared to those in extant literature is using the same building (scenario based) for the study which has been constructed for the evaluation of obtaining a certification. This implies that all the parameters of comparison are the same.

Paper 3 was a collaboration between Aalto University, Iceland University, and the Finnish Environment Institute for a case building study. There were six co-authors, out of which three were professors; thus, the paper was evaluated from different perspectives. The scenarios for material selection were designed in a manner that the building had similar energy use; thereafter, the LCA study was conducted, and this made the results as trustworthy as possible. In addition, the possibility of construction for the designed scenarios in practice were evaluated carefully, thereby making them a worthy option for constructors.

Paper 4 attempted to include a basement in future wooden building constructions in Europe, which can provide the most accurate results. Therefore, 50 wooden case building from journal articles were analysed not only for GHG emission differences from other buildings but also their carbon storage potential. This implies that the definition for three levels of a wooden building is based on a thorough and detailed study. The future scenario for the development of wooden buildings is practically possible to execute and a gradual change from concrete or steel to wooden buildings has been set.

4.2 Contribution of the findings

The world is currently facing one of the most important challenges of our time—that is, climate change. Buildings use a large amount of energy and material during their use and pre-use stages; therefore, they are one of the potential solutions for climate change. The idea of a green building certificate is a good one, as there can be a scale and reference to the definition of the buildings that are considered as green. The research question of this study has been set to answer how these green certificates are fulfilling the requirements for the mitigation of climate change.

This thesis conducted detailed studies on the point-based system of green building certificates and evaluated the possible improvements, an aspect which can be helpful for projects worldwide. A unique green building certificate cannot be applied to all countries, as there are different kinds of regulations and environmental situations in different locations. There might be differences in the availability of technology, richness of the country, material access, rate of construction growth, and building regulations. On the other hand, it is important to consider the willingness of the society to construct greener buildings and assess the people' awareness regarding climate change in the location of the project. Therefore, it is recommended to the policymakers to prepare a well-suited green building certificate for the desired location.

It is emphasized by the study that regular update and improvement of the green building certificates is important. The focus of research on the use stage of buildings in the past as well as its move toward the pre-use stage confirms this. Both the use and pre-use stages are vital bearing in mind that the pre-use stage emissions occur in a very short time compared to the use stage.

Paper 1 has well answered the question related to the use stage, with a reasonable number of studies focused on this stage. Different questions have been discovered when the parameters influencing the energy efficiency of buildings were considered; thus, it was necessary to go through the details of green building certificates. Paper 2 fulfilled this goal and assessed the allocation of aspects that are useful for any investor who is willing to get the certificate, including a valuable discussion on the best technical cost-worthy option to become certified. With more focus on the pre-use stage, paper 3 compared different material selection scenarios for Iceland, which is a country where the most material for building construction is imported. This piece of research is not only beneficial for Iceland but also for the countries that import their construction material, such as Qatar, Kuwait, Saudi Arabia, and the UAE. In addition, the results of paper 3 are useful for the countries in which climate change is important and are willing to have quick reactions to climate change, such as Finland, Sweden, Norway, Germany, or other similar countries in Europe.

The study did not stop here and continued to paper 4, which used the findings of paper 3 as the basis of scenario design for European countries. The scenarios provide an accurate estimate to the decision-makers in Europe. One feasible scenario is proposed which presents the roadmap to switch to wooden buildings in order to have one of the fastest reactions to climate change. Both the emission levels of wooden buildings and the number of wooden buildings compared to others increased continuously in the proposed scenario. The annual amount of stored carbon is 55 Mt for 2040, 15 Mt for 2030, and 2 Mt for 2020, while the amount of cumulative carbon storage is 0.42 Gt; thus, the numbers are noteworthy. It is necessary to mention that EoL stage of wooden buildings plays an important role regarding CO_2 emissions as the wood after demolition of wooden buildings can be reused in buildings and other products, recycled, used as fuel or landfilled.

4.3 Limitations and recommendations for further research

Each piece of research might have certain limitations according to the accessibility of data, research time period, small or limited sample size, flawed methodology, etc. which applies to this thesis as well. Here, for example, it is not possible to answer certainly if green building certificates have been successful in limiting the environmental impacts during the use stage of buildings. There has been continuous improvement in the certificates, while the number of buildings which obtain certification is increasing. There will be more case studies available not only in developed countries but also in developing countries. On the other hand, our evaluation of pre-use stage was based on limited case buildings and, therefore, the research on a larger number of cases is appreciated.

Papers studying the use stage of case buildings have mainly focused on the older version of green building certificates, while these certificates are continuously updated. For example, with regard to LEED, most studied buildings had LEED v3 which is for the year 2009. It was predictable that the studies include these buildings, as it takes time to construct and then evaluate their energy consumption in the use stage. Therefore, research on buildings that have the newer version of green building certificates is valuable.

The country or location of the studied case buildings is also important. Most studied cases were located in the US (Figure 9), while the construction of green certified buildings is increasing in other countries, particularly in China. As the location plays an important role, it is necessary to conduct research on the cases in other countries when the number is reasonable. Becoming certified in different countries might differ based on the local regulations and the environmental situation. A few tough regulations in certain countries might automatically result in becoming green certified, particularly at lower levels. Therefore, research in different locations of the world is necessary.

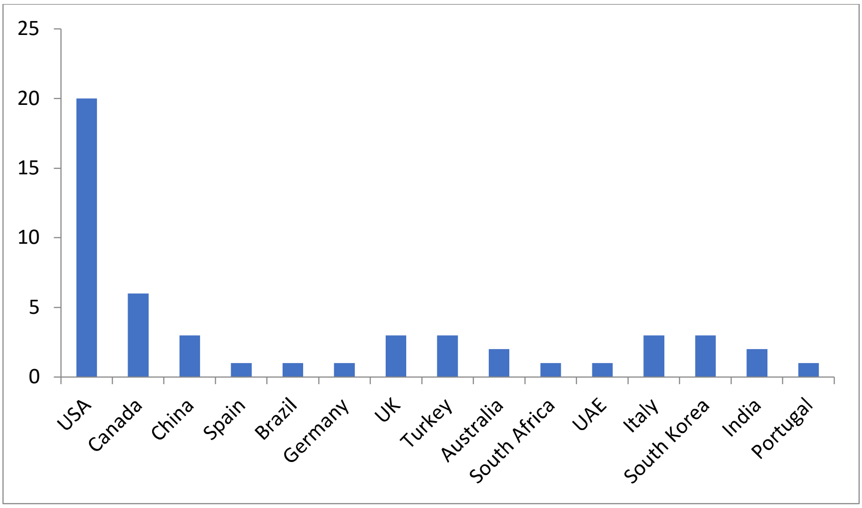


Figure 9. Location distribution of reviewed studies.

There are diverse available materials that might work in a similar manner as wood—that is, they emit lower GHG emissions during their production while storing carbon, which helps to mitigate climate change. There might be new concrete types with potential carbon storage that are beneficial for the short-term climate change mitigation plans. Thus, it is important to design feasible scenarios at the scale of a country or continent to lower environmental impacts. The cement industry is an example of a low-carbon producer which needs improvements. While the environmental impact of concrete production is low per unit volume, what makes the issue important is the absolute amount of used concrete [22]. Habert et al. [22] discovered that it is possible to lower the GHG emissions of producing concrete by 50% if all stakeholders in construction sector are engaged, without heavy investment in future industrial infrastructure or the existing standards modification. In addition, it is important to consider whether it is possible to replace cement by other materials at a large scale within the next decade.

In addition to low-carbon concrete there are other alternative materials which are not only low-carbon but can also store carbon similar to wood. For example, fast-growing biogenic materials like straw has the potential to act as carbon sink and can be used as insulation material for both new construction and renovation [103].

While forests are considered as natural carbon sinks, there has been discussion if wooden building construction is a reliable carbon mitigation strategy as it needs harvesting forest. Generally, there is common argument that it is better to leave forest untouched and allow its natural functioning as carbon sinks. But the issue arises when the forests get older, and their carbon production becomes equal to its carbon capture. In addition, there is surplus of unused wood in forests [56,95] while most engineered wood in Europe come from sustainably managed forests [104].

An efficient way of constructing wooden buildings is the plantation of wood before usage. If plantation is done, there will be benefits like water retention, sequestration [105], and biodiversity conservation [106]. The harvest ratio of 2 to 25 times higher than natural forest is accessible if intensively managed planted forest is taken into account [107]. Based on the recommended scenario in the results chapter, in the year 2030 when the wooden building level reaches to mid-level (200 CO_2 kg m^{-2}) and the share of wooden building reaches to 35%, the wood use will be 14.8 million cubic meters (Mm^3); It is good to notice that based on Food and Agriculture Organization of the United nations (FAO) report in 2018, the annual roundwood use was 2,028 Mm^3 and the wood used as fuel was 1,943 Mm^3 in the world. On the other hand, there is an emphasis in recent research in which it is recommended to use wood in long-lived products like building construction instead of short-lived products like pulp or energy [108].

LCA results used as literature in paper 4 differ significantly from each other. This implies that the decision by policymakers will be a difficult one and they cannot trust the numbers in order to be used for future plans. The difference arises from the LCA method—that is, the process, input, output, or hybrid, apart from the boundary assumptions. It is necessary to conduct more research in this area in order to find reasonable results that can be offered to decision makers.

In addition, the focus of the thesis is on climate change mitigation. However, green building certificates have different categories. Energy and material were evaluated in this study but there are also other main categories, including indoor environmental quality. Future research can be focused on how the quality of the indoor environment can be improved, with the lowest rise in energy use. Moreover, the relationship between material selection and indoor environmental quality during the pre-use stage can also be assessed.

The last suggestion is to conduct research on the end of life (EoL) stage. Although it plays small role in the entire life cycle of buildings, the potential of reuse, recycle, and landfill scenarios have a significant impact on the environment. One of the best solutions is the consideration of EoL stage at the design stage and benefitting from prefabricating, but there are other innovative solutions that are worthy of being researched. In the case of wooden buildings, it is necessary to find solutions in order to retain the stored carbon for a longer period of time instead of landfilling or using the waste wood as renewable energy.

References

1. Gurgun, A.P.; Arditi, D. Assessment of Energy Credits in LEED-Certified Buildings Based on Certification Levels and Project Ownerships. *Buildings* **2018**, *8*, 29.

2. Nilforooshan Razieh , Adamo-Villani Nicoletta , Dib Hazar A study of the effects of computer animation on college students' learning of Leadership in Energy and Environmental Design - LEED. **2013**, *01*, 1-9.

3. Ferreira, J.; Pinheiro, M.D.; de Brito, J. Portuguese sustainable construction assessment tools benchmarked with BREEAM and LEED: an energy analysis. *Energy Build* **2014**, *69*, 451-463.

4. Suh, S.; Lenzen, M.; Treloar, G.J.; Hondo, H.; Horvath, A.; Huppes, G.; Jolliet, O.; Klann, U.; Krewitt, W.; Moriguchi, Y. System boundary selection in life-cycle inventories using hybrid approaches. *Environ Sci Technol* **2004**, *38*, 657-664.

5. Intergovernmental Panel of Climate Change, (IPCC) Climate Change 1995. The Science of Climate Change, Contribution of Working Group II to the Second Assessment Report of the IPCC. **1996**.

6. Manoliadis, O.; Tsolas, I.; Nakou, A. Sustainable construction and drivers of change in Greece: a Delphi study. *Constr Manage Econ* **2006**, *24*, 113-120.

7. Matar, M.M.; Georgy, M.E.; Ibrahim, M.E. Sustainable construction management: introduction of the operational context space (OCS). *Constr Manage Econ* **2008**, *26*, 261-275.

8. Ortiz, O.; Castells, F.; Sonnemann, G. Sustainability in the construction industry: A review of recent developments based on LCA. *Constr Build Mater* **2009**, *23*, 28-39.

9. Säynäjoki, A.; Heinonen, J.; Junnila, S. Carbon footprint assessment of a residential development project. *International Journal of Environmental Science and Development* **2011**, *2*, 116.

10. Junnila, S.I. Empirical comparison of process and economic input-output life cycle assessment in service industries. *Environ Sci Technol* **2006**, *40*, 7070-7076.

11. Junnila, S. *The environmental impact of an office building throughout its life cycle,* Helsinki University of Technology: 2004;.

12. Junnila, S.; Horvath, A. Life-cycle environmental effects of an office building. *J Infrastruct Syst* **2003***, 9*, 157-166.

13. Davis, S.J.; Lewis, N.S.; Shaner, M.; Aggarwal, S.; Arent, D.; Azevedo, I.L.; Benson, S.M.; Bradley, T.; Brouwer, J.; Chiang, Y. Net-zero emissions energy systems. *Science* **2018***, 360*, eaas9793.

14. Scheuer, C.; Keoleian, G.A.; Reppe, P. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. *Energy Build* **2003***, 35*, 1049-1064.

15. Dokka, T.H.; Houlihan Wiberg, Aoife Anne Marie; Georges, L.; Mellegård, S.E.; Time, B.; Haase, M.; Maltha, M.M.; Lien, A.G. A zero emission concept analysis of a single family house. **2013**.

16. Ferrante, A.; Cascella, M.T. Zero energy balance and zero on-site CO2 emission housing development in the Mediterranean climate. *Energy Build* **2011***, 43*, 2002-2010.

17. Ryu, H.; Park, K. A study on the LEED energy simulation process using BIM. *Sustainability* **2016***, 8*, 138.

18. Pitt, M.; Tucker, M.; Riley, M.; Longden, J. Towards sustainable construction: promotion and best practices. *Construction innovation* **2009***, 9*, 201-224.

19. Tam, V.W.; Hao, J.L.; Zeng, S.X. What affects implementation of green buildings? An empirical study in Hong Kong. *International Journal of Strategic Property Management* **2012***, 16*, 115-125.

20. Schwartz, Y.; Raslan, R. Variations in results of building energy simulation tools, and their impact on BREEAM and LEED ratings: A case study. *Energy Build* **2013***, 62*, 350-359.

21. Menassa, C.; Mangasarian, S.; El Asmar, M.; Kirar, C. Energy consumption evaluation of US Navy LEED-certified buildings. *J Perform Constr Facil* **2011***, 26*, 46-53.

22. Habert, G.; Röck, M.; Steininger, K.; Lupísek, A.; Birgisdottir, H.; Desing, H.; Chandrakumar, C.; Pittau, F.; Passer, A.; Rovers, R. Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions. *Buildings and Cities* **2020***, 1*, 429-452.

23. Yudelson, J. *The green building revolution,* Island Press: 2010;.

24. Kibert, C.J. *Sustainable construction: green building design and delivery,* John Wiley & Sons: 2016;.

25. Dall'O, G.; Bruni, E.; Panza, A. Improvement of the sustainability of existing school buildings according to the Leadership in Energy and Environmental Design (LEED)® Protocol: A case study in Italy. *Energies* **2013***, 6*, 6487-6507.

26. Fuerst, F. Building momentum: An analysis of investment trends in LEED and Energy Star-certified properties. *Journal of Retail & Leisure Property* **2009***, 8*, 285-297.

27. Sameni, S.M.T.; Gaterell, M.; Montazami, A.; Ahmed, A. Overheating investigation in UK social housing flats built to the Passivhaus standard. *Build Environ* **2015**, *92*, 222-235.

28. Consoli, A.; Costanzo, V.; Evola, G.; Marletta, L. Refurbishing an existing apartment block in Mediterranean climate: towards the Passivhaus standard. *Energy Procedia* **2017**, *111*, 397-406.

29. Saldaña-Márquez, H.; Gómez-Soberón, J.M.; Arredondo-Rea, S.P.; Gámez-García, D.C.; Corral-Higuera, R. Sustainable social housing: The comparison of the Mexican funding program for housing solutions and building sustainability rating systems. *Build Environ* **2018**, *133*, 103-122.

30. Vyas, G.S.; Jha, K.N. What does it cost to convert a non-rated building into a green building? *Sustainable Cities and Society* **2018**, *36*, 107-115.

31. Burnett, J. Sustainability and sustainable buildings. *HKIE Transactions* **2007**, *14*, 1-9.

32. Shen, L.; Li Hao, J.; Tam, V.W.; Yao, H. A checklist for assessing sustainability performance of construction projects. *Journal of civil engineering and management* **2007**, *13*, 273-281.

33. Poveda, C.A.; Young, R. Potential benefits of developing and implementing environmental and sustainability rating systems: Making the case for the need of diversification. *International Journal of Sustainable Built Environment* **2015**, *4*, 1-11.

34. Scofield, J.H. Do LEED-certified buildings save energy? Not really…. *Energy Build* **2009**, *41*, 1386-1390.

35. Scofield, J.H. Efficacy of LEED-certification in reducing energy consumption and greenhouse gas emission for large New York City office buildings. *Energy Build* **2013**, *67*, 517-524.

36. Scofield, J.H.; Doane, J. Energy performance of LEED-certified buildings from 2015 Chicago benchmarking data. *Energy Build* **2018**, *174*, 402-413.

37. Newsham, G.R.; Mancini, S.; Birt, B.J. Do LEED-certified buildings save energy? Yes, but…. *Energy Build* **2009**, *41*, 897-905.

38. Issa, M.H.; Attalla, M.; Rankin, J.H.; Christian, A.J. Energy consumption in conventional, energy-retrofitted and green LEED Toronto schools. *Constr Manage Econ* **2011**, *29*, 383-395.

39. Chen, H.; Lee, W.L.; Wang, X. Energy assessment of office buildings in China using China building energy codes and LEED 2.2. *Energy Build* **2015**, *86*, 514-524.

40. Sabapathy, A.; Ragavan, S.K.; Vijendra, M.; Nataraja, A.G. Energy efficiency benchmarks and the performance of LEED rated buildings for Information Technology facilities in Bangalore, India. *Energy Build* **2010**, *42*, 2206-2212.

41. Uğur, L.O.; Leblebici, N. An examination of the LEED green building certification system in terms of construction costs. *Renewable and Sustainable Energy Reviews* **2017**.

42. Cubi Montanya, E.; Keith, D.W. LEED, Energy Savings, and Carbon Abatement: Related but Not Synonymou. *Environmental Science and Technology* **2011**, 1757-1758.

43. Kern, A.P.; Antoniolli, C.B.; Wander, P.R.; Mancio, M.; González, M.A.S. Energy and water consumption during the post-occupancy phase and the users' perception of a commercial building certified by Leadership in Energy and Environmental Design (LEED). *J Clean Prod* **2016***, 133*, 826-834.

44. Reichardt, A. Operating expenses and the rent premium of energy star and LEED certified buildings in the central and eastern US. *The Journal of Real Estate Finance and Economics* **2014***, 49*, 413-433.

45. Suh, S.; Tomar, S.; Leighton, M.; Kneifel, J. Environmental performance of green building code and certification systems. *Environ Sci Technol* **2014***, 48*, 2551-2560.

46. Hu, M.; Cunningham, P.; Gilloran, S. Sustainable design rating system comparison using a life-cycle methodology. *Build Environ* **2017***, 126*, 410-421.

47. Lessard, Y.; Anand, C.; Blanchet, P.; Frenette, C.; Amor, B. LEED v4: where are we now? Critical assessment through the LCA of an office building using a low impact energy consumption mix. *J Ind Ecol* **2018***, 22*, 1105-1116.

48. Pierobon, F.; Huang, M.; Simonen, K.; Ganguly, I. Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the US Pacific Northwest. *Journal of Building Engineering* **2019***, 26*, 100862.

49. Takano, A.; Hughes, M.; Winter, S. A multidisciplinary approach to sustainable building material selection: A case study in a Finnish context. *Build Environ* **2014***, 82*, 526-535.

50. Takano, A.; Hafner, A.; Linkosalmi, L.; Ott, S.; Hughes, M.; Winter, S. Life cycle assessment of wood construction according to the normative standards. *European journal of wood and wood products* **2015***, 73*, 299-312.

51. Hafner, A.; Winter, S.; Takano, A. Wooden products as building material in life cycle analysis, Life-cycle and Sustainability of Civil Infrastructure Systems: Proceedings of the Third International Symposium on Life-Cycle Civil Engineering (IALCCE'12), 2012; , pp. 1530-1537.

52. Passer, A.; Kreiner, H.; Maydl, P. Assessment of the environmental performance of buildings: A critical evaluation of the influence of technical building equipment on residential buildings. *The International Journal of Life Cycle Assessment* **2012***, 17*, 1116-1130.

53. Gong, X.; Nie, Z.; Wang, Z.; Cui, S.; Gao, F.; Zuo, T. Life cycle energy consumption and carbon dioxide emission of residential building designs in Beijing: a comparative study. *J Ind Ecol* **2012**, *16*, 576-587.

54. Fuller, R.J.; Crawford, R.H. Impact of past and future residential housing development patterns on energy demand and related emissions. *Journal of housing and the built environment* **2011**, *26*, 165-183.

55. Fay, R.; Treloar, G.; Iyer-Raniga, U. Life-cycle energy analysis of buildings: a case study. *Build Res Inf* **2000**, *28*, 31-41.

56. Gustavsson, L.; Pingoud, K.; Sathre, R. Carbon dioxide balance of wood substitution: comparing concrete-and wood-framed buildings. *Mitigation Adapt Strat Global Change* **2006**, *11*, 667-691.

57. European Commission. Available online: https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2.html (Accessed on 14.10. 2019).

58. European Union CO2 emissions data from cement plants in 2018. Available online: https://www.globalcement.com/news/item/9060-european-union-co2-emissions-data-from-cement-plants-in-2018 (Accessed on 4 April 2020).

59. Dodoo, A.; Gustavsson, L.; Sathre, R. Carbon implications of end-of-life management of building materials. *Resour Conserv Recycling* **2009**, *53*, 276-286.

60. Reddy, B.V.; Jagadish, K.S. Embodied energy of common and alternative building materials and technologies. *Energy Build* **2003**, *35*, 129-137.

61. Thormark, C. The effect of material choice on the total energy need and recycling potential of a building. *Build Environ* **2006**, *41*, 1019-1026.

62. Verbeeck, G.; Hens, H. Life cycle optimization of extremely low energy dwellings. *Journal of Building Physics* **2007**, *31*, 143-177.

63. Creswell, J.W.; Creswell, J. *Research design,* Sage publications Thousand Oaks, CA: 2003;.

64. Patton, M.Q. Qualitative research. *Encyclopedia of statistics in behavioral science* **2005**.

65. Clandinin, D.J. *Handbook of narrative inquiry: Mapping a methodology,* Sage Publications: 2006;.

66. Mayer, P. Guidelines for writing a Review Article. **2009**.

67. Yin, R.K. Case study research: Design and methods, applied social research. *Methods series* **1994**, *5*.

68. Tetnowski, J. Qualitative case study research design. *Perspectives on Fluency and Fluency Disorders* **2015**, *25*, 39-45.

69. Klopffer, W. Life cycle assessment-from the beginning to the current state. *Environmental Science and Pollution Research* **1997**, *4*, 223-228.

70. Crawford, R. *Life cycle assessment in the built environment,* Routledge: 2011;.

71. Crawford, R.H.; Bontinck, P.; Stephan, A.; Wiedmann, T.; Yu, M. Hybrid life cycle inventory methods–A review. *J Clean Prod* **2018***, 172*, 1273-1288.

72. Suh, S.; Lenzen, M.; Treloar, G.J.; Hondo, H.; Horvath, A.; Huppes, G.; Jolliet, O.; Klann, U.; Krewitt, W.; Moriguchi, Y. System boundary selection in life-cycle inventories using hybrid approaches. *Environ Sci Technol* **2004***, 38*, 657-664.

73. Säynäjoki, A.; Heinonen, J.; Junnila, S.; Horvath, A. Can life-cycle assessment produce reliable policy guidelines in the building sector? *Environmental Research Letters* **2017***, 12*, 013001.

74. Yang, Y.; Heijungs, R.; Brandão, M. Hybrid life cycle assessment (LCA) does not necessarily yield more accurate results than process-based LCA. *J Clean Prod* **2017***, 150*, 237-242.

75. Stephan, A.; Crawford, R.H.; Bontinck, P. A model for streamlining and automating path exchange hybrid life cycle assessment. *The International Journal of Life Cycle Assessment* **2019***, 24*, 237-252.

76. Majeau-Bettez, G.; Strømman, A.H.; Hertwich, E.G. Evaluation of process-and input–output-based life cycle inventory data with regard to truncation and aggregation issues. *Environ Sci Technol* **2011***, 45*, 10170-10177.

77. Hildebrandt, J.; Hagemann, N.; Thrän, D. The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe. *Sustainable cities and society* **2017***, 34*, 405-418.

78. Abergel, T.; Dean, B.; Dulac, J. Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector. **2018**.

79. Michael, M.; Zhang, L.; Xia, X. An optimal model for a building retrofit with LEED standard as reference protocol. *Energy Build* **2017***, 139*, 22-30.

80. Fuerst, F.; McAllister, P. Eco-labeling in commercial office markets: Do LEED and Energy Star offices obtain multiple premiums? *Ecol Econ* **2011***, 70*, 1220-1230.

81. Jeong, J.; Hong, T.; Ji, C.; Kim, J.; Lee, M.; Jeong, K. Development of an evaluation process for green and non-green buildings focused on energy performance of G-SEED and LEED. *Build Environ* **2016***, 105*, 172-184.

82. Al-Ghamdi, S.G.; Bilec, M.M. Life-cycle thinking and the LEED rating system: global perspective on building energy use and environmental impacts. *Environ Sci Technol* **2015***, 49*, 4048-4056.

83. Heidarinejad, M.; Dahlhausen, M.; McMahon, S.; Pyke, C.; Srebric, J. Cluster analysis of simulated energy use for LEED certified US office buildings. *Energy Build* **2014***, 85*, 86-97.

84. Fuertes, G.; Schiavon, S. Plug load energy analysis: The role of plug loads in LEED certification and energy modeling. *Energy Build* **2014***, 76*, 328-335.

85. Chokor, A.; El Asmar, M. Data-Driven Approach to Investigate the Energy Consumption of LEED-Certified Research Buildings in Climate Zone 2B. *J Energy Eng* **2016***, 143*, 05016006.

86. Wedding, G.C.; Crawford-Brown, D. Improving the link between the LEED green building label and a building's energy-related environmental metrics. *Journal of Green Building* **2008***, 3*, 85-105.

87. Ng, T.K.; Kwok, S.M. Carbon emission estimation—A design verification tool for new public housing developments in Hong Kong, Proceedings of the HKU-HKHA International Conference, Hong Kong, China, 2013; , pp. 2-3.

88. Dong, Y.H.; Ng, S.T. A life cycle assessment model for evaluating the environmental impacts of building construction in Hong Kong. *Build Environ* **2015***, 89*, 183-191.

89. Amiri, A.; Ottelin, J.; Sorvari, J.; Junnila, S. Economic and Technical Considerations in Pursuing Green Building Certification: A Case Study from Iran. **2020**.

90. Amiri, A.; Emami, N.; Ottelin, J.; Sorvari, J.; Marteinsson, B.; Heinonen, J.; Junnila, S. Embodied emissions of buildings-A forgotten factor in green building certificates. *Energy Build* **2021***, 241*, 110962.

91. Amiri, A.; Ottelin, J.; Sorvari, J. Are LEED-Certified Buildings Energy-Efficient in Practice? *Sustainability* **2019***, 11*, 1672.

92. Stoppel, C.M.; Leite, F. Evaluating building energy model performance of LEED buildings: Identifying potential sources of error through aggregate analysis. *Energy Build* **2013***, 65*, 185-196.

93. Brown, C.; Gorgolewski, M. Assessing occupant satisfaction and energy behaviours in Toronto's LEED gold high-rise residential buildings. *International Journal of Energy Sector Management* **2014***, 8*, 492-505.

94. Winther, B.N.; Hestnes, A.G. Solar versus green: the analysis of a Norwegian row house. *Solar Energy* **1999***, 66*, 387-393.

95. Robertson, A.B.; Lam, F.C.; Cole, R.J. A comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: Laminated timber or reinforced concrete. *Buildings* **2012***, 2*, 245-270.

96. Amiri, A.; Ottelin, J.; Sorvari, J.; Junnila, S. Cities as carbon sinks-classification of wooden buildings. *Environmental Research Letters* **2020**.

97. Leskinen, N.; Vimpari, J.; Junnila, S. A Review of the Impact of Green Building Certification on the Cash Flows and Values of Commercial Properties. *Sustainability* **2020***, 12*, 2729.

98. Emami, N.; Marteinsson, B.; Heinonen, J. Environmental impact assessment of a School building in Iceland using LCA-including the effect of long distance transport of materials. *Buildings* **2016***, 6*, 46.

99. Takano, A.; Hughes, M.; Winter, S. A multidisciplinary approach to sustainable building material selection: A case study in a Finnish context. *Build Environ* **2014**, *82*, 526-535.

100. Passer, A.; Kreiner, H.; Maydl, P. Assessment of the environmental performance of buildings: A critical evaluation of the influence of technical building equipment on residential buildings. *The International Journal of Life Cycle Assessment* **2012**, *17*, 1116-1130.

101. Heräjärvi, H. Wooden buildings as carbon storages–Mitigation or oration? *Wood Material Science & Engineering* **2019**, *14*, 291-297.

102. Churkina, G.; Organschi, A.; Reyer, C.P.O.; Ruff, A.; Vinke, K.; Liu, Z.; Reck, B.K.; Graedel, T.E.; Schellnhuber, H.J. Buildings as a global carbon sink. *Nature Sustainability* **2020**.

103. Pittau, F.; Lumia, G.; Heeren, N.; Iannaccone, G.; Habert, G. Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. *J Clean Prod* **2019**, *214*, 365-376.

104. Dickson, M.; Parker, D. *Sustainable Timber Design,* Routledge: London, 2015;.

105. Pawson, S.M.; Brin, A.; Brockerhoff, E.G.; Lamb, D.; Payn, T.W.; Paquette, A.; Parrotta, J.A. Plantation forests, climate change and biodiversity. *Biodivers Conserv* **2013**, *22*, 1203-1227.

106. Paquette, A.; Messier, C. The role of plantations in managing the world's forests in the Anthropocene. *Frontiers in Ecology and the Environment* **2010**, *8*, 27-34.

107. Jagels, R. Management of wood properties in planted forests. A paradigm for global forest production. **2006**.

108. Sterman, J.D.; Siegel, L.; Rooney-Varga, J.N. Does replacing coal with wood lower CO2 emissions? Dynamic lifecycle analysis of wood bioenergy. *Environmental Research Letters* **2018**, *13*, 015007.

Aalto-DD 147/2021

Buildings have three stages in their life cycle: pre-use (construction), use (operation) and end of life (EoL). During the main stages, pre-use and use, buildings use a large amount of energy and materials, which results in greenhouse gas (GHG) emissions. To limit the environmental impact of buildings while providing better indoor air quality, various types of green building certificates have been issued from 1998 onwards. This thesis used the literature in addition to original research to evaluate whether green building certificates have been successful in reaching their main goal of limiting environmental impact. It found that in the use stage of the buildings, green building certificates have been successful in higher levels of the certificates (more stringent requirements), but in lower levels, the success is questionable. In the pre-use stage, there is a need for improvements in the certificates, especially regarding low-carbon materials.
Wood, as a low-carbon material, can be considered an option for future building construction. Not only does it have lower GHG emissions than concrete and steel, but it also has the potential to store carbon for a long time. With sustainable forest management and practical planning, the switch to wooden buildings is an intelligent solution for climate change.

9789526405629

ISBN 978-952-64-0562-9 (printed)
ISBN 978-952-64-0563-6 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

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