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Green isn't just a colour – sustainable buildings already exist

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Preface

Green isn’t just a colour – sustainable buildings already exist

The Norwegian project ‘*Kartlegging av gjennomførte klimaberegninger på eksisterende bygg*’ was launched by the Norwegian Directorate for Cultural Heritage in 2019. This is the English version of the report "*Grønt er ikke bare en farge: Bærekraftige bygninger eksisterer allerede. SINTEF Fag 68. ISBN: 978-82-536-1669-8*".

The work has been carried out by Selamawit Mamo Fufa, Cecilie Flyen, and Christoffer Venås at SINTEF Community. Marianne Kjendseth Wiik and Kristin Fjellheim at SINTEF Community, and Anne-Cathrine Flyen at the Norwegian Institute for Cultural Heritage Research (NIKU), have carried out quality assurance of the project.

Oslo, December 2021

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Executive Summary

This report has been commissioned by the Norwegian Directorate for Cultural Heritage with the aim of providing an overall picture of the environmental significance of the reuse of existing buildings. The approach used has involved a systematic assessment and meta-analysis of life cycle assessments performed in connection with the rehabilitation and upgrading of existing buildings. The study has reviewed Norwegian and international publications containing life cycle assessments of existing buildings. The selection of Norwegian case studies was made based on previously completed research projects. Some international case studies were also reviewed, some of which were suggested by the Norwegian Directorate for Cultural Heritage. Data from these sources were used to carry out a high-level meta-analysis, and to provide an overview of results taken from known life cycle assessments of existing buildings. As part of the background to, and discussion included in, this report, major focus has been directed towards the cultural heritage value of existing building stock.

A key factor behind this study is Norway's target to become a low-emissions society by 2050, which has its foundation in the Paris Agreement and the UN Sustainable Development Goals. In spite of the emergence in many countries of climate-related ambitions and political targets, the volume of global greenhouse gas (GHG) emissions continues to increase. The UN Environment Programme's 'Emissions Gap Report 2019' highlighted the limited realisation of national commitments in the Paris Agreement, and which at current implementation rates will not be sufficient to achieve the goals set out in the agreement. Achievement of the 1.5-degree Celsius global warming target will require greater levels of ambition, combined with the much faster implementation of a wide range of measures during the coming decades. This situation shows just how important it is to be researching how our existing building stock can contribute towards achieving our climate-related political targets for emission reductions. About 80 to 90% of our existing building stock will still be in use in 2050. In Norway, current building upgrade rates are low (at about 1 to 1.4%). The EU Commission has pointed out that 75% of the EU's current building stock is energy inefficient, and that building upgrades have the potential to provide energy savings and GHG emission reductions of between 5 and 6%. Considering that most of the world's building stock in 2050 already exists today, the rehabilitation and adaptive reuse of existing buildings will make a decisive contribution to a sustainable future.

The research front indicates that the potential environmental benefits of upgrading existing buildings are great compared with the potential benefits from new-build projects, because the emissions generated during rehabilitation represent only a half of those associated with new builds. Results from Life Cycle Assessment (LCA) studies indicate that GHG reductions in the case of existing buildings are mainly the result of reduced embodied GHG emissions. This means that by conserving existing buildings, and the materials in them, we can avoid the embodied emissions that are inherent in the construction of new buildings. New builds involve not only more waste generation from the demolition of old buildings, but the energy and emissions associated with the production, transport, and installation of new materials, products, and elements, as well as waste generation in the construction process. The Norwegian case studies reveal that GHG emissions linked to the use of materials for the upgrading of existing buildings amount to only a third of those linked to new build projects.

This study demonstrates that, if possible, the environmentally sound upgrading of existing buildings should be favoured in preference to their demolition and replacement by new builds, because reuse is more in harmony with the targets set out in the Paris Agreement and the UN Sustainable Development Goals. In the case of new buildings, results indicate that it takes ten years before the environmental benefits from lower annual emissions from in-use energy consumption offset the negative impacts from the increase in emissions from their construction. Findings in the literature support the idea that rehabilitation is preferable in the 30-year perspective as we approach 2050, because it may take anything from 10 to 80 years before a new building can offset the GHG emissions that are generated during its construction (in year zero). We may conclude from this that, from an environmental perspective, the rehabilitation of existing buildings will be more beneficial to the environment in the short and medium term.

The selection of locally sourced low-carbon materials, combined with the use of renewable energy and the implementation of energy efficiency measures, are the most important ways of reducing emissions, and should be given due consideration during the upgrading of existing buildings. There is wide variation in the energy efficiency potential of the existing building stock, depending on factors such as age, materials use, construction elements, conservation value, and current status of preservation. Requirements related to energy consumption and efficiency measures should be tailored to the type of building in question and its specific circumstances. The case studies presented in this report exhibit large variations in possible GHG emission reductions, which are the result of a number of methodological choices. Naturally enough, the results also vary depending on case-specific factors such as the rehabilitation measures considered. For this reason, we conclude that comprehensive life cycle assessments offer important decision-making tools in our search to identify exactly what constitutes effective rehabilitation measures.

A life cycle approach is key to obtaining more thorough assessments of the sustainability of existing buildings. This study has revealed that few LCAs of existing buildings have been carried out. Moreover, there are major uncertainties linked to the studies that have been performed, largely due to variability and deficiencies inherent in the methods applied. A life cycle assessment is of greater value when it incorporates environmental indicators other than simply GHG emissions, combined with social/societal and economic factors. Such assessments help avoid problem-shifting, and can help ensure that environmentally-friendly measures are not implemented at the expense of other important factors such as cultural and historic conservation considerations.

If life cycle assessments are to be used to support decision-making, the scenarios used to evaluate the various approaches to building rehabilitation or demolition should be as realistic as possible. Basic uncertainties inherent in the scenarios must be discussed to a much greater extent than is currently the case. Assessments that examine only materials use and use-phase energy consumption are insufficient to provide an informed basis for decision making in a scenario involving the choice between the rehabilitation of a building versus demolition and new construction. The assessments should take into account the emissions generated during the construction phase, as well as those related to waste disposal activities linked to both the existing and new building. Inherent uncertainties in the energy calculations must also be highlighted as part of such assessments because they are crucial to the results.

This report draws the following three main conclusions based on the findings from this study:

1) There exists a major unrealised potential in terms of environmental benefits linked to existing building stock. If possible, rehabilitation should be favoured in preference to demolition and the construction of new buildings, in accordance with Norwegian and international climate change targets.
2) When assessing environmentally friendly rehabilitation measures, both cultural and historic conservation considerations should be taken into account.
3) Comprehensive life cycle assessments represent key decision-making support tools, helping to identify the most effective rehabilitation measures.

In conclusion, the following list of recommendations is presented based on the findings and conclusions drawn from this study:

- Ambitions related to building rehabilitation projects must be clearly defined.
- Comprehensive life cycle assessments should be used as decision support tools.

- Environmental LCAs should be combined with Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) in order to obtain more holistic and sustainable perspectives on existing buildings.
- All possible rehabilitation measures should be considered when it comes to cultural heritage buildings, provided that these are not implemented at the expense of their conservation value.
- A process of gathering documentation related to best practice should be started.
- Incentives and subsidy schemes for the extensive rehabilitation projects should be evaluated and introduced.
- The UN Sustainable Development Goals should be used as a tool to influence the sustainable development of our building stock.

Glossary of Terms

This glossary has been compiled from a variety of sources with the aim of providing definitions of the most important terms used in this report. Many of the terms used in the report are not normally used in connection with activities linked to cultural heritage buildings. However, many of the terms that are used in the literature reviewed cannot be expressed in any other way. This is due to a great extent to an awareness, or lack thereof, regarding the use of terminology regarding measures used in connection with cultural heritage buildings.

Adaptive reuse: Addresses a process whereby an existing building is reused or recycled for a purpose other than that for which it was originally intended. In doing so the major part of the original building is preserved, such as its fundamental structure, while other elements may be upgraded in order to adapt to new standards or modified user needs. The term 'adaptive' embraces rehabilitation, upgrading or restoration work that does not necessarily involve changes in use (Bullen Peter, 2007).

Conditional Nationally Determined Contributions (NDCs): Under the Paris Agreement, signatory countries submit their emission reduction targets. Conditional NDCs are country-based targets which are dependent on a given set of conditions being in place for them to be valid. These conditions may involve external financial, political, or legal support. This distinguishes Conditional NDCs from Unconditional NDCs that are intended to be achieved without external support, and which are generally less ambitious (UNEP, 2019d).

Embodied energy: The total energy required for extraction, manufacturing and transport of building materials, energy used in building construction, as well as energy used for production and delivery of the materials used in the use phase (SINTEF, 2016).

Embodied greenhouse gas (GHG) emissions: In the case of buildings, this term refers to the accumulated carbon footprint embodied in the products, building and other materials, resulting from emissions generated during their manufacture and the maintenance and disposal of the building itself. These emissions are considered to be 'embodied' in the building's materials.

UN Climate Conferences (Conferences of the Parties/COP): The COPs represent the highest decision-making bodies for signatory countries to the United Nations Framework Convention on Climate Change and are convened annually to evaluate progress and pre-negotiate more binding treaty protocols (UNEP, 2019d).

Carbon dioxide emissions budget, or carbon budget: For a given temperature increase (global warming) limit, such as the stated long-term limits of 1.5 °C or 2 °C, the carbon budget reflects the equivalent volume of carbon dioxide (CO_2) that can be emitted in order to ensure that temperatures remain below the stated limit (UNEP, 2019d).

Carbon dioxide equivalent (CO_2eq): Greenhouse gas (GHG) emissions, which cause global warming and climate change, are the sum of the curve incorporating all six GHGs listed in Annex A of the Kyoto Protocol. This is expressed in terms of CO_2eq, under assumptions about the gases' potential to generate global warming over a period of 100 years. The most important GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) (UNEP, 2019d).

Lifetime (Reference study period): A building's lifetime is defined as the period of time after construction during which it meets or exceeds its specified performance requirements (ISO 15686-1:2011). It is defined by a general reference study period (NS-EN 15978:2011) and a mandatory study period (as required by developers or regulations) (NS-EN 15643-1:2010)).

Meta-analysis: A statistical analysis of results from a variety of studies that provide an overall quantitative estimate of the parameters under investigation (Petticrew & Roberts, 2008).

Zero-emissions building: A building that generates sufficient renewable energy to compensate for the GHG emissions it generates during its lifetime (SINTEF, 2016).

Nationally Determined Contribution (NDC): An NDC represents the value of the current ambition or target for emission reductions submitted by a signatory country as its contribution towards meeting the overall targets set out in the Paris Agreement. New or updated contributions shall be submitted in 2020 and subsequently every five years. So-called 'Intended Nationally Determined Contributions' (INDCs) represent a country's initial targets and signal the country's emission reduction ambitions and strategies, as well as the conditions that have to be in place for it to be able to meet its stated targets. These are later ratified, and in doing so become Nationally Determined Contributions (NDCs) (UNEP, 2019d).

Upgrading/energy upgrading: The term 'upgrading' is used in its broadest sense to describe anything from extensive improvements to a given building to individual measures that boost its performance.

Energy-plus house: This is a building that during its lifetime produces more renewable energy than was consumed in the manufacture of its building materials, construction, use and disposal (SINTEF, 2016).

Powerhouse: A powerhouse is defined as a building, including the land on which it stands, which generates more renewable energy than is required for the manufacture of its component building materials, construction, use, maintenance and ultimate demolition (SINTEF, 2016).

Rehabilitation/renovation: In this report, the terms rehabilitation and renovation are used primarily to describe activities that involve the repair of an existing building, where said activities take place over a limited time period (such as in a building project), and which are of limited scope.

Systematic (literature) review: A systematic literature review is an approach used to address current research questions by means of the identification and critical evaluation of findings presented in relevant publications. The aim of such reviews is to investigate the scope of the existing literature within a given field of research and to identify trends and shortcomings within the field, including trends that emerge within a given period of time.

Unconditional NDCs: Under the Paris Agreement, signatory countries submit their emission reduction targets. Unconditional NDCs represent targets that shall be achieved without external support (UNEP, 2019d).

Emissions gap: The 'emissions gap' represents the difference between reported or expected trends in GHG emissions based on actual or submitted reductions, and the emissions pathways that are estimated to be required to limit global warming to 2 °C or 1.5 °C (above pre-industrial levels) in the year 2100 (UNEP, 2019d).

Contents

1 Introduction

This report is the result the CLIMAP-X project, funded by the Norwegian Directorate for Cultural Heritage. The project studied and evaluated the actual environmental benefits and drawbacks of existing buildings taken from a systematic assessment of accessible Norwegian and international publications and project reports.

1.1 Objectives and scope of this study

The main objective of the project is to provide a clear and holistic overview of the relevance of the existing building stock to the current debate surrounding greenhouse gas (GHG) emissions. This is achieved by investigating the actual environmental benefits, shortcomings, and opportunities inherent in the upgrading of existing buildings viewed from a life cycle perspective.

The scope of this study is limited to existing buildings, with a specific focus on cultural heritage buildings. It takes a Life Cycle Assessment (LCA) approach, involving comparisons with a number of new buildings.

The subsidiary objectives of the project are as follows:

- to identify the potential environmental benefits to be gained from the upgrading and/or rehabilitation of the existing building stock
- to identify the overall performance levels of existing buildings and compare these with corresponding levels for new buildings.

The main and subsidiary objectives shall be achieved by taking the following methodological approach:

- A systematic literature review of studies considering the building life cycle as a means of assessing environmental performance levels in connection with the upgrading of existing buildings. This approach may help to highlight knowledge gaps and point to new areas of research.
- The study shall provide a holistic assessment of many aspects of the rehabilitation of buildings as described in the literature. These include the results of rehabilitation and restoration projects, such as the incorporation of new construction components and energy systems, heritage value, adaptive reuse, direct and indirect environmental impacts during the building life cycle, and methodological approaches linked to life cycle assessment. The study have also investigated potential mitigations of environmental impact from the reuse and recycling of materials and products during rehabilitation processes, as well as possible benefits derived from the end of life of the building.
- A meta-analysis, analysing and comparing the results from the selected case studies, serves to quantify, and provide support for a better understanding of, environmental impacts incurred during the life cycle of existing buildings.

The terms renovation, restoration, rehabilitation, rebuilding, and adaptive reuse are often used interchangeably, and there seems to be little public awareness of the meanings of these terms. This report adopts a deliberate awareness of this issue, consistently using the terms upgrading and/or rehabilitation as collective expressions for all the terms mentioned above. Please refer to the *Glossary of Terms* at the beginning of this report.

The following research questions were developed to address the objectives of this study:

- What is the current status of research in terms of the significance of the environmental impact of existing buildings?
    - What relevant aspects, such as building rehabilitation processes, circular measures, heritage value, and choice of method, are highlighted in the literature?
    - What consideration is given to cultural heritage in the literature?

- What is the environmental performance of the existing building stock following upgrading/rehabilitation, compared with demolition and new construction?
    - What are the direct and indirect environmental impacts of the projects described in the literature?
    - To what extent are the various reference studies comparable?
    - What criteria are needed to enable a comparison between the different reference studies?
    - What research gaps emerge from the literature, and can these be considered as foundations for further research?

1.2 About this report

This first chapter provides a brief introduction to the purpose of the study and sets out its scope and objectives. Chapter 2 offers an expanded introduction to the thematic aspects of the project, combined with an overview of the relevant studies relating to the motivations, barriers and opportunities that strengthen the basis of the study. Chapter 3 provides a description of the methodology used to evaluate and discuss the systematic review of the selected case studies, as well as the meta-analysis carried out on the results of the LCAs presented in these studies. Chapter 4 presents the results of the systematic literature review. Chapter 5 presents the results from the case studies. Chapter 6 discusses the main findings of the study, with an emphasis on the findings described in Chapters 4 and 5. Chapter 7 presents conclusions and recommendations for further work.

2 Background

This chapter summarises the current knowledge that forms the basis of project research into the significance of existing buildings in the debate surrounding greenhouse gas (GHG) emissions. The key basic information is addressed and summarised, along with its relevance and significance. Since this is a global issue, this basic information is presented both in a global and a Norwegian perspective, and usually in that order. Much of the work carried out by the EU in the fields of the environment and climate change is highly relevant both to Norway and the world, so much of the discussion focuses on important information obtained from EU sources.

2.1 The UN's Sustainable Development Goals, climate change policy and ambitions

The UN Millennium Goals constituted a key joint plan agreed among the member countries with the aim of reducing extreme poverty and inequality during the period 2000 to 2015. The extension of this work to achieve a better world resulted in 2015 in the decision to define a set of Sustainable Development Goals (SDGs). In accepting these, member countries recognised the significance of sustainable development as a means of achieving a peaceful and less unequal world.

https://www.un.org/sustainabledevelopment/)

The 17 SDGs, together with their subsidiary objectives (Figure 2.1) that fully incorporate environmental, social, and economic sustainability, have assigned sustainability research a more prominent status in the global debate (Filho et al., 2018). SDGs not only constitute a tool that enables the holistic integration of a sustainability perspective into national policymaking, but also serve to promote a frame of reference within which sustainability is incorporated into the activities of private sector organisations. Goubran & Cucuzzella (2019) discuss how the SDGs can be integrated into construction projects and highlight eight of the goals in particular where the construction industry must exert a crucial influence if the overall goals are to be met by 2030. Tools can be used to implement the SDGs in the Integrated Design Process (IDP) to develop more sustainable building practices and are especially promising for addressing sustainability in the early design.

The Kyoto Protocol, which was signed in 1997 at the COP3 Climate Change Summit, constituted the first ever framework for a globally binding agreement to limit GHG emissions (Amanatidis, 2019). It mandated industrialised countries to reduce their total GHG emissions by at least 5% in the period 2008–2012, and by at least 18% in the period 2013–2020, compared with emissions levels in 1990.

The extension of the Kyoto Protocol took place with the signing of the Paris Agreement in December 2015 (at COP25) and represented a major step towards a global action plan to mitigate the impact of climate change. The agreement was signed by 195 countries with the aim of keeping global warming below 2 °C above pre-industrial levels, and to continue existing efforts to keep warming below 1.5 °C. In terms of global action, the EU was the first to take steps by setting ambitious energy and climate change targets for the periods leading up to 2020 and 2030, combined with an ambition to make Europe carbon neutral by 2050 (Amanatidis, 2019, EU). The target for 2030 is to reduce GHG emissions by 40% compared with 1990 levels (taken from the Kyoto Protocol), to boost energy efficiency by 32.5%, and to increase the share of renewables in the energy system to at least 32%.

2.1.1 Major gap between ambitions and actual emissions

Despite progress made in many countries in terms of climate change ambitions and policies, global GHG emissions continue to rise. The UN Environmental Programme's annual 'Emissions Gap Report' presents an analysis of the gap that exists between actual emissions and the aspirational emission reduction targets of 1.5 and 2 °C set out in the Paris Agreement. In its 2019 report, UNEP stated that global emissions continued to rise during 2018, with a 1.5% annual increase since 2008, and trends suggesting that as of 2020 the targets would be missed (Figure 2.2) (UNEP, 2019a; UNEP, 2019b).

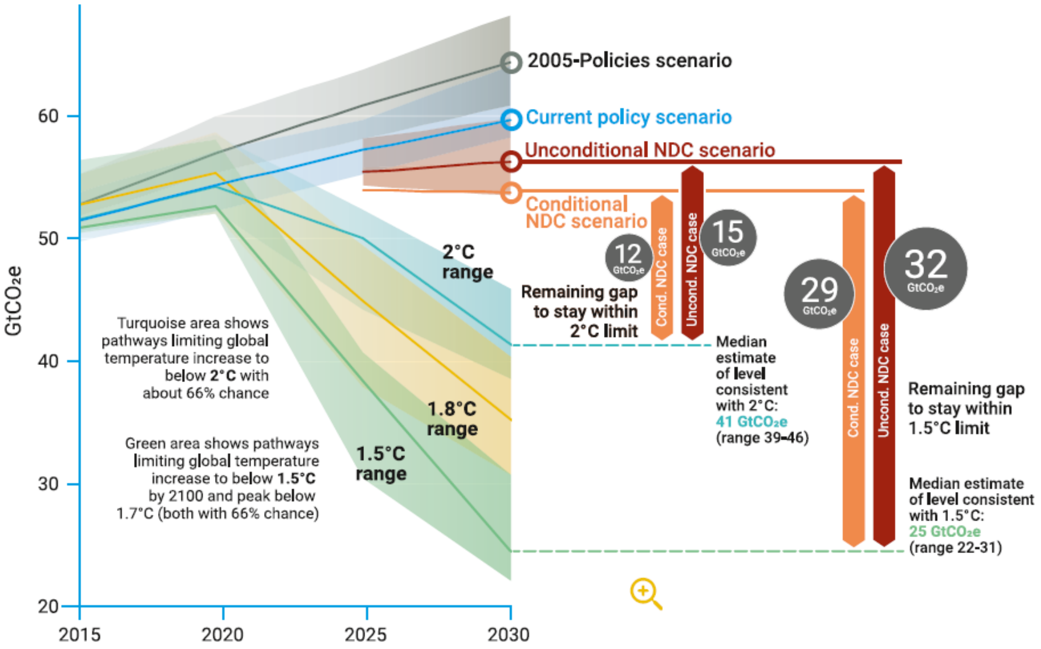


Figure 2.2. Global greenhouse gas emissions for a series of scenarios, combined with resulting 'emissions gaps' in 2030. Current policies will result in emissions of 60 $GtCO_2eq$ in 2030. For the least costly pathway towards the 2030 targets, the current estimates are 41 $GtCO_2eq$ for the 2 °C target, 35 $GtCO_2eq$ for the 1.8 °C target, and 25 $GtCO_2eq$ for the 1.5 °C target. In 2030, annual emissions need to be 15 $GtCO_2eq$ lower than the unconditional Nationally Determined Contributions (NDCs) set out in the Paris Agreement in order to achieve the 2 °C target, and 32 $GtCO_2eq$ lower to achieve the 1.5 °C target (UNEP, 2019a).

The report shows that the levels achieved in relation to country commitments agreed in Paris are limited, and that reduction rates set out in the various countries' plans are insufficient to meet the agreed targets. In 2030, emissions need to be 25% and 55% lower than those in 2018 if the world is to achieve the least costly pathway towards keeping global warming below 2 °C and 1.5 °C, respectively (UNEP, 2019d). Achievement of the 1.5 °C target will require greater levels of ambition, combined with the much faster implementation of a wide range of measures during the coming decades.

2.1.2 Norway's overall targets and progress in reducing greenhouse gas emissions

Norway has ratified both the Kyoto Protocol and the Paris Agreement and has set itself the target of a minimum 30% reduction in GHG emissions by 2020, and a 50% reduction by 2030 compared with its 1990 levels. This is in addition to its ambition to become a carbon neutral society by the year 2050. In Norway, a total of 52 million tonnes of CO_2eq was emitted in 2018 (Figure 2.3), which represents a reduction of 0.9% (450,000 tonnes) since 2017, and the lowest since 1995. However, levels are still 1.1% higher than in 1990 (Statistics Norway, 2019b).

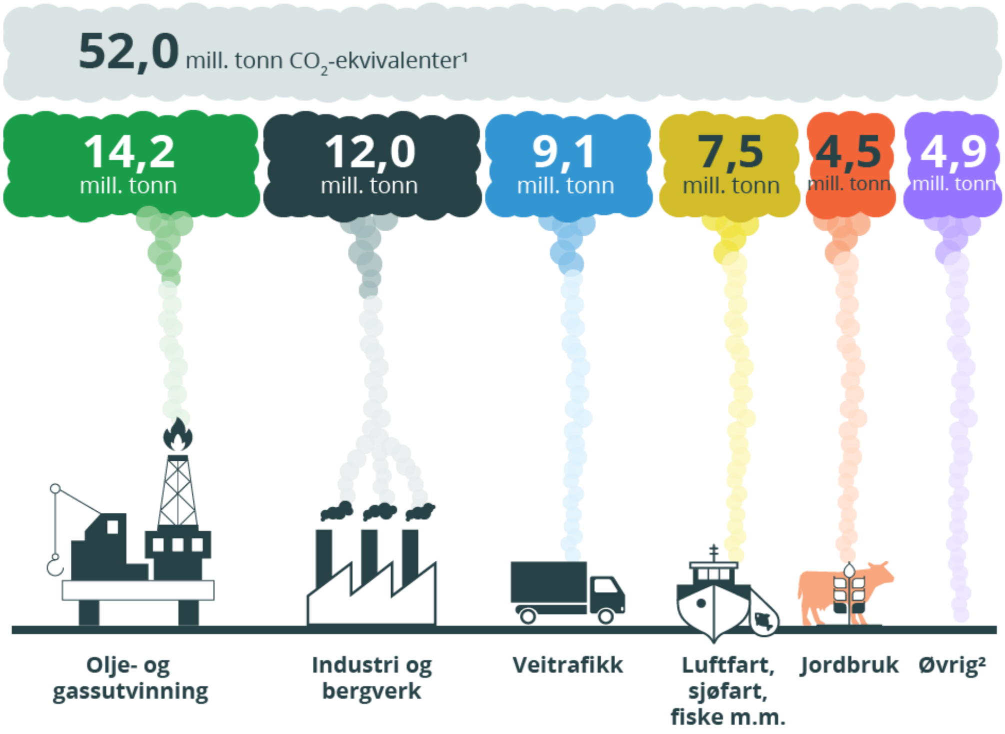


Figure 2.3. Norwegian GHG emissions in 2018. Source: Statistics Norway

The increase from 1990 to 2018 is primarily the result of emissions increases from oil and gas production (an increase of 73%) and road traffic (26%). In Figure 2.3, the construction sector is included in the category 'Industry and mining'. No specific figures are available for the contribution that the construction sector makes to the overall total. Another report containing data from 2017 points to a 13% increase in GHG emissions from the Norwegian construction sector in the period between 2007 and 2017 (Larsen, 2019). For Norway to achieve its ambitions, committed efforts and more extensive measures will be required to reverse current trends both within the construction sector and in Norway in general.

2.2 Environmental impact of the building and construction sector

2.2.1 GHG emissions

The building and construction sector has a key role to play in the work being carried out to achieve the GHG emission reduction targets set out in the Paris Agreement and the UN's Sustainable Development Goals. In 2018, the sector accounted for about 36% of global energy consumption and 39% of GHG emissions (UNEP, 2019c). Global emissions from buildings increased by 2% from 2017 to 2018, while energy consumption increased by 1% (approx. 125 EJ or 36% of global energy consumption), as illustrated in Figure 2.4 (UNEP, 2019c).

Buildings account for 28% of global energy-related CO_2 emissions, 11% of which result from the manufacture of building materials and products such as steel, concrete, and glass. These emissions are driven mainly by population growth, limited progress in policy development, and a decline in investment in improved energy efficiency initiatives. In Norway, the proportion of energy-related emissions from buildings is much lower due to higher levels of electrification, and high renewable energy utilisation in the electric grid (see more details in the succeeding text and in Figure 2.5).

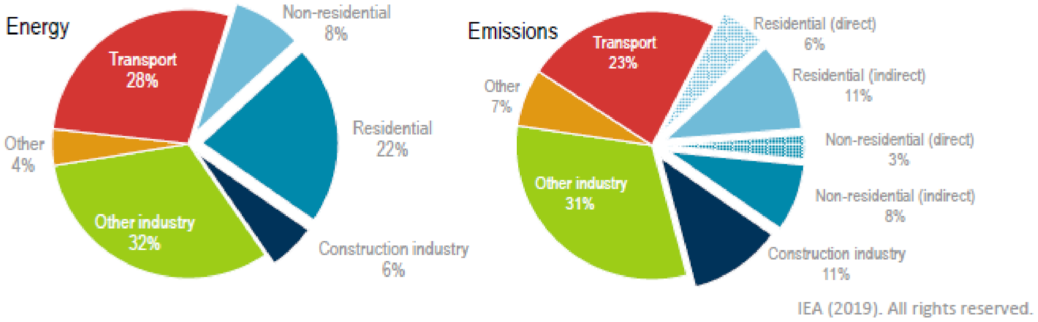


Figure 2.4. Sector-based energy consumption and GHG emissions in 2018. Source: UNEP (2019c).

The transition to renewable energy and a carbon neutral economy represents one of the biggest challenges that the world currently faces (EU, 2019). Building energy requirements are globally recognised as the most important contributor to construction related GHG emissions, and the EU has enacted stricter legislation in order to address this issue (Malmqvist et al., 2018). The European Performance of Buildings Directive (EPBD, 2010/31/EU) and the Energy Efficiency Directive 2012/27/EU (EU, 2012) form parts of this legislation and have made a major contribution to the positive trends observed in building-related energy consumption in Europe (EU, 2020). This has been achieved by the implementation of energy efficiency measures and the decarbonisation of national energy mixes, primarily involving the greater use of renewable energy. The term 'energy mix' is used to describe the relative proportions of energy sources (renewables, nuclear and/or fossil) that contribute to a country's energy supplies.

Amendments made to the EPBD in 2018 introduced requirements for more focused and long-term strategies for building upgrading and restoration, with the goal of enabling existing buildings to use low emission energy sources and become more energy-efficient by 2050. Overall milestones were also introduced in support of short- (2030), medium- (2040) and long-term (2050) targets. The objective is to facilitate the cost-effective upgrading of existing buildings to low-energy buildings, with the aim of meeting overall EU GHG emission reduction targets of between 80 and 90% compared with 1990 levels (EU, 2018).

As regards the Norwegian building and construction sector, the proportion of GHG emissions is lower than the global average, at 15.3% (Figure 2.5) according to Larsen (2019). This is mainly the result of the fact that electricity production in Norway is for the most part fossil-free. Only 11% of the total GHG emissions from the building and construction sector is derived from energy use, and this in spite of the fact that the sector accounts for an estimated 40% of Norway's total energy consumption. In the future, the proportion of these emissions is expected to decline because of the ban on fossil fuels for the heating of buildings in Norway and the introduction of fossil-free construction sites in the major cities.

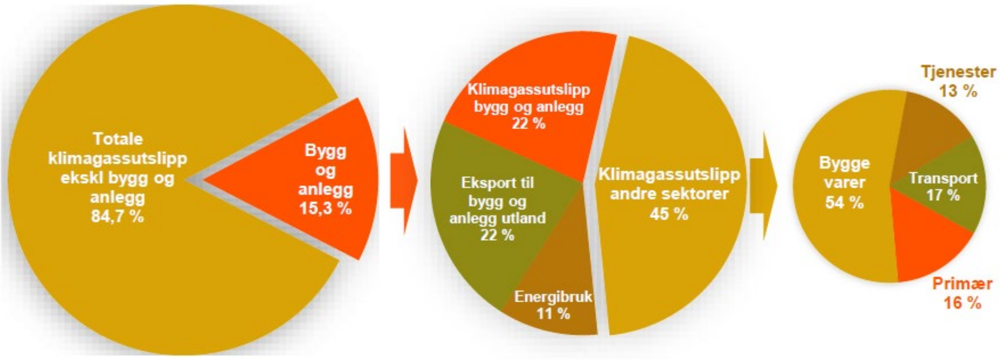


Figure 2.5. The contribution of GHG emissions from the building and construction sector as a proportion of Norway's total emissions. Source: Larsen (2019)

The results presented by Larsen (2019) indicate that GHG emissions from building and construction activities in Norway are in the process of becoming greater than those resulting from energy consumption in the building stock. This is due to a great extent to the decarbonisation of electricity supply systems and the transition to low-energy buildings (Larsen, 2019). The energy mix used in these analyses is key to the interpretation of the significance of energy-related comparison with other emissions, and this is discussed in Chapter 2.4.

2.2.2 Resource consumption

Since the building and construction sector consumes about 40% of total global material resources, a transition to a circular economy is essential in order to achieve reductions in total resource consumption (CGRi, 2020). In its report '*Circularity Gap Report 2020*' the Circularity Gap Reporting Initiative emphasises the importance of maintaining and preserving what has already been constructed, and it is this principle that constitutes the prioritised circular strategy for the built environment in Europe (CGRi, 2020). About 35% of the EU's building stock is more than 50 years old and almost 75% of this stock is energy inefficient (EU, 2020). Moreover, the report demonstrates that the global economy is only 8.6% circular. In the case of the building and construction sector, it is its underlying waste management practices, inherited from the traditional linear economy, that represent the major challenge (CGRi, 2020). The building and construction sector generates a major proportion of total waste volumes, accounting in 2018 for about 30% in Denmark (Høibye & Sand, 2018) and 25% in Norway (Byggemiljø, 2020). The EU's Waste Framework Directive requires about 70% material recycling of all non-hazardous waste from construction and demolition activities by 2020 (EU, 2008).

Data from Statistics Norway show that waste volumes from building, rehabilitation, and demolition activities, estimated to be 1.9 million tonnes in 2017, increased by 1% in the year between 2016 and 2017 (Statistics Norway, 2018a). Of this, about 65% was waste from demolition and rehabilitation activities, which constituted a 2.7% increase from 2016. Only 34% of building-related waste was recycled in 2017, a reduction of 8% from the previous year (SSB, 2019a). Compared with 2016, the proportion of waste derived from rehabilitation projects in 2017 declined by about 3%, while the proportion of demolition-related waste increased by about 6%.

2.3 Rehabilitation of existing building stock

The reuse and rehabilitation of existing buildings thus plays a key role towards more efficient resource utilisation and mitigation of the environmental impact of the building sector. A Nordic study has indicated that there is major potential in the positive impact that the reuse of building materials can make. In Nordic countries, a reduction of 20% in resource use will correspond to a reduction of about 900,000 tonnes of GHG emissions, and result in social and economic benefits to private sector businesses equivalent to 1.7% of their annual growth (Høibye & Sand, 2018).

To achieve the 1.5 °C target, the UN's Intergovernmental Panel on Climate Change (IPCC) has concluded that rapid and universal changes are required in the building sector (Rogelj et al., 2018). For Norway to meet its commitments made in the Paris Agreement, its existing building stock must be upgraded as part of the transition to a low-emissions society.

Limits on energy consumption, GHG emissions and pollution from the built environment are key factors embodied in the Norwegian Planning and Building Act and will exert a major influence on Norway's ability to achieve its domestic GHG emission reduction targets. Requirements set out in the Act have an impact on land use planning, and thus also on the upgrading of existing buildings. However, discrepancies often arise between the letter of the requirements and what an existing building may be able to tolerate in terms of comprehensive upgrading without it effectively being reconstructed.

When upgrading the existing building stock, it is commonly assumed that emission reductions will be similar to emissions levels linked to a new build project (Almås, et.al., 2011; Kaslegård, 2010). The upgrading of buildings can offer immediate environmental benefits (Flyen et al., 2020; Lendlease, 2017). Reinar & Miller (2012) have concluded that the upgrading of cultural heritage buildings by means of repair and, insofar as this is possible, the reuse/recycling of existing materials, represents what they call 'sustainability in action'. Meanwhile, Foster (2020) points out that several analyses derived from recent research demonstrate how the adaptive reuse of existing buildings offers environmental benefits, while at the same time emphasising that this view is not widely shared in practice.

2.3.1 Limited rehabilitation rate

The current level of building rehabilitation in Norway is estimated to involve about 1.0 to 1.4% of the country's building stock (Sartori et al., 2016). The EU Commission has stated that only between 0.4 and 1.2% of the EU's building stock is being upgraded each year, although increases of up to between 2 and 3% are anticipated, depending on the member country and the availability of financial subsidies (EU, 2020). The upgrading of existing buildings has the potential to reduce the EU's total energy consumption by between 5 and 6%, and its GHG emissions by about 5% (BUILD UP, 2019). Between 80 and 90% of existing buildings in Europe are anticipated to still be in use in the year 2050 (Wrålsen et al., 2018), and the Norwegian building stock is expected to follow the same trend (Figure 2.6).

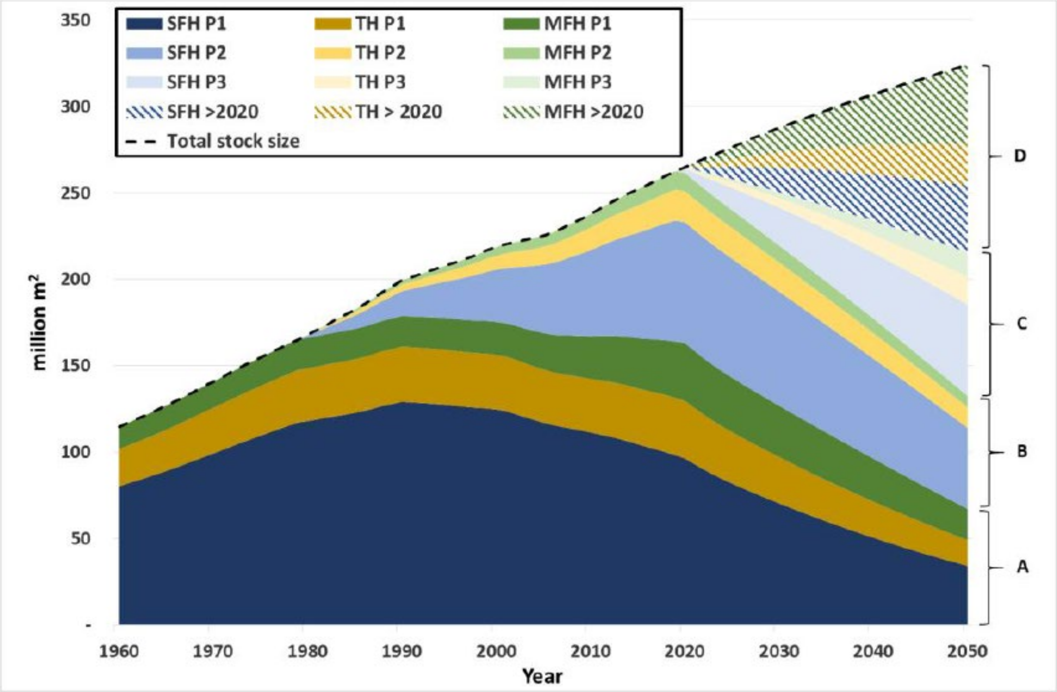


Figure 2.6. Historical and projected trends in the growth of Norwegian building stock for the period 1960 to 2050, measured in square metres. The figure shows developments for both the total building stock together with the relative contribution from different types of homes and upgrading periods as part of a basic scenario. The section marked A (on the right-hand y-axis) shows homes built before 2020 that remain either unmodified from their original form, or which were upgraded before 1980. Section B shows homes for which upgrading was completed in the period 1980 to 2020. Section C shows buildings for which there are plans for upgrading after 2020, and Section D shows anticipated building projects planned for after 2020. The blue-shaded areas denote Small Family Homes (SFH). The yellow areas denote semi-detached, terraced, chain and other small houses (TH), while the green areas represent apartment blocks and other buildings containing multiple homes. Source: Sandberg (2017)

Apartment buildings constitute about 23% of the total building stock in Norway. By upgrading Norwegian apartment buildings from average levels of energy consumption to the current Norwegian standard (TEK17), it will be possible to approximately halve energy consumption from about 200 kWh/m^2/year to 95 kWh/m^2/year (Figure 2.7). Moreover, even greater reductions can be achieved by enhancing building energy performance to levels approaching ‘zero energy’ or ‘energy plus’ status (Wrålsen et al., 2018). The relative proportions of GHG emissions resulting from materials manufacture and transport, as well as building construction, maintenance, upgrading, and demolition, will increase as part of the process to achieve improved energy efficiency.

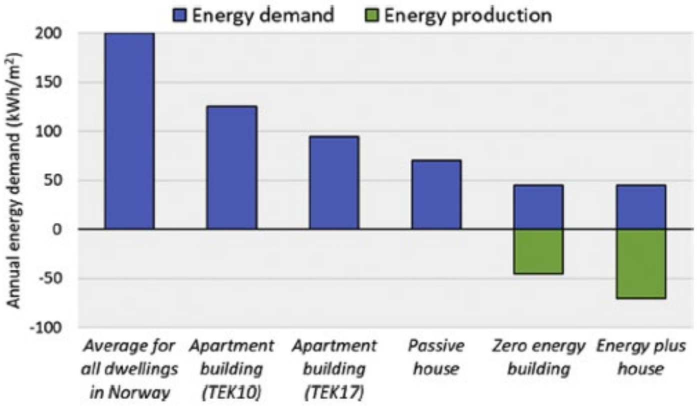


Figure 2.7. Average energy consumption for buildings in Norway. Source: Wrålsen et al. (2018)

Studies (Fouseki & Cassar, 2014; Gram-Hanssen, 2018) have shown that user behaviour in buildings commonly has a greater impact on energy consumption than the energy efficiency systems introduced as part of upgrading. According to Fouseki & Cassar (2014), this applies both to assessments of the amount of energy saved and the ways in which the buildings were utilised. It is important to be aware that relatively major discrepancies may arise between calculated and actual energy consumption. Moreover, even minor energy efficiency measures can result in relatively major and positive improvements in a building's energy efficiency. It is the first few centimetres of retrofit insulation that have the greatest effect, relative to the additional centimetres offered by thicker insulation layers (Svensson et al., 2012; Grytli, 2004). However, most existing studies have restricted their investigations to modern buildings, materials and constructions (Fouseki & Cassar, 2014).

2.3.2 The heritage value of the Norwegian building stock

The public report *'Tilpasning til eit klima i endring'* (Adapting to a changing climate), published by the Norwegian Ministry for the Environment in 2010, emphasises that cultural heritage buildings constitute a significant proportion of Norway's current building stock. A total of 515,000 buildings are listed in the Norwegian heritage building (SEFRAK) register. These include buildings and heritage sites dating from before 1900. In Finnmark county in northernmost Norway, all buildings dating from before 1945 are also included in the register. Norway has about 6,000 formally protected buildings, approximately 5,500 buildings in museums, and about 1,000 listed churches, which in practice are administered as protected (see Table 2.1).

Table 2.1. An overview of all buildings in Norway as of 1 January 2020, the number of buildings listed in the SEFRAK heritage register, protected buildings, and buildings in museums. Unfortunately, no figures were available for buildings designated for protection, listed heritage buildings, or the total number of heritage buildings (including those not currently protected or designated for protection). Nor were there figures available for heritage buildings on Oslo's so-called 'gule liste'.

Buildings in Norway	Number
Total as of 1 January 2020	4 212 721
Listed in the SEFRAK register	515 000
Protected buildings	6 000
Buildings in museums	5 500
Listed churches	1 000
Designated for protection	No figures found
Listed heritage buildings	No figures found
Heritage buildings in Oslo (amber list)	No figures found

These figures have not changed to any significant degree since 2010. There are also many buildings that are designated for protection pursuant to the Norwegian Municipal Planning Act. The buildings in the SEFRAK register are not all necessarily formally protected, but the majority are very valuable in terms of the conservation value they represent. Numbers for either the number of buildings that are designated for protection or for the total of listed heritage buildings were unavailable.

2.3.3 Political action on heritage issues – inherent and sustainable value

The Norwegian building stock represents an important cultural and material resource, not least because many buildings have special significance due to their historical, architectonic, and cultural value (NS-EN 16883:2017). The Paris Agreement, the UN Sustainable Development Goals, and the EU Building Energy Directive all specifically acknowledge the role of cultural heritage in determining the implementation of measures to limit emissions and promote climate change adaptation (the ICOMOS Climate Change and Cultural Heritage Working Group, 2019).

Population growth and associated urbanisation in Norway brings with it an increased need for buildings and will lead to greater levels of construction activity, combined with an increasing demand for the reuse and recycling of existing building stock. To address these issues, the Norwegian Ministry of Climate and the Environment sets out the following priorities, in terms of research needs, in the document "Klima- og miljødepartementets prioriterte forskningsbehov (2016–2021)":

- An awareness of the cultural, social, and socioeconomic value of Norwegian natural and cultural heritage
- Cultural heritage sites and artefacts as a resource in the process of sustainable development
- The significance and value to wealth creation of protected areas and cultural and historical heritage
- The long-term preservation of various categories of cultural heritage sites and artefacts, including those for which Norway has a specific and endemic responsibility

Two of the six key research needs are of particular significance to the central theme of this report:

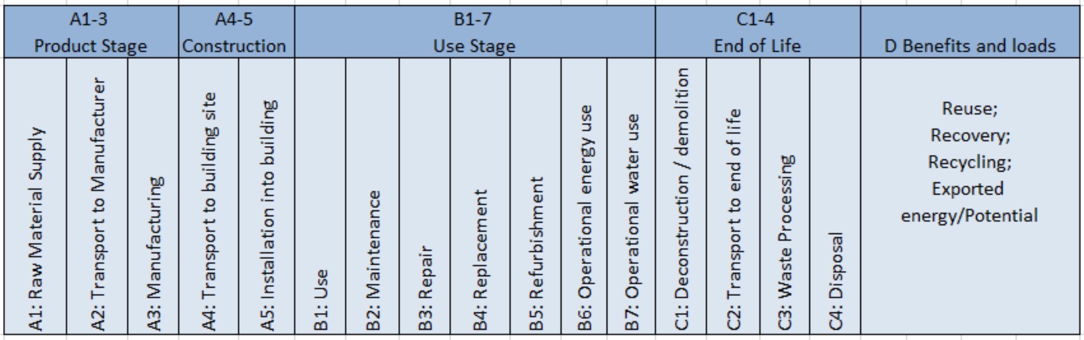
1) The role of cultural heritage as a resource and as a basis for the development of attractive urban built environments, for wealth creation in its broadest sense, and for business development
2) The environmental adaptation of historical urban environments and heritage building stock, and the potential offered by the built environment in the process to promote development with lower climate and environmental impacts.

2.4 Life cycle assessment

2.4.1 The LCA approach and principles

Life Cycle Assessment (LCA) is a widely recognised method of assessing potential environmental impacts due to materials-, product- and building-related factors that arise during the building lifetime. The LCA methodology has been improved over time, with the aim of harmonising the approach and promoting the simplification of calculations and comparisons, as well as the dissemination of results. Relevant current building-related standards include the ISO 21931:2010 standard that sets out the LCA approach and the principles for the assessment of environmental performance of construction works, the EN 15897:2011 (NS-EN 15978, 2011) standard for the environmental assessment of buildings, and Norwegian standard NS 3720 (2018), which addresses the calculation of GHG emissions in buildings (see Figure 2.8).

The EN 15978 standard describes a modular structure on defining five main life cycle phases: the product stage (modules A1–A3), the construction process (modules A4–A5), the use stage (modules B1–B7), the end-of-life stage (modules C1–C4) and benefits and loads beyond the system boundary (Module D).



A1-3 Product Stage			A4-5 Construction		B1-7 Use Stage							C1-4 End of Life				D Benefits and loads
A1: Raw Material Supply	A2: Transport to Manufacturer	A3: Manufacturing	A4: Transport to building site	A5: Installation into building	B1: Use	B2: Maintenance	B3: Repair	B4: Replacement	B5: Refurbishment	B6: Operational energy use	B7: Operational water use	C1: Deconstruction / demolition	C2: Transport to end of life	C3: Waste Processing	C4: Disposal	Reuse; Recovery; Recycling; Exported energy/Potential

Figure 2.8. Building life cycle stages in accordance with EN 15978 standard (NS-EN 15978, 2011)

The results of building LCAs are commonly communicated via building certification schemes such as the LEED rating system (USA), BREEAM (UK) and its adapted Norwegian counterpart BREEAM-NOR, as well as the DGNB in Germany. These schemes use LCAs based reference values (benchmarks) with the dual aim of setting environmental performance targets and using the LCA results in the assessment of certification criteria (Hollberg et al., 2019). Life cycle based national GHG emission benchmarks are getting more attention in different countries, and there are on-going discussions on the possibility of legal bindings. In Norway, there is great demand for applying LCAs in buildings (Schlanbusch et al., 2016; Fufa et al., 2019b). There is also an on-going initiative aiming at developing national benchmarks and the possibility of using these values in upcoming Norwegian building codes (Wiik et al., 2020).

The use of LCA studies and the establishment of reference values is currently complicated by a lack of harmonised basic data, combined with inconsistencies in the methodologies used in the various published studies (Hollberg et al., 2019; Frischknecht et al., 2019a; 2019b). This challenge has been brought to the fore by the results of the 'IEA BC Annex 72' project, in which the authors carried out an investigation of the environmental impacts of use of an identically constructed office building (called 'be2226') using round robin tests (Frischknecht et al., 2019b). The study assumed equivalent use of technology and materials and equal energy consumption. Building assessment was performed using the respective countries' LCA methods and highlights the challenges that arise due to the lack of consistency in the various LCA approaches, as illustrated in Figure 2.9. One of the reference buildings located in Lustenau in Austria, which was investigated using assessment methods and LCA databases from 21 different countries, reported values of total GHG emissions that varied from 10 to 71 kg CO_2eq/m^2.

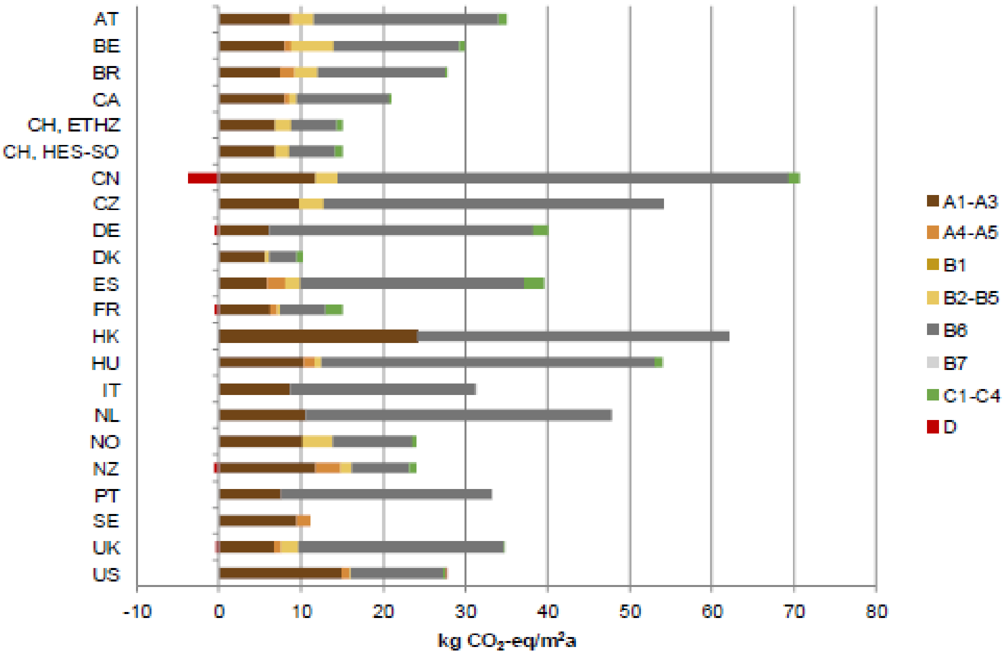


Figure 2.9. GHG emissions from studies carried out on the office building 'be2226'. Source: Frischknecht et al. (2019b)

The differences in GHG emissions values can be attributed primarily to the difference in energy mixes and reference study period applied in the different countries. Figure 2.9 presents a visualisation of the significance difference in GHG emission results from energy mix (module B6), illustrating the major differences in LCA results based on the approaches adopted in the different countries, and not least the fact that countries with a major coal-based component in the energy mix generated high GHG emissions volumes. However, there are also major differences in the methodologies applied, and in the LCA modules that are included. For example, there are major differences between countries (plotted along the y-axis in Figure 2.9) in relation to life cycle modules A1–A3, which address the production of building materials. The development of LCA reference values based on harmonised methodologies will promote greater transparency and repeatability of LCA results and will make it possible for all users of the analyses to make better informed decisions.

2.4.2 Limited LCA studies of existing buildings

Life cycle assessments of buildings demonstrate that there are often trade-offs with energy efficiency strategies, between reduced operational energy use and the embodied energy (and emissions) from installed materials, products, and elements. Increased insulation thickness, new energy-efficient windows, efficient ventilation systems, and solar panels are examples of systems which can reduce use-phase energy consumption but might have significant energy and emissions implications over the entire life cycle of a building (Moncaster et al., 2019; Wiik et al., 2018; Chastas et al., 2016;). These indirect or embodied emissions may be related to the manufacture of building materials, transport, construction activities, repair, replacement, and rehabilitation while the building is in use, as well as demolition and waste management at the building end-of-life. Such emissions represent the accumulated climate footprint embodied in the GHG emissions generated by the manufacture of the various building materials and other products, and by the combined processes of a building's maintenance and its ultimate demolition and disposal. Even though the upgrading and adaptive reuse of existing buildings with the aim of reducing embodied emissions has been proposed (Hasik et al., 2019), few LCA studies have been carried out to examine how the relevant environmental parameters are affected by such interventions in the existing building stock (Pombo et al., 2016). There are even fewer studies that have evaluated embodied emissions and the contribution made in relation to heritage, historical and other social values inherent in the same building stock (Hasik et al., 2019; Foster, 2020; Wrålsen et al., 2018).

The LCA study conducted through IEA EBC Annex 57 (IEA EBC (b)) includes 80 project case studies found that the production phase dominates total embodied emissions with 64% of emissions, followed by replacements at 22% and end-of life at 14% (Moncaster et al. 2019). They also found that the impact from the production phase of eleven rehabilitation projects in case studies, in which energy efficient measures and low carbon technologies were retrofitted to existing buildings, was under half of that for new built projects. A Norwegian study on Zero Emission Building (ZEB) has demonstrated that embodied GHG emissions generated during the production stage, and from maintenance in the operational phase, accounted for between 55 and 87% of the total embodied GHG emissions. The building envelope accounted for up to 65% of these emissions (Wiik et al., 2018). Emissions generated during the building phase may account for up to 10% of the total emissions (Fufa et al., 2019; Wiik et al., 2017). With the growing carbon spike and climate change impacts, renovation and adaptive reuse of existing buildings can help to take immediate action and achieve carbon reduction goals.

3 Approach

This section is divided into two parts. The first part describes a systematic literature review and the qualitative meta-analysis (see Chapter 4) used to select relevant studies for further analysis. The second part is a presentation of the background data for the Norwegian and international case studies used in the quantitative meta-analysis.

3.1 General approach

The methodology includes a systematic review and meta-analyses of life cycle assessment studies on the rehabilitation of existing buildings (Figure 3.1). A systematic review is a method used to identify, critically evaluate and integrate the findings of relevant studies in order to address research questions. Meta-analysis is a quantitative review used to combine and analyse different studies to provide a quantitative answer to specific research questions. The systematic literature review and the meta-analysis presented in this study are based on established methods (Gradeci et al., 2019; Petticrew & Roberts, 2008; Gradeci & Labonnote, 2019; Zumsteg et al., 2012).

Bibliometric mapping is used to carry out systematic searches to identify, evaluate and collate relevant literature during the systematic study. The term ‘scoping review’ is used to refer to supplementary research of any relations, differences and gaps revealed in the existing research. The meta-analysis combines and summarises the results of the various studies, in which data are acquired from the systematic literature study, in addition to other literature found without the systematic ‘snowball approach’.

Figure 3.1. An outline of the systematic literature study and meta-analysis process

3.1.1 Data sources and overview of the search

Three literature databases were selected for use in this study: Web of Science, Engineering Village, and Scopus. Boolean operators (combining search terms in three different ways: using AND, OR and NOT) were used to refine the search process involving the keywords presented in Table 3.1, categorised as object (what), context (where) and outcome (how).

Table 3.1. Keywords

What		Where		How	
LCA OR ‘life-cycle assessment’	AND	‘Existing building’ OR ‘cultural heritage building’ OR ‘historic building’	AND	Renovation rehabilitation retrofitting upgrading conservation restoration	OR OR OR OR OR

The keywords were identified through preliminary searches performed in the Scopus database. The keywords were then searched in the title, abstract, keywords and subject levels. The search was performed without time boundaries for the year of publication in order to get an overview of the evolution of the study with time. Furthermore, there was no restriction on the language and types of documents to include literatures in a Scandinavian language, if any, and grey literature (research that is either unpublished or has been published in a non-commercial form), respectively. The search scheme and the search results per databases are shown in Table 3.2.

Table 3.2. Search terms and results

Database	Search terms	Records identified
Web of Science*	TS=(LCA OR 'life-cycle assessment') AND TS=('existing building' OR 'historic building' OR 'cultural heritage building') AND TS=(renovation OR rehabilitation OR retrofitting OR upgrading OR conservation OR restoration)	32
Engineering Village**	(((((lca) WN KY) OR (('life-cycle assessment') WN KY)) AND (((existing building) WN KY) OR (('historic building') WN KY) OR (('cultural heritage building') WN KY) AND (((renovation) WN KY) OR ((rehabilitation) WN KY) OR ((retrofitting) WN KY) OR ((conservation) WN KY) OR ((restoration) WN KY) OR ((upgrading) WN KY)))))	89
Scopus***	(TITLE-ABS-KEY(lca) OR TITLE-ABS-KEY('life-cycle assessment') AND TITLE-ABS-KEY('existing building') OR TITLE-ABS-KEY('historic building') OR TITLE-ABS-KEY('cultural heritage building') AND TITLE-ABS-KEY(renovation) OR TITLE-ABS-KEY(rehabilitation) OR TITLE-ABS-KEY(retrofitting) OR TITLE-ABS-KEY(upgrading) OR TITLE-ABS-KEY(conservation) OR TITLE-ABS-KEY(restoration))	90
Overall (after removing duplicates)		**137**

* TS signifies that the search was performed in titles, abstracts, and keywords.

** WN signifies that the search was performed in a specific subject area and KY signifies subject area/title/abstract.

*** Signifies combined fields searching in abstracts, keywords, and titles.

Additional references were searched for using Google Scholar, using the keywords described in Table 3.1 in Norwegian, English, Swedish, and Danish. This was done to include relevant published and unpublished literature, particularly from the Scandinavian countries (see Table 3.3).

Harzing's software application, Publish or Perish, version 7.15.2643.7260 Windows ×64, running under Windows 10.0.18362 (×64) was used to download references from Google Scholar. The search strings from Table 3.2 were used. No restrictions were applied. We used 'intitle' in the first section of the search string, to limit hits to words in document titles.

Table 3.3. Keywords used when searching in Google Scholar

English (EN)	Norwegian (NO)	Swedish (SE)	Danish (DK)	Search results
LCA	Livssyklusanalyse; livsløpsanalyse; klimagassregnskap	Livscykelanalys; LCA	Livscyklus-analyse/LCA	
Building	Bygning; bygg; Boliger	Byggnad; bostad/bostäder; bostadshus	Bygning; bolig	
cultural heritage building	vernede bygninger, kulturminne	kulturminne	bevaringsværdig bygning; kulturminne	
renovation	renovering	renovering	renovering	
rehabilitation	rehabilitering	återställande restaurering	restaurering	
retrofitting	ombygging;	ombyggning	retrofitting	
upgrading	oppgradering	uppgradering	opgradering	
conservation	bevaring	bevarande	konservering	
restoration	Restaurering	restaurering	restaurering	
2 486	29	103	29	Search results
857	11	42	18	After removing duplicates

In addition, a less structured 'snowball' approach was used to include relevant literature not captured by the systematic search. This was achieved by checking the reference lists of literature already found, by checking relevant national and European reports and by obtaining input from experts. The last searches were performed in November 2019. All the references were exported to the EndNote reference manager, where any duplicates were removed.

3.1.2 Selection criteria

The screening of the studies was performed in two steps (Figure 3.2). First, titles and abstracts of peer-reviewed publications and titles or table of contents of grey literature were screened for relevance to the review questions and exclusion criteria by two reviewers. Second, the screening was performed by full text reading by one reviewer. Additional studies have been added through snowball sampling for the systematic review and meta-analysis. The final set of articles included have been evaluated by two reviewers.

211 review articles were filtered and retrieved from the selected articles in order to get an overview of the challenges and opportunities. The inclusion criteria include: 1) studies with good qualitative and quantitative description of the LCA study and transparent documentation of what is done 2) present the LCA approach in one or more case studies.

An overview of the search and selection process considered in the systematic review and meta-analysis is shown in Figure 3.2.

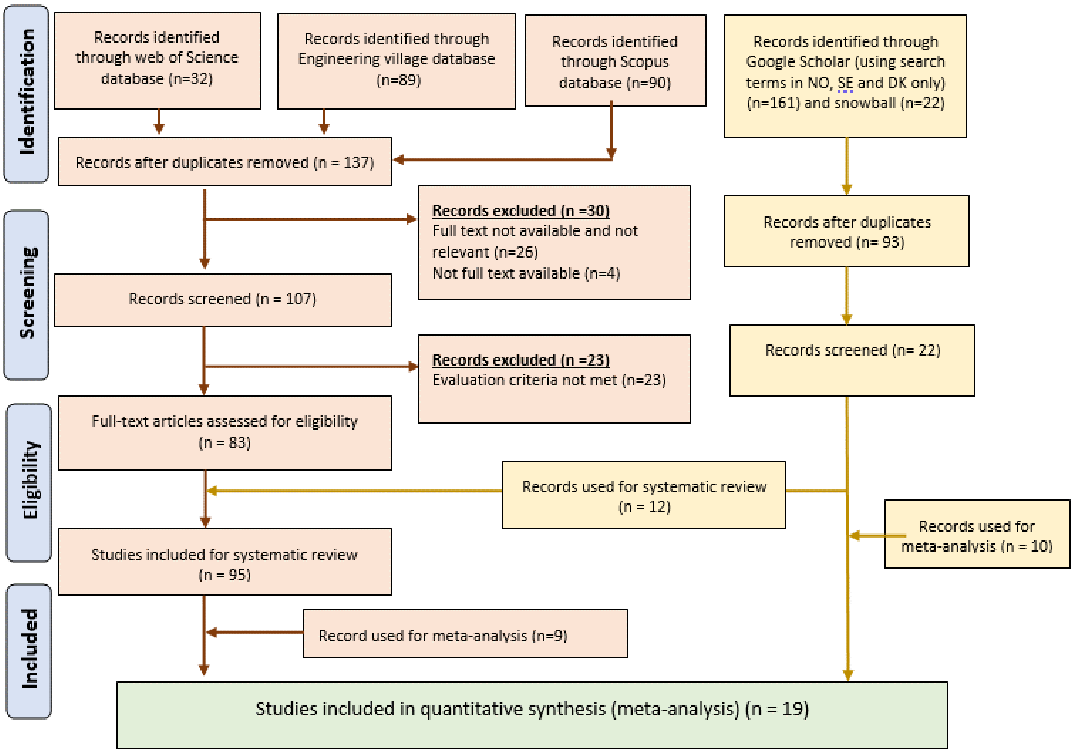


Figure 3.2. The Prisma (Preferred Reporting Items for Systematic Reviews and Meta Analysis) diagram shows the method used for the systematic literature study and data analysis. Source: Moher et al. (2009). (2015)

Of a total of 211 potentially relevant articles, 74 duplicate references were eliminated. 30 studies were not considered to the related to the study in hand and 19 were found to be incomplete. 83 studies (listed in Appendix 1) were collected from the three selected databases.

In addition, 87 publications (in Norwegian, Swedish, and Danish) were selected using an unstructured 'snowball' approach and collected through Google Scholar. Specifically, this meant that other publications found during the work were added to the literature review if they were found to be of special interest. Of these 93 publications, 71 were eliminated as not being relevant to the subject. In other words, 22 studies were adopted. Only search terms associated with NO, SE, and DK among the search results from Google Scholar were included in the analysis. A total of 857 English-language publications were found by searching in Google Scholar. Because of the large number of publications, certain references that were particularly interesting were added using a snowball approach.

In the meta-analysis, only publications were used that include results from Norwegian case buildings accompanied by good descriptions of the LCA approach– identified through the systematic analysis and snowball approach. In the comparative assessment, a selection of international studies following the LCA approach and containing a transparent description of background data and results were also included.

In all, 12 Norwegian case studies were selected for the meta-analysis. 11 non-Norwegian building cases were also identified in 7 international publications. In addition, two case studies were included that were submitted to the Norwegian Directorate for Cultural Heritage after completion of the systematic literature review (see Section 3.2.2).

3.1.3 Extraction of data and data synthesis

The open-source software application VOSviewer 1.6.14 was used to assess and visualise interesting themes using a matrix of keywords provided by the authors. VOSViewer is a network visualisation tool that has been used to display keywords based on their importance. The commercially available software NVivo version 9 (QSR) was used for systematic review and qualitative meta-analysis, to carry out detailed investigation of specific themes identified using VOSviewer.

Microsoft Excel was used for the quantitative meta-analysis. Data synthesis was performed quantitatively by extracting data from selected Norwegian case studies as shown in Table 3.4.

3.2 Description of case studies

This section examines the LCA studies identified during the systematic analysis and snowball approach starting with identified Norwegian case studies containing an adequate description of the LCA approach. A selection of international case studies is also included. These studies were selected because they follow the LCA methodology and include a transparent description of their background data and results.

3.2.1 Case studies from Norway

The Norwegian case studies were selected from recognised national innovation arenas, including the FutureBuilt programme, Framtidens byer, and the Norwegian research centre Zero Emission Buildings (ZEB).

- The calculations were based on a functional unit of 1m^2 and a building lifetime of 60 years.

- LCA users have used four different tools to calculate GHG emissions:
  - The earlier Norwegian tool for calculating GHG emissions (klimagassregnskap.no), which used the Ecoinvent database and Environmental product declarations (EPDs) as background data.
  - OneClick LCA: a commercial LCA tool that replaced klimagassregnskap.no in 2018 using a similar approach.
  - The ZEB tool: an Excel-based tool for estimating GHG emissions developed by the Norwegian ZEB Centre. It uses the Ecoinvent database and EPDs as background data.
  - SimaPro: a commercial LCA software application using the Ecoinvent database

- The calculations follow the LCA approach as outlined in LCA standards NS 3720, EN 15978 and/or ISO 14040/44. In this study, the results of the transport in the use phase (module B8, only in NS 3720) are excluded to allow comparison of the findings with other international studies (which follow EN 15978).
- The results for each project phase are presented for three scenarios:
  - Before rehabilitation –the building continues to operate without rehabilitation.
  - After rehabilitation – where the building is upgraded and made usable (rather than being demolished and rebuilt)
  - A reference building– which is a new building generated using the various tools or by some other specified means. OneClick LCA states that 'the reference building provides the user with the carbon performance of each type of building if built according to normal Norwegian market conditions. The reference building is used to specify carbon reduction requirements for the project, which in turn are quantified using the NS 3720 standard'. Selvig (2015) sets out the following main principles for reference buildings developed using klimagassregnskap.no: 'A rectangular (shoebox) building with no projections or inset elements in the façade apart from balconies in some types of building."
    - Material types specified in the experience database prepared by Norwegian quantity surveying company AS Bygganalyse, but adapted and adjusted based on architectural assessments
    - Energy efficiency level as specified in technical regulations pertaining to the Norwegian Planning and Building Act
    - Energy supply in compliance with technical regulations
    - Average travel patterns for the living and working market in question according to the Norwegian Travel Pattern Study (NRVU), supplemented by local and municipal travel pattern studies

- It must therefore be pointed out that these reference buildings are not optimised with regard to materials use or the use of environmentally sound materials and are intended to represent a simplified reference with which it is possible to compare the existing building, rather than to represent a real building design.

- The results are also presented per life cycle module according to EN 15978. The results per building unit (in accordance with NS 3451) are also included in the discussion in those cases where they are available and of interest.

- The data acquired through the case studies are used to perform a statistical analysis which provides an overview of the reference values. The results are presented according to building typology, rehabilitation type, year of construction, year of rehabilitation, location, physical system boundary, LCA system boundary, indicators, and other LCA-related information. In addition, a simplified comparative assessment was carried out involving other international studies from the systematic literature review, to obtain a comprehensive overview.

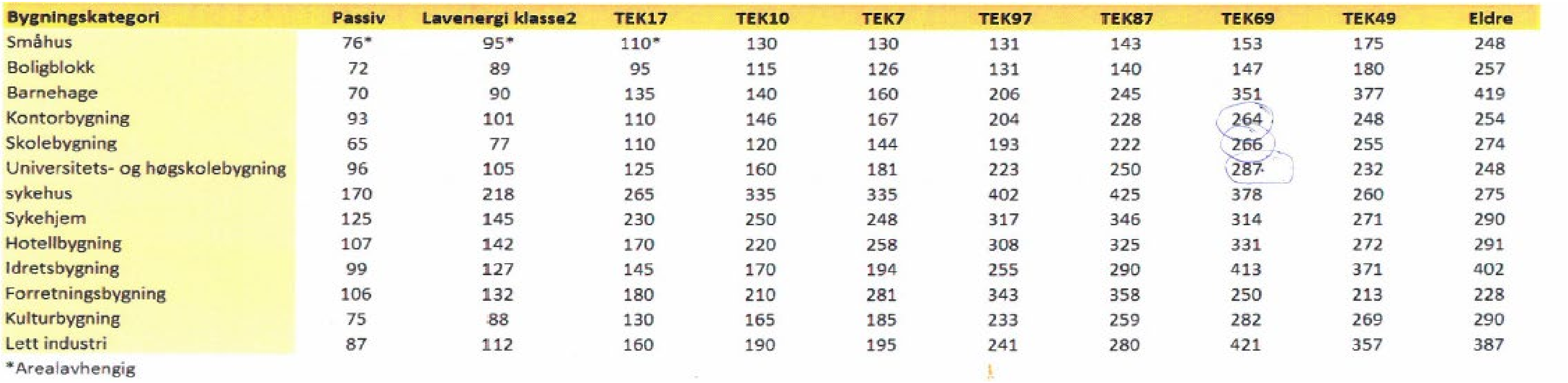
The case studies comprise four types of residential buildings, five office buildings, one school, one university building, and one nursing home. Two reference buildings are also used – one detached house and one office building – from the Norwegian ZEB Centre. These are used to represent new buildings in the two building typologies in comparison with the results for the existing buildings.

Table 3.4 provides general information about the selected case studies. A brief description of the case studies is provided under the table.

Table 3.4 General information about the selected case studies.

	Case study	**Reference**	**Location**	**Building typology**	**Year of construction**		**Rehabilitation period**	**Number of storeys**	**GFA (m^2)**	**Stated lifetime**	**Life cycle modules**	**Indicator**	**Applications**
					Year	**TEK***	**Year**						
1	Villa Dammen	Fuglseth (2016)	Moss	Residential building	1936	Older	2014	2	117	60	A1-A3; B4; B6, C1-C4	GHG	OneClick LCA
2	Ulsholtsveien	Civitas (2018)	Oslo	Residential building	1953	TEK49	2017	3	760	60	A1-A3; B6	GHG	KGR.no
3	Stjernehuset Housing Co-operative	Context AS (2018a); Rønningen (2018)	Kristiansand	Residential building	1965	TEK49	2015	10	4 543	60	A1-A3; B6	GHG	OneClick LCA
4	Vestlia Housing Co-operative	Skeie et al. (2018) (2015)	Trondheim	Residential building	1970	TEK69	2017	3	1 680	60	A1-A3; B6	GHG	KGR.no and/or ZEB tool
5	City Hall district	Context AS (2018b)	Kristiansand	Office	1970	TEK69	2014	5	13 071	60	A1-A3; B6	GHG	ZEB tool
6	Powerhouse Kjørbo	Sørensen et al. (2017) (2015)	Sandvika	Office	1980	TEK69	March 2013 – February 2014	4 & 5	5 180	60	A1-A3; A4-A5; B4; B6; C1-C4, D	GHG; primary energy	KGR.no
7	Grensesvingen 7	Enlid & Selvig (2018)	Oslo	Office	1986	TEK69	2014	8	16 422	60	A1-A3; B6	GHG	ZEB tool
8	Bergen City Hall	Ulvan & Reenaas (2019)	Bergen	Office	1974	TEK69	2019	14	10 756	60	A1-A3; A4-A5; B4-B5; B6; C1-C4, D	GHG	OneClick LCA
9	Stasjonsfjellet School	School building (2015)	Oslo	School	1982	TEK69	2014	2	4 278	60	A1-A3; B6	GHG	KGR.no
10	Økernhjemmet Nursing Home		Oslo	Nursing home	1950	Older	2014	4	9 818	60	A1-A3; B6	GHG	KGR.no
11	Norwegian School of Economics, Bergen (NHH)	HENT (2019)	Bergen	University building	1963	TEK49	2020	9	10 167	60	A1-A4; B6	GHG	OneClick LCA
12	Statens Hus Vadsø, Building B	Hagen (2020)	Vadsø	Office	1963	TEK49	In planning	4	4 555	60	A1-A3, B6	GHG	OneClick LCA

- In accordance with the value given below



Bygningskategori	Passiv	Lavenergi klasse2	TEK17	TEK10	TEK7	TEK97	TEK87	TEK69	TEK49	Eldre
Småhus	76*	95*	110*	130	130	131	143	153	175	248
Boligblokk	72	89	95	115	126	131	140	147	180	257
Barnehage	70	90	135	140	160	206	245	351	377	419
Kontorbygning	93	101	110	146	167	204	228	264	248	254
Skolebygning	65	77	110	120	144	193	222	266	255	274
Universitets- og høgskolebygning	96	105	125	160	181	223	250	287	232	248
sykehus	170	218	265	335	335	402	425	378	260	275
Sykehjem	125	145	230	250	248	317	346	314	271	290
Hotellbygning	107	142	170	220	258	308	325	331	272	291
Idretsbygning	99	127	145	170	194	255	290	413	371	402
Forretningsbygning	106	132	180	210	281	343	358	250	213	228
Kulturbygning	75	88	130	165	185	233	259	282	269	290
Lett industri	87	112	160	190	195	241	280	421	357	387

*Arealavhengig


Villa Dammen. Photo: Boro M.

Villa Dammen is the oldest building included in the case studies. It is a private house of cultural heritage significance, built in 1936 (Fuglseth, 2016). Before rehabilitation in 2014-15, it was constructed from uninsulated timber framework and wooden cladding with a concrete basement. Heating was provided by an oil-fired furnace supplemented by electric radiators. The owners wanted to renovate the house to be both environmentally sound and energy-efficient, while retaining the character of the building. Rehabilitation measures included sealing around windows and doors, improved floor and roof insulation, replacement of heat sources with a wood stove, and installation of a grey water heat recovery unit. An LCA was performed by Fuglseth (2016) enabling comparison of the rehabilitated building with a scenario before rehabilitation, and a second scenario where the existing building was demolished and replaced by a new house complying with Norwegian building regulation TEK10 (based on a reference building heated by electricity and a modern wood stove).


Ulsholtsveien. Source: Tove Lauluten/FutureBuilt

The main building (Furuhuset) in Ulsholtsveien 31 is a FutureBuilt model project which was originally a Methodist children's home and kindergarten, which was fully rehabilitated to provide 9 flats with a communal area on the ground floor. A new entrance hall was added, and a lift to the attic, which is now habitable. The total heated floor area (BRA) is 760 m^2, with a gross floor area (BTA) of 859 m^2, with 14–20 residents. The following measures were part of rehabilitation: Foundations: new lift shaft, casting of new concrete foundation for cellar floor. Superstructure: Some new steel pillars. Exterior walls: new windows, upgraded insulation. Interior walls: new interior walls. Separating floors: new surfaces (floor and ceiling). Ceilings: new insulation (retaining roof structure). One new staircase. The reference building was generated using klimagassregnskap.no V.5, which was used for GHG estimates. The transformation project also included the construction of two new buildings with a heated floor area (BRA) of 1,581 m^2 and a gross floor area of 1,905 m^2 (BTA), with 36–54 residents.

Stjernehuset Housing Co-operative in Kristiansand carried out rehabilitation of an eleven-storey block of flats dating from 1965 to the Norwegian 'energimerke B' standard. The total heated floor area area was 4,543 m^2 (BRA). An important element of the project was converting the heating system from oil-fired to district heating and installing a ventilation system incorporating heat recovery. Thermal bridges in the building were systematically surveyed using thermography and were eliminated or minimised. The energy efficiency of the building was also improved using measures such as additional insulation in walls, floors and roofs, and the replacement of windows and doors. The 'in use' calculations were carried out using OneClick LCA.


Stjernehus housing co-operative. Photo: Moen O.H.

Vestlia Housing Co-operative. Photo: Skeie K.S.

The Vestlia Housing Co-operative case study considers two scenarios: A simple rehabilitation and a more comprehensive nZEB (nearly Zero Emission Building) rehabilitation based on a SINTEF report prepared on behalf of the TOBB housing association. The study deals with Vestlia Housing Co-operative, built in the 1970s, as a case study examining TOBB's potential for upgrading its existing buildings. The two rehabilitation scenarios are based on proposals designed and put forward before actual rehabilitation took place in 2012–2013 (resembling the simple scenario in the report). This scenario includes additional insulation in roofs (100 mm additional insulation) and exterior walls (100 mm additional insulation), as well as modification of the façades and windows (to achieve a U-value of 1.1). During the upgrade, individually balanced ventilation was also installed (paired fans with heat recovery), in addition to existing exhaust systems from bathrooms and kitchens. This simple upgrade results in a net energy requirement of 179 kWh/m^2/year, which does not satisfy TEK17, TEK10 or TEK7 requirements for apartment blocks. The ambitions nZEB scenario incorporate more modifications and additional insulation of the building shell including: 200 mm additional insulation in roofs, 150 mm additional insulation in walls, and replacement of three-layer windows (U-value 0.8). Work was also done to reduce thermal bridges linked to balconies, cellars, and staircases. Also included was the installation of balanced ventilation with heat recovery. The comprehensive upgrade results in a net energy requirement of 91 kWh/m^2/year, satisfying the requirements of TEK17 for apartment blocks.

Powerhouse Kjørbo. Source: powerhouse.no.
Photo: Aadland C.

Powerhouse Kjørbo is the world's first rehabilitated office building that produces more energy than it consumes. It is also a FutureBuilt model project. The office building, located in Sandvika, consists of two blocks dating from the 1980s, with a total heated floor area (BRA) of 5,180 m^2 (Sørensen et al., 2017). The original foundation and supporting structure were retained during the rehabilitation. The outer laminated glass façade was reused as internal glass partitions, and the exterior walls were rebuilt using a timber frame structure, charred timber cladding, and increased insulation thickness. The roof and the basement exterior walls were insulated during rehabilitation. The heating system consists of heat pumps (obtaining heat from an energy wells), while electricity is generated by solar panels mounted on the roofs of the two office buildings, as well as the adjacent parking garage. Powerhouse Kjørbo is certified as 'Outstanding' according to the BREEAM-NOR assessment system.

Grensesvingen 7 is an office building dating from 1986. The building has been completely renovated, retaining only the foundation and superstructure. Most of the façade was also dismantled and re-used. With high environmental ambitions, the façade was insulated, windows and doors were replaced, and an additional floor was added to the top of the building. The building satisfies the low-energy standard (NS3701) and has been awarded Norwegian 'energimerke A' and certified as BREAM-NOR Excellent.

The *Rådhuskvartalet (City Hall district)* involves rehabilitation of buildings with some cultural heritage value around Øvre Torg in Kristiansand. While the brick façades have been retained, the block now houses a modern, climate-smart office building. The goal was to satisfy the requirements for 'energimerke B' and the low-energy standard, NS 3701. In addition to the historical façades, some of the superstructure in some buildings was retained. Klimagassregnskap.no v. 5.0 was used to calculate GHG emissions and to model the reference building.

Bergen City Hall. Source: Ulvan & Reenaas (2019)

Bergen City Hall is a 14-storey building dating from 1971-74. Bergen City Government decided to rehabilitate the City Hall (externally and internally) after evaluating the damage on the concrete columns in the façade which leads structural deficiency (due to low concrete strength, insufficient reinforcement and corrosions). The assessment of the building also included wind loading and structural safety, and the decision was made to rehabilitate, with the ambition of achieving an environmentally sound building, while extending the lifetime by about 50 years. A comparative environmental impact assessment was performed to evaluate rehabilitation as compared with demolition and rebuilding. The rehabilitation scenario included an assessment of the option of retaining the existing foundations, exterior walls, cladding, floor structures, horizontal support beams, and 10% of the vertical support structure. Heating requirements are to be met using district heating, and other technical installations are to be powered by electricity from the grid. The GHG emissions resulting from rehabilitation were compared with the option of rebuilding, with the contribution from materials based on a reference building in OneClick LCA. Energy calculations were conducted based on a new building of 'passive house' standard. The impact of demolition of the building was not considered.

Stasjonsfjellet School.
Source: Tove Lauluten/FutureBuilt

The original Stasjonsfjellet School is a FutureBuilt project and dates from 1982. Rehabilitation was carried out in 2014. The school was upgraded to passive house standard. The energy upgrade included improvement of insulation in walls and roofs, while the cladding, windows and doors were replaced. The electrical heating system was replaced by water-borne heating using heat pumps. The GHG emission calculations were carried out using klimagassregnskap.no, Version 4.

Økernhjemmet Nursing Home. Source: Tove Lauluten/FutureBuilt

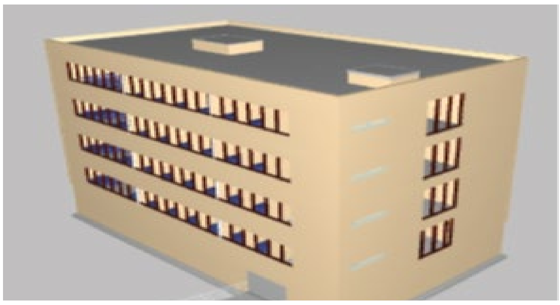
Økernhjemmet Nursing Home is a FutureBuilt model project. The nursing home was completely rehabilitated in 2014. The building's structure, dating from 1975, was retained and the rehabilitation project focussed on the reuse of materials. Windows were replaced and the external walls were re-insulated. A new roof structure was added. Low-energy Class 1 was achieved by minimising thermal bridges and installing a new ventilation plant and new, energy-efficient lighting. In addition, PV panels were installed on the roof to satisfy 10% of the building's total energy requirements.

The main building of the Norwegian School of Economics (NHH), referred to as the '1963 building', is undergoing an upgrade in 2020 (HENT 2020). Both the high-rise block and the low-rise block making up the main building are to be rehabilitated. The 1963 building primarily houses offices, both for the central administration and for technical and administrative staff from three institutes. The low-rise block contains an auditorium, classrooms, and meeting rooms. The high-rise block is being completely upgraded, and in the low-rise block the climatic protection and technical installations are being upgraded. In addition, several modifications are being carried out to the interior to improve flexibility, human interaction, and space efficiency. Parts of the high-rise block have cultural heritage value, in particular the reception area and corridors. There have been problems particularly with the façade of the high-rise block. The goal of the rehabilitation is to attain something closer to passive house standard while reducing materials use by 38% compared with an equivalent reference building prepared as part of the preliminary project.

Statens Hus Vadsø, Building B, is a protected government office building dating from 1960-1963, and formed part of the reconstruction of Finnmark after the Second World War (Hagen 2020). It is a classic example of the co-location of public services (in this case central government services) in a large multi-function building, and has protected status. Tenders were invited for the rehabilitation project in the spring of 2020, and for the purposes of this study, an internal Statsbygg analysis from the project planning has been used as a reference. Three of the four storeys are to be completely rehabilitated internally, establishing a new floor plan. All technical installations will be replaced, but the heating system will be retained, as this is based on relatively new electrically powered boilers. Exterior walls and the ceiling below the attic will be re-insulated, windows and doors will be replaced, and all interior features, such as walls, floors and sanitary installations, will be renewed. The report (Hagen 2020) compares the actual rehabilitation scenario with a new build scenario, not with a reference building. The new build scenario envisages a smaller area than the rehabilitation scenario, since it is assumed that the area norm of 23 m^2 per employee will be adhered to in a new building.

The two conceptual case studies developed by the Norwegian ZEB Centre in 2013 include single family house (SFH) and office buildings (Dokka et al., 2013a; 2013b). The two buildings are theoretical and built using conventional or traditional concepts. They are used as reference buildings at the Norwegian ZEB research centre and are theoretically located in Oslo. The aim is to achieve ZEB-OM ambition levels, meaning that embodied GHG emissions from operational energy use and building materials should compensated for through on-site, renewable energy production. The SFH building has a heated floor area of 160m2 and made of reinforced concrete slab foundation, timber framed walls, compact roof, a well- insulated building envelope combined with solar façade mounted thermal collectors and air-to-air heat pump and a roof mounted and grid connected PV system.

Detached house concept. Source: Dokka et al. (2013a)



Office building concept. Source: Dokka et al. (2013b)

The office concept building is a four-storey structure with a basement (housing utility rooms and car parking). The office building has 1,980 m^2 heated floor area. The building is conceptually designed with a mixture of individual and open-plan office space, meeting rooms and communal areas. The building has a steel and concrete structure. Solar panels and solar thermal collectors are integrated in the south-facing façade of the building.

3.2.2 Case studies from other countries

By means of a systematic study, suitable case studies were selected from other countries and compared with the Norwegian ones. Studies have been selected that follow recognised LCA methods with transparent presentation of background data and results. Two case studies contributed by the Norwegian Directorate for Cultural Heritage have also been included. These are from a British report on historical buildings (Duffy et al. 2019), referred to here as the Historic England report. Below is a description of the case studies from the Historic England report, followed by a list of case studies resulting from the literature review in Table 3.5. The numerical results are based on the figures reported in the documentation. The results of some studies are normalised per year and/or per m^2, depending on the reference study period and the reference area, respectively, as specified in the case studies. The results applying to the system boundaries covered by each case study (as shown in Table 3.6) are included.

Case studies from the Historic England report

The Historic England report includes two case studies as presented in this section: The Victorian Terrace and Chapel Transformation projects.

The Victorian Terrace project consisted of the rehabilitation of a Victorian terraced house that is representative of many British homes. The project was primarily an energy upgrade. The objective of the rehabilitation was to improve energy efficiency by installing insulation in walls, the attic and floors and upgrading the windows with additional glass layers.

The Chapel Transformation project was a less traditional conversion of a small two-room disused Gothic chapel in London into a detached house. The objective of the transformation and upgrade was to improve energy efficiency using better windows (retaining the original windows and adding secondary double glazing internally) and improving the insulation of walls, roofs, and floors, in addition to internal rebuilding, while retaining interior and exterior materials.

The emissions from the rehabilitation/transformation scenario were compared with a base case or reference scenario in which the building remains in operation without modifications or intervention. A new build scenario has also been used here, involving comparison with a new house, and including demolition and the adoption of modern building standards. The base case considers only emissions linked to energy consumption in the operational phase, while the new build scenario considers the emissions associated with demolition and construction of a new building in addition to energy consumption in the operational phase.

Calculation of GHG emissions throughout the life cycle included sensitivity analyses for: different reference periods (60 years and 120 years in two 60-year steps), indoor temperature varying from 21 °C to 18 °C in steps of one degree, two scenarios for emission factors for electricity, and estimated cumulative GHG emissions in 2030 and 2050, which represent the years associated with political goals for decision-makers. In addition, a life cycle costing (LCC) approach was used to calculate cradle-to-grave construction costs. This included capital costs associated with construction and site location, energy-related operational costs, and maintenance costs (for replacement of windows, roofs and boilers). All future costs are discounted to a base year using a bank rate in the region of 5-10%, with a sensitivity analysis for a 0-10% bank rate in steps of 2.5%.

Table 3.5. General information on the case studies from the Historic England report

Case study	The Victoria Terrace rehabilitation			Chapel transformation projects		
Scenarios	Base case	Rehabilitation	New building	Base case	Transformation	New building
Location	Finningley, UK	Finningley, UK	Finningley, UK	London, UK	London, UK	London, UK
Building typology	Victorian era terraced house	Victorian era terraced house	Residential building	Chapel	Historical chapel converted to residential use	Residential building
Year of construction	1891	1891	2019	Mid 19th C	Mid 19th C	2019
Rehabilitation period		2019			2015	
Number of storeys	2	2	2	1	1	1
Gross area (m^2)	83.1	83.1	83.1	56	56	56
Building materials	Supporting structure of masonry, clad with brick, single-glazed windows	Supporting structure of masonry, internally insulated brick, single-glazed windows with secondary panes	Supporting structure of masonry, insulated brick cavity walls, triple-glazed windows	Supporting structure of masonry, solid brickwork, uninsulated solid floor, single-glazed windows with wooden frames	Supporting structure of masonry, solid insulated brickwork, insulated solid floor, single-glazed windows with secondary panes and wooden frames	Supporting structure of masonry, insulated brick cavity walls, triple-glazed windows
Stated lifetime		60				
Life cycle modules	Construction phase (A1-A5), energy consumption during operation (B6), maintenance and redecoration (B4, B5) and demolition (C1-D)					
Indicator	Greenhouse gas emissions (GWP)					
Database	Inventory of Carbon and Energy (ICE) database and EPDs					

Case studies from international studies obtained in the systematic literature review

Table 3.6. General information about selected international case studies

Almeida et al. (2018); Sedlak et al. (2015)	*Objective of the study*: to understand the relevance of embodied energy and GHG emissions in the evaluation of the cost-efficiency of rehabilitation to nearly zero-energy buildings, as well as the significance of the embodied emissions when reducing emissions and embodied energy for primary energy reductions expected to result from an energy upgrade. *Building typology*: four case studies used for Annex 56, five houses and a primary school, representing various climate conditions and different national contexts in six European countries. 1) Office building (ARE, Bruck an der Mur) in Austria with gross floor area of 6,486 m^2; construction period 1963-1965 and rehabilitation years 2010-2012 2) Primary school (Kamínky 5) in the Czech Republic with gross floor area of 7,296 m^2; year of construction 1987 and rehabilitation years 2009-2010 3) Block of flats (Koniklecová 4) in the Czech Republic with gross floor area of 5,412 m^2; year of construction 1983 and rehabilitation years 2009-2010 4) Two family homes in Portugal with gross floor area of 123 m^2; year of construction 1953 and rehabilitation years 2009-2014 *Service life*: 60 years *System boundary*: A1-A5, B1-B7, C1-C4 *Environmental impact categories evaluated:* GHG emissions (GWP, quantified for each rehabilitation package), cumulative non-renewable primary energy (NRPE) demand and cumulative total primary energy (TPE) demand. Scenarios: 1) reference or 'irrespective of rehabilitation' case (rehabilitation in which the building's energy performance is not improved, focusing on aesthetic, functional and structural aspects), 2) two alternative scenarios using increased insulation thickness (in walls, roofs and floors and a combination

	of technical systems integrated into the building (heating, cooling, lighting, ventilations) with renewable energy sources (measures for producing renewable energy in or associated with the building), 3) scenario with the implemented rehabilitation work. The buildings in the northerly countries were already insulated, so the upgrade packages involved increasing insulation thickness. Most of the windows in the northerly countries were triple-glazed, while they were double-glazed in Portugal and Spain. In the Czech Republic, a new ventilation system was added because this was a school building with a large number of users during the day, and air quality was a problem. Approach and background data: The approach developed for Annex 56 was used. This includes estimates of energy consumption corresponding to local regulations, climatic conditions and construction techniques, estimates of GHG emissions and estimates of costs such as investment costs, maintenance costs, energy costs, replacement and disposal.
Eskilsson (2015)	*Objective of the study*: to compare the climate impact of two potential scenarios involving multi-family residential buildings in Sweden. *Building typology*: Residential building 1) A 9-storey block of flats in Bredäng, Stockholm, built in 1964 with a living area of 5,228 m² 2) A 4-storey block in Nacka, Stockholm, built in 2013-2014 with a living area of 811 m² 50 years *Service life:* 50 years *System boundaries*: Production phase, transport of materials to building site and energy consumption during operation *Scenarios*: Rehabilitation of existing building or demolition and replacement with a new, more energy-efficient building *Rehabilitation measures*: Various rehabilitation efforts were assessed with an eye to improving energy efficiency. Energy system: distant heating, electricity *Approach*: LCA methods using GWP as an indicator.
Famuyibo et al. (2013)	*Objective of the study*: to develop an approach that evaluates energy and GHG emissions throughout the life cycle for the upgrade of the building stock *Building typology*: 13 different archetypes (6 residential buildings, 4 semi-detached houses and 3 flats), which in combination make up 65% of the residential buildings in the existing Irish building stock *Service life*: 50 years *System boundaries*: upgrading, operation (energy consumption for heating, lighting and technical installations), maintenance and demolition of the three selected scenarios. primary energy consumption and potential impact on global warming *Scenarios*: No action (business as usual), measures to achieve currently applicable standards (Irish construction regulations) and measures to achieve passive house standard (according to international passive house standards) *Approach:* a hybrid model of the existing Irish building stock, comprising a process-based LCA approach in addition to input-output data for the installation of materials and maintenance. LCA was carried out in accordance with: ISO 14040/44 (2006)
Jorgji et al. (2019)	*Objective of the study*: to evaluate potential environmental and economic consequences of three different alternatives for upgrading, using a probable LCA approach. *Building typology*: Albanian residential building from 1961-1980 *Service life*: 50 years *System boundaries*: cradle-to-grave system boundary (A1-A3, B4-B6, C + D) *Environmental impact categories evaluated:* primary energy consumption and potential impact on global warming *Scenarios*: 1) standard upgrade (only changes to building shell, with no action involving energy systems), 2) comprehensive upgrade and 3) new building, replacing the existing building type with a new building of the same geometry and energy standard, in accordance with the requirements of EnEV2014) *Approach*: The results of the previous study (SLED Study, 2015) of Albanian building typology were used, while the new construction model is defined in accordance with the requirements of the German EnEV2014 standard. The use of sustainability tools corresponding with the LCA approach for the comprehensive upgrade, as well as for the new build scenario
Hasik et al. (2019)	*Objective of the study*: to analyse the environmental consequences of a rehabilitation project and compare the impact with a hypothetical new build scenario *Building typology*: Two-storey, 5,500 m², free-standing building in an urban location in Philadelphia, Pennsylvania. *Service life*: 60 years *System boundaries*: A1-A3, A4, B2-B4, C2-C4, D *Environmental impact categories evaluated*: acidification potential, eutrophication potential, global warming potential, ozone depletion potential, smog formation potential, and non-renewable energy demand *Scenarios*: two scenarios – rehabilitation and new building *Rehabilitation measures*: Reuse of as much as possible of the original building, including the supporting structure (steel pillars, joists and roof trusses), concrete floor and building shell of brick and terracotta tile, and selected terracotta interior dividing walls. Some of the most importance modifications during the rehabilitation were the complete replacement of windows, replacement of roof covering, raised entrance floor and new interior dividing walls. *Approach*: The existing building was laser scanned and the data uploaded to an Autodesk Revit 3D Building Information Model (BIM). Assessment of the effects of the environmental indicators was carried out using the Tally LCA plugin TRACI 2.1
Asdrubali et al. (2019)	*Objective of the study*: to evaluate the energy and environmental impacts of upgrade work on an existing building. *Building typology*: School building in Turin (northern Italy) dating from 1940, with heated floor area of 8,935 m²

	Service life: 50 years *System boundaries*: A1-A3, A4-A5, B1-B7, C1-C4 *Environmental impact categories evaluated*: GWP (quantifying the amount of CO2 involved in each renovation package), cumulative non-renewable primary energy demand (NRPE) and cumulative total primary energy demand (TPE). *Scenarios*: four different upgrade scenarios involving two NZEB concepts (as defined in Italian regulations) and a cost-optimal upgrade (enabling upgrading to current national limits for U values and system efficiency). *Rehabilitation measures*: additional insulation of the building shell, heating system and lighting, sun shading and other control units *Approach:* Energy simulation, LCA in accordance with ISO 14040 and ISO 14044

4 Results of systematic literature review

This chapter summarises the findings of the systematic literature review and presents the patterns and focus areas of the publications, as well as gaps in previous research.

4.1 Status of research involving existing buildings

The number of publications per year is presented in Figure 4.1 for the 95 articles selected for the systematic literature study. The results show an increase in the number of publications about life cycle assessments (LCAs) of rehabilitation projects in the last five years.

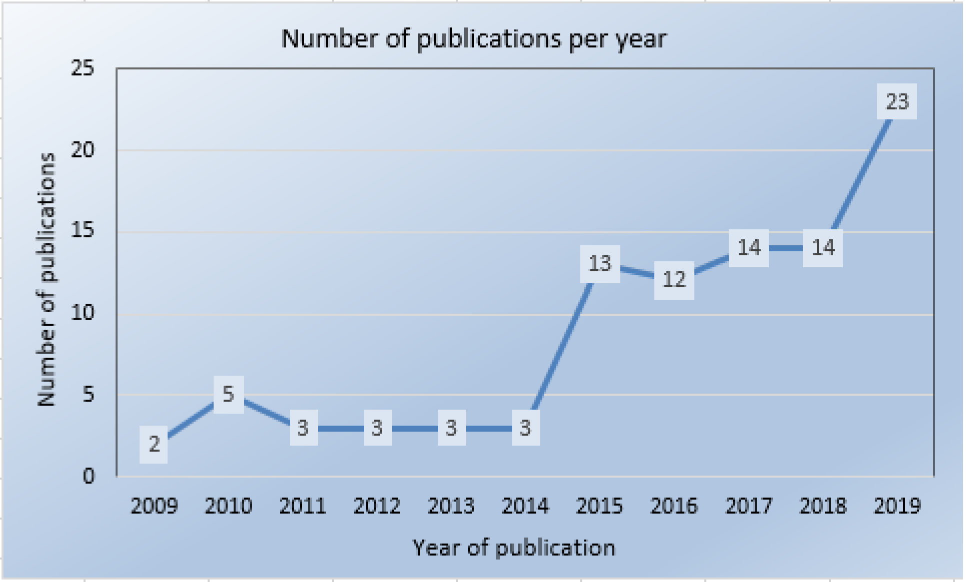


Figure 4.1. Number of annual publications for LCAs of existing buildings

4.2 Analysis of the simultaneity of authors' keywords

Figures 4.2 and 4.3 show the results of analysis of the simultaneity of 576 authors' keywords, identified using VOSviewer 1.6.14 (http://www.vosviewer.com). The simultaneity of the keywords is represented by different cluster sizes and colours. The size of each cluster represents how many times a keyword occurs, while the colour represents the cluster to which the word belongs. The curved lines show the connection between the keywords. The keywords closest to the centre of the diagram have higher frequency.

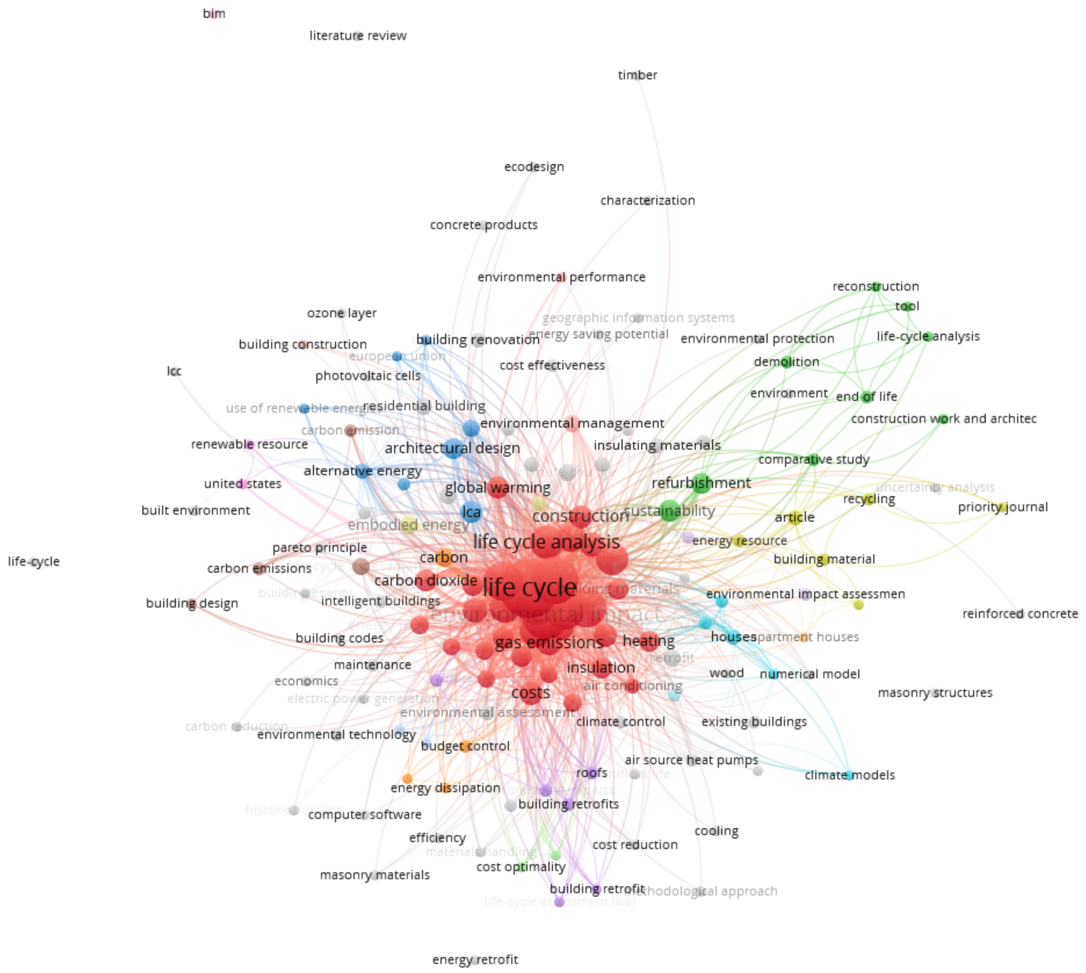


Figure 4.2. Simultaneity of authors' keywords with the minimum number of occurrences specified as a standard value of 5.

Of the 593 keywords identified, the 506 clusters with a limiting value of 1 with regard to simultaneous references presented in Figure 4.2 show that most publications focus on life cycle assessment, which is one of the keywords used in the search criteria.

To attain a more detailed analysis, Figure 4.3 shows the result from the 30 keywords that satisfy the criterion of a standard value of 7 for the minimum number of occurrences. As can be seen from Figure 4.3, 'life cycle analysis', 'environmental impact', 'energy utilisation', 'retrofitting' and 'energy saving' are the five most commonly used keywords.

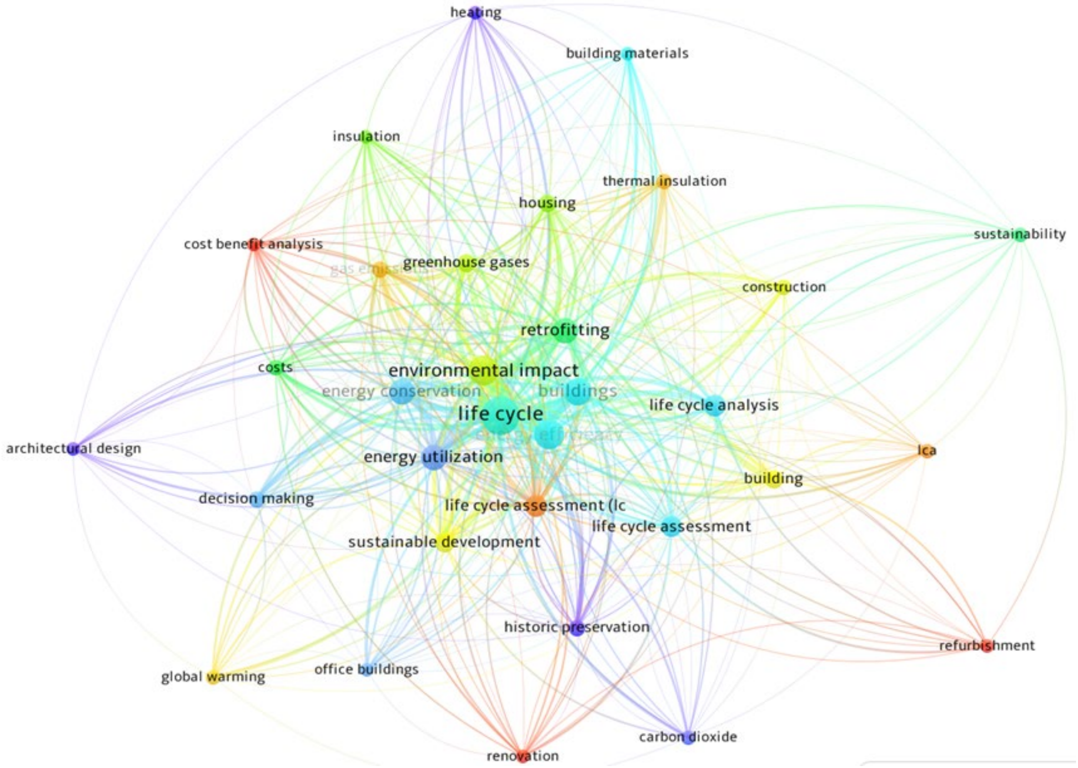


Figure 4.3. Simultaneity of authors' keywords with the minimum number of occurrences specified as a standard value of 7.

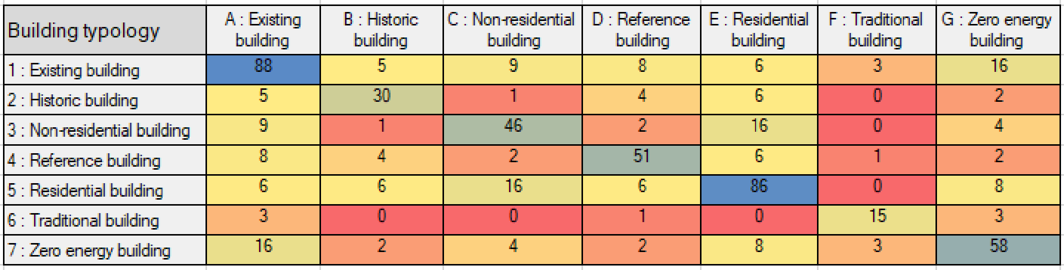
The results also show that the majority of publications use terminology such as 'LCA' and 'energy saving' without including specific keywords.

4.3 Classification of the publications studied

The keywords were found in the systematic assessment in VOSviewer and additional keywords were found by means of 'autocoding' of different themes, carried out using NVivo 12, to classify and analyse the studies. The classification is based on occurrences of the words in the publications without considering the context more closely.

Table 4.1 shows a matrix of most of the building categories included in the studies. The terms under the diagonal line show the building topology as specified in the studies.

Table 4. Results of systematic literature review.1. Matrix of building categories



Building typology	A : Existing building	B : Historic building	C : Non-residential building	D : Reference building	E : Residential building	F : Traditional building	G : Zero energy building
1 : Existing building	88	5	9	8	6	3	16
2 : Historic building	5	30	1	4	6	0	2
3 : Non-residential building	9	1	46	2	16	0	4
4 : Reference building	8	4	2	51	6	1	2
5 : Residential building	6	6	16	6	86	0	8
6 : Traditional building	3	0	0	1	0	15	3
7 : Zero energy building	16	2	4	2	8	3	58

4.4 Findings of the systematic literature review

Based on the systematic analysis described in Sections 4.1 to 4.3, findings in the detailed, studied publications were categorised under four themes. The following themes were considered important for clarifying the issue: (1) Rehabilitation scenarios, (2) Rehabilitation or demolition and rebuilding, (3) Emissions in the operational phase compared with embodied emissions in the building, and (4) User behaviour and use of buildings.

4.4.1 Rehabilitation scenarios

Rehabilitation scenarios deal with the assessment of the various alternative measures that are of interest in connection with rehabilitation. These are analysed in the form of various scenarios. Asdrubali et al. (2019) discussed the findings of a comparison between economic, energy and environmental payback times for the various upgrade scenarios, such as improving the thermal properties of the building shell by increasing insulation thickness, installation of heat pumps with solar collectors and solar panels, and installation of LED lamps. The case study dealt with an existing school building dating from 1940 in Turin, Italy. They point out that rehabilitation of the building shell is less attractive because of the long payback period for costs and emissions. Installation of renewable energy systems showed good economic and environmental results with a shorter payback time. The authors also emphasise that the postponement of environmental impacts by increasing the embodied energy and the environmental impact in the rehabilitation year and by reducing the impact of energy consumption in the operational phase is highly dependent on climatic conditions, technological development, future energy policy scenarios, and choice of materials. The longer environmental and economic period for paying back costs of emissions and costs of a comprehensive upgrade (to nZEB) compared with a cost-effective upgrade are also discussed. that the report showed that it was important to include LCA and LCC analyses in the evaluation of the environmental and economic aspects of various upgrade scenarios. Every case is unique and should be analysed.

Wang et al. (2015) discuss the importance of assessing small-scale rehabilitation efforts involving the building shell (such as replacement of windows and re-insulation of outer walls), combined with low-temperature heating (district heating concepts in combination with small heat pumps operating at lower temperature than normal systems). This was discussed in relation to relatively old houses, where one wishes to avoid a long period before the embodied energy consumption during rehabilitation is compensated by the lower energy consumption in the operational phase (the break-even point). Small-scale rehabilitation projects which improve the airtightness and ventilation systems of the building shell were found to be the most effective measures for use in multi-family buildings. For relatively new (high-rise) residential blocks it was found to be more advantageous to carry out a more comprehensive upgrade, such as replacement of windows, combined with a transition to low-temperature heating systems. Several of the upgrade efforts studied resulted in a break-even point after less than five years. The authors also identified a lack of standardised evaluation methodology for evaluating both energy and environmental effects of rehabilitation projects in Sweden. This was the result of the complexity of rehabilitation and variations in the existing users' conditions. They recommended assessment of the building type before strategic decisions are made with respect to rehabilitation. This enables one to compare the embodied and operational energy reductions connected with various measures. They also pointed out the importance of considering embodied energy GHG emissions from materials used in rehabilitation of the building shell and ventilation system – to avoid overestimating the sustainability of the selected measures.

Ramirez-Villegas et al. (2019) evaluated the environmental impacts of four energy-efficient rehabilitation scenarios for three-storey multi-family buildings built in 1969-1771 in Borlänge, Sweden. They found that the overall (negative) environmental impact associated with technical installations can be compared with those of rehabilitation of the building shell and replacement of ventilation systems. They also pointed out that energy consumption during operation represented the greatest environmental impact.

Dodoo et al. (2010) analysed a multi-family residential building constructed of timber around 1995 in Växjö, southern Sweden. They found that upgrading a building to passive house standard reduces the total energy consumption. However, a significantly larger reduction of the primary energy consumption is achieved for the entire life cycle if the building is heated with electricity (61 vs. 52%) than by upgrading with district heating as the energy source, because of higher energy efficiency and thereby lower total energy consumption over the entire lifetime.

Moncaster et al. (2019) studied the challenges connected with analyses of the environmental impact of rehabilitation efforts and suggested developing reference values for environmental impacts connected with typical rehabilitation efforts.

4.4.2 Rehabilitation or demolition and rebuilding

Sometimes one should consider not only different rehabilitation scenarios for a building, but also whether one should demolish it and rebuild. The decision as to whether to demolish an existing building depends on several factors. The decision will often depend mainly on the costs involved. The costs throughout the lifetime are uncertain, with rehabilitation often turning out to be just as expensive as, or more expensive than, demolition and rebuilding (Lucuik et al., 2010). In 'Annex 72' (IEA EBC (a)) it is pointed out that the decision involves weighing additional investments today against potential costs and savings during the building's use and lifetime for many years to come. Since the economic analysis by no means fully considers all the environmental impacts involved, it is also necessary to quantify the environmental impacts in connection with this decision. LCA is a useful tool for justifying or supporting decisions regarding the need for rehabilitation of existing buildings and comparing scenarios involving demolition and rebuilding.

Assefa & Ambler (2017) examined the environmental impacts associated with adaptive reuse of a thirteen-storey library building at the University of Calgary in Canada as an administration building. They carried out a comparative assessment of two scenarios: complete demolition followed by rebuilding, and selective deconstruction and subsequent reuse of the building. The results indicate that the effect of the selective deconstruction and reuse scenarios resulted in a reduction of 28-33% in seven environmental impact categories (eutrophication, smog, global warming, fossil fuel consumption, human health, acidification of water and soils and ozone decomposition) compared with a scenario involving complete demolition and rebuilding. Although detailed, specific comparative analyses are challenging, the authors stress the importance of such specific assessments of reuse versus rebuilding, since they are so dependent on the unique properties and locations of buildings.

Hasik et al. (2019) propose an approach to carrying out comparative assessments of rehabilitation versus rebuilding and demonstrate the approach by means of a case study of adaptive reuse. The results show a 36-75% reduction in environmental impacts in at least six indicators (potential for pollution, eutrophication, global warming, ozone decomposition, smog generation, and non-renewable energy demand) when rehabilitation is compared with rebuilding. Reuse of structural components provides most of the reduction in environmental impact, while most of the environmental impact from rehabilitation originates in interior components and surface treatment. The case study also shows the effectiveness of comparative scenarios using consistent system boundaries and a well-described, clearly defined scope for studies. The challenges connected with the lack of a clear description of system boundaries for life cycle modules in the analyses for existing buildings and upgrade projects are also emphasised.

The study carried out by Preservation Green Lab (2011) of six building topologies in four American towns shows reductions of from 4 to 46% in environmental impact from rehabilitation and reuse of existing buildings, compared with demolition and rebuilding. The study also argues that upgrading of existing buildings to an energy standard on a level with the average for the existing building stock can lead to an immediate reduction in GHG emissions. The higher environmental impact of a new building occurs early in its life cycle, and it takes some time before the lower emissions during operation compensate for this. Even in the case of new, energy-efficient buildings (with up to 30% higher efficiency than the average for existing buildings) it may take 10 to 80 years to overcome the negative effects of GHG emissions during the building period.

The LCA and LCC study carried out by Raposo et al. (2019) integrates an LCA into a Building Information Modelling (BIM) model and analyses the rehabilitation of a single-storey industrial building in Portugal. In connection with rehabilitation of the building, with the primary objective of reinforcing the supporting structure to withstand earthquake impact, they reveal savings of up to 128.5 times with regard to GHG emissions and 138.5 times with regard to smog generation, compared with savings for a new build, while costs for a new build are 3.79 times those for rehabilitation.

When environmental factors are taken into consideration, Meijer & Kara (2012) point out that the energy consumption connected with heating and the expected life span after rehabilitation are very important in deciding whether to rehabilitate or rebuild. They considered three types of Dutch housing: flats built before 1966, terraced houses built between 1946 and 1965, and a block built before 1966. They compared these in the light of four scenarios: no upgrade (but less maintenance), rehabilitation to modern (minimum) standard to extend the building's lifetime, a transformation scenario with comprehensive rehabilitation, and a rebuilding scenario. The LCA results showed a positive environmental effect connected with demolition and rebuilding, as compared with the rehabilitation alternative, if the expected lifetime after rehabilitation is long (> 30 years) and if high energy reductions are achieved in the operational phase (mainly in connection with heating). In the case of a shorter expected lifetime for the building and lower energy consumption for the existing building in the operational phase, they found that rehabilitation was the better alternative.

On the other hand, Eskilsson (2015) demonstrated that higher GHG emissions can be expected in connection with the building of a new block of flats, compared with upgrade scenarios for the existing building, based on a 50-year lifetime. The Swedish study showed that for a lifetime of up to 126 years, it was most advantageous to retain the existing building.

In Canada, Lucuik et al. (2010) demonstrated significant environmental impact reduction by retaining existing historical buildings, compared with rebuilding. A comparison was made between the energy consumption in an existing building with optimal rehabilitation, a typical new build and a new build with the best scenario. The results were relatively similar. It was found that a more solid building shell and smaller window area in historical buildings had a positive effect on energy consumption. The authors claimed that there are no physical limitations to achieving reasonably good energy efficiency in historical buildings. However, the most serious limitation is how drastic action may be taken. Furthermore, the authors point out other aspects that can count against rehabilitation of historical buildings. These were, among other things, the complexity of rehabilitation work, lack of evidence to demonstrate the environmental benefits, and the reduction in available area due to increasing building density in urban environments.

4.4.3 Operational versus embodied emissions

In Chapter 2 it was pointed out that GHG emissions related to energy consumption in the operational phase are often lower for newer buildings, while embodied emissions are proportionately greater for new buildings than for upgrades. However, embodied GHG emissions are less represented in the literature than operational GHG emissions. Ghose et al. (2017), who analysed a comprehensive energy upgrade of an office building in New Zealand, demonstrated that the environmental impacts of eliminated energy consumption in the operational phase for the rehabilitated building are substantial if the building's lifetime is extended significantly and its high energy efficiency is maintained. The calculations are based on New Zealand's electricity generation, to which coal-firing makes major contributions. The study concludes that measures to promote energy upgrading of office buildings in which a significant amount of the energy consumption during operation comes from renewable sources should be carefully considered, since the overall environmental impact may be increased.

Iyer-Raniga & Wong (2012) evaluated eight buildings in Victoria, Australia. They found that GHG emissions reductions were most dependent on energy consumption during operation, in the form of heating and cooling, the energy mix, and the efficiency of the electricity supply grid.

In their study, Hasik et al. (2019) investigated the embodied emissions. They found that buildings that are built with a lighter supporting structure ('light buildings'), using the minimum insulation requirements in the regulations at the time of construction, may well need major structural upgrades to achieve a reasonable energy standard. Such upgrades may to a large extent affect emissions estimates for a rehabilitated or upgraded building, thereby favouring a new building.

Langston et al. (2018) analysed empirical results from Hong Kong, which showed a 33–39% reduction in embodied emissions and 22–50% lower costs in rehabilitation projects than for new buildings. Preservation Green Lab (2011) pointed out that the actual environmental impact of energy upgrades depends on the choice of materials. Upgrades result in lower energy consumption throughout the lifetime of a building, thereby leading to lower GHG emissions and resource use and less serious consequences for human health. However, the energy efficiency measures also result in increased pressure on the ecosystem because of the effects of materials. The importance was emphasised of assessing several environmental impact indicators when considering energy upgrade projects, since the choice of materials is crucial to minimising the total negative environmental impact.

Marique & Rossi (2018), who performed an assessment of the rehabilitation of an office building dating from 1934 in Brussels, compared with complete disposal and rebuilding, found that rehabilitation led to 54.5% of the impact of a new building as regards energy consumption and 56.6% as regards GHG emissions. Regarding the impact of demolition of the existing building, future demolition of the new building, the construction phase and the embodied environmental impact of the building materials, there were significant differences between the two scenarios. They stressed the importance of analysing the significance of a building's preservation value, the consequences of demolition and the total cost of rebuilding.

4.4.4 Occupancy and user behaviour

The user aspect is important when the use of buildings is to be assessed. Assumptions regarding user behaviour can affect environmental analyses to a considerable extent, both as regards its effect on energy consumption and how the number of users and persons per m² may affect the buildings. Rodrigues & Freire (2017) discussed how potential environmental and cost benefits of the rehabilitation of historical buildings depend on their use and degree of occupation. LCA calculations were carried out for alternative scenarios involving the adaptive reuse of an existing detached house (dating from the early 1900s in Coimbra, Portugal) for residential or office use. The scenarios included low and high occupancy and different levels of upgrading of insulation in the roof and outer walls. A scenario involving a high degree of upgrading using thicker insulation was found to be more beneficial when occupancy was high (high level of use) and the requirements for thermal comfort were high. Residential use with a requirement for higher thermal comfort leads to higher environmental and cost benefits in connection with more intensive upgrading. Residential use with high occupancy leads to higher net annual cost savings using increased insulation thickness on the inside of the outer walls. For scenarios with both high occupancy and low occupancy, improved interior insulation leads to larger savings than does external insulation of outer walls. There are no marginal cost savings from improving roof insulation since the energy savings do not compensate for the additional material costs.

Wastiels et al. (2016) pointed out that even though the scenario involving demolition and rebuilding results in the highest total environmental impact (approximately 20% higher than the rehabilitation scenario) and the highest life cycle costs (approximately 30% higher than the rehabilitation scenario), it is true that rebuilding leads to better environmental and cost results per square metre of heated floor area. They maintained that the increased environmental impact and costs resulting from demolition are compensated for by benefits in the form of a larger accessible user area and that a new build scenario can be more attractive in urban areas with limited space. This is also in agreement with the findings of Lavagna et al. (2018), who pointed out that the reduction in the effect of increased energy efficiency does not compensate for the effect of the increasing average living area (per person, in addition to the reduction in the number of residents per household).

Assefa & Ambler (2017) also discussed the potential economic and practical significance of considering ways of increasing the functional area within the existing building shell to address the challenge of limited areas available for expansion in the form of new buildings. Preservation Green Lab (2011) also highlights this type of adaptive reuse and reasons why an existing building does not fit the proposed new use of the building, including: demographic changes, unfavourable surroundings and/or geographical location, or urban development issues. However, it is pointed out that it is important to place more weight on the relative environmental benefits of reuse when deciding whether to demolish.

5 Results of meta-analysis of existing buildings

This chapter presents the results of the Norwegian and international case studies used in the quantitative meta-analysis. The results are divided into three main groups: 1) Presentation of results of the 12 case studies in Norway, 2) presentation of results of case studies from other countries, 3) comparison of average results of the national case studies with reference values from other countries. Scenario analyses in which the rehabilitation scenario is compared with the new build and reference building scenario are also included to evaluate whether rehabilitation of existing buildings may make it possible to achieve the emissions targets for 2030 and 2050.

5.1 Results of the case studies in Norway

5.1.1 Total GHG emissions

Table 5.1 and Figure 5.1 summarise the results for GHG emissions for the selected case studies in the three scenarios: before rehabilitation, after rehabilitation, and reference building (new build scenario). In the case of the ‘after rehabilitation’ scenario, ‘as built’ GHG accounting is applied, in which the energy consumption is based on estimates. The results show that GHG emissions before rehabilitation have only been studied in two of the case studies: for Stjernehuset Housing Co-operative and Villa Dammen.

All the studies except Vestlia present results for a reference building as a basis for comparison. The reference building is explained in detail in Section 3.2.1. The reference building is usually created from GHG calculation tools (klimagassregnskap.no or OneClick LCA). Some projects create their own reference buildings, a modified model or a building based on similar buildings or studies. Any special assumptions applying to reference buildings are commented on in the relevant case studies below. See also the discussion of the use of reference buildings in Chapter 6.

Table 5.1. Summary of results of GHG estimates for the case studies

	GHG emissions (kg CO_2eq/m^2/year)	**A1-A3**	**A4-A5**	**B4**	**B6**	**C1-C4**	**D**	**Total**	**Reference**
1	Villa Dammen – before rehabilitation	0	-	0.9	60.3	0.8	-	62.0	Fuglseth (2016)
	Villa Dammen – after rehabilitation	0.4	-	0.9	18	0.9	-	20.2	
	Villa Dammen – reference (new building)	4.6	-	1.7	11.6	0.7	-	18.5	
2	Ulsholtsveien – before rehabilitation	0	-	-	-	-	-	-	CIVITAS (2018)
	Ulsholtsveien – after rehabilitation	3.19	-	**	7.2	-	-	10.39	
	Ulsholtsveien – reference (new building)	7.36	-	**	10.8	-	-	18.16	
3	Stjernehuset Housing Co-operative – before rehabilitation	0	-	-	45.4	-	-	45.4	Context (2018a)
	Stjernehuset Housing Co-operative – after rehabilitation	0.7	-	-	13.2	-	-	13.9	
	Stjernehuset Housing Co-operative – reference (new building)	5.5	-	**	10.3	-	-	15.8	
4	Vestlia Housing Co-operative nZEB upgrade – after rehabilitation (ZEB factor^a)	1.13	-	-	11.77	-	-	12.9	Skeie et al. (2018)
	Vestlia Housing Co-operative nZEB upgrade – after rehabilitation (NO factor^b)				2.26			3.39	
	Vestlia Housing Co-operative simple upgrade – after rehabilitation (ZEB factor^a)	0.64	-	-	23.22	-	-	23.86	
	Vestlia Housing Co-operative simple upgrade – after rehabilitation (NO factor^b)				4.47			5.11	
5	City Hall district – before rehabilitation	-	-	-	-	-	-	-	Context (2018b)
	City Hall district – after rehabilitation	3		**	9			12	
	City Hall district – reference (new building)	4		**	20			24	
6	Powerhouse Kjørbo – before rehabilitation	-	-	-	-	-	-	-	Ref. 1: Sørensen et al. (2017) Ref. 2: Thyholt & Lystad (2016)
	Powerhouse Kjørbo – after rehabilitation (Ref. 1)	3.77	0.25	1.82	6.54	0.74	-5.82	7.30	
	Powerhouse Kjørbo – after rehabilitation (Ref. 2)	1.5		**	8.4		-12.3	-2.4	
	Powerhouse Kjørbo – reference (new building. Ref. 2)	5	-	**	12.1			17.1	
7	Bergen City Hall – before rehabilitation	-	-	-	-	-	-	-	Ulvan & Reenaas (2019)
	– after rehabilitation (NO factorc$^{)}$	1.1	0.2	0.4^e	3.7	0.03		5.4	
	Bergen City Hall – after rehabilitation (EU factor^d)				19.0			20.7	
	Bergen City Hall – reference (new building) (NO factor^c)	5.0 ^{f}			2.9	^{f}		7.9	
	Bergen City Hall – reference (new building) (EU factor^d)				18.3			23.3	
8	Grensesvingen 7 – before rehabilitation	-	-	-	-	-	-	-	Enlid & Selvig (2018)
	Grensesvingen 7 – after rehabilitation	2.16	-	**	8	-	-	10.16	
	Grensesvingen 7 – reference (new building)	5.09	-	-	14	-	-	19.09	
9	Stasjonsfjellet School – before rehabilitation	0	-	-	-	-	-	-	School building (2018)
	Stasjonsfjellet School – after rehabilitation	2.26	-	**	6	-	-	8.26	
	Stasjonsfjellet School – reference (new building)	12.56	-	**	11.6	-	-	24.16	
10	Økernhjemmet Nursing Home – before rehabilitation	-	-	-	-	-	-	-	Arkitektur.no
	Økernhjemmet Nursing Home – after rehabilitation	2.2	-	?	11.5	-	N/A	13.7	
	Økernhjemmet Nursing Home – reference (new building)	5.2	-	**	21.3	-	-	26.5	
11	NHH – before rehabilitation	-	-	-	-	-	-	-	HENT (2019)
	NHH – after rehabilitation	1.5			15.2			16.7	
	NHH – reference (adapted rehabilitated reference building)	2.8	-	-	25.5	-	-	28.3	
12	Statens Hus Vadsø. Building B – before rehabilitation	-|	-		-				Hagen (2020)
	Statens Hus Vadsø. Building B – after rehabilitation (EU factor)^f	2.9^h	0.12	-	14.00	-	-	17.02	
	Statens Hus Vadsø. Building B – after rehabilitation (NO factor)^g				1.38			4.40	
	Statens Hus Vadsø. Building B – reference (new building) (EU factor)^f	6.33^h	0.3	-	8.35	-	-	15.28	
	Statens Hus Vadsø. Building B – reference (new building) (NO factor)^g				0.38			7.31	

[a]NO-f: NO emission factor for electricity, averaged over 60 years – 0.025 kg CO_2eq/kWh; [b]ZEB-f: ZEB emission factor for electricity, averaged over 60 years – 0.13 kg CO_2eq/kWh

[c]NO-f: NO emission factor for electricity, averaged over 60 years – 0.024 kg CO_2eq/kWh; [d]EU-f: European emission factor for electricity, averaged over 60 years – 0.195 kg CO_2eq/kWh

[e]includes B4-B5; [f] includes A1-A3, A4-A5, B4-B5 and C1-C4

[f] EU-f: European emission factor for electricity, averaged over 60 years – 0.13 kg CO_2eq/kWh; [a]NO-f: NO emission factor for electricity, averaged over 60 years – 0.0128 kg CO_2eq/kWh

[h]According to the assumptions, materials use includes A1-A3, A4, B4-B5 and C1-C4, but results for materials use are only presented as an aggregate. Technical installations are included in materials use (results are also available in the report that exclude technical installations)

In the case of Villa Dammen, rehabilitation leads to a 67% reduction in total GHG emissions over 60 years, compared with the scenario before rehabilitation. Net GHG emissions for the new build scenario (a reference building to TEK10 standard produced for an MSc dissertation) are 8% lower than for the rehabilitation scenario over a period of 60 years. However, for the after rehabilitation scenario the time needed to compensate for emissions from materials is approximately 6 months, thanks to energy efficiency measures in the rehabilitation process. In the case of the building in the reference scenario, it will take 52 years to compensate for the lower annual energy consumption and the associated emissions, as shown in Figure 5.2.

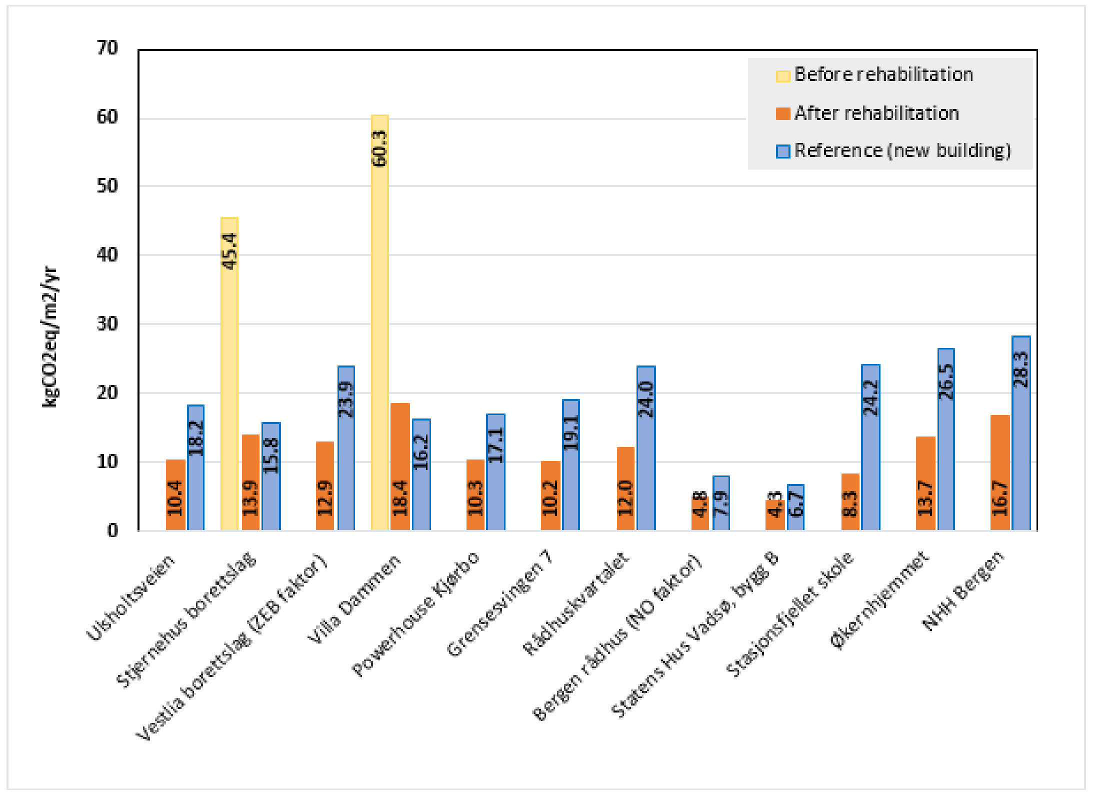


Figure 5.1. GHG emission results (A1-A3, B6) of the selected case studies

5.1.2 GHG emissions from materials and energy consumption

Figure 5.2 shows GHG emissions from materials and energy use for the three scenarios considered in the case studies. The GHG emissions from the operational phase are higher than the embodied emissions for all scenarios in the case studies. The GHG emissions from operational energy in the reference scenario for Villa Dammen and Stjernehuset are however significantly higher than for the after rehabilitation scenario. In Villa Dammen the emissions from energy consumption in the operational phase amount to 97% in the scenario before rehabilitation, 89% in the scenario after rehabilitation and 60% for the reference building. In all the scenarios for Villa Dammen it is assumed that emissions from the use of a wood stove is zero. There is also a difference between actual and estimated energy consumption, where the actual measurements in the operational phase after rehabilitation show 50% lower energy consumption than the estimated consumption for the rehabilitation scenario. The report clearly demonstrates the effect of user behaviour on emissions associated with energy consumption. The emissions from materials use for the reference building are around 12 times greater than for the rehabilitated building. The choice of background data for use in estimating energy-related emissions in the operational phase may be the reason for the variation in the results.

In the Powerhouse Kjørbo project, integrated design strategies were used to minimise materials use and waste and to improve the indoor environment and reduce energy consumption during operation. The stairway was used as a ventilation duct, 80% of the ceiling construction was exposed concrete instead of traditional system ceilings, and reuse of foundations, supporting structure and laminated glass façade were some of the factors that minimised the embodied environmental impacts (Sørensen et al., 2017). Emissions associated with energy consumption during operation were estimated in the ZEB report, which used an emission factor for electricity of 0.132 kg CO_2eq/kWh. This is the emission factor used in the Norwegian ZEB pilot projects (Fufa et al., 2016). The emission factor is based on the assumption of the future scenario involving a carbon-free European electricity grid in 2050 (a stated political goal) using a linear reduction in the years up to 2050. The LCA calculations follow the Norwegian ZEB centre ambition level definition ZEB-COME, which means that all embodied GHG emissions from construction (C), energy use during operation of the building (O), production and replacement of building materials (M) and disposal of the building (E) should be compensated for by renewable energy generation (Fufa et al., 2016). The results show that 42% of ZEB-COME emissions (13.12 kg CO_2eq/m^2/year) are compensated for by local renewable energy generation (-5.82 kg CO_2eq/m^2/year).

A BREEAM report for Kjørbo (Thyholt & Lystad, 2016) supplements the results of the ZEB report and includes a reference building from klimagassregnskap.no. The emission factor for electricity used in this report is 0.278 kg CO_2eq/m^2/year (according to the BREEAM-NOR manual), which is significantly higher than the factor used in the ZEB report (0.132 kg CO_2eq/kWh). Rather different methods of energy estimation are described, with the BREEAM report using standardised values from energy estimates in the Simien simulation application, while Sørensen et al. (2017) have adapted the estimates according to actual expected consumption. This may explain why the difference in the estimated emissions in B6 is not so great (28% higher in the BREEAM report). Correspondingly, in the BREEAM report, the emissions during operation are 49% higher than estimated (at 12.5 kg CO_2eq/m^2/year), since the energy consumption is higher than estimated. The energy production is approximately as estimated, with the result that the overall energy balance is close to zero.

In the Vestlia case study, a comparative analysis of simple rehabilitation versus comprehensive ('ambitious') rehabilitation to a nearly zero emission building (nZEB) demonstrates the importance of reducing the energy demand to reduce GHG emissions. The scenario involving a more comprehensive upgrade, referred to as an 'ambitious upgrade', requires only half as much annual energy consumption as compared with the simple upgrade (with more than 60% lower energy consumption than in the existing situation). The comprehensive rehabilitation results in higher GHG emissions in the year of rehabilitation (year 0) but catches up with the simple rehabilitation after 13.5 years (using the Norwegian electricity factor of 25 g CO_2eq/kWh) and after 2.5 years using the ZEB electricity factor (130 g CO_2eq/kWh). The case study also illustrates the dependence on the electricity factor used, which makes it difficult to compare the emissions from energy consumption with those from materials use (which is important in the context of this report). The research report from the Vestlia case also draws attention to the aspect of the decision-makers' time frames: The members of the housing co-operative have varying time frames and tend to make short-term decisions based on financial profitability. The higher investment costs for the comprehensive rehabilitation, which will result in greater environmental and economic benefits in the long term, form a barrier to attaining a sustainable building stock on the future. Hence, support tools are needed that can assist the owners in decision-making and resolution processes related to energy upgrading.

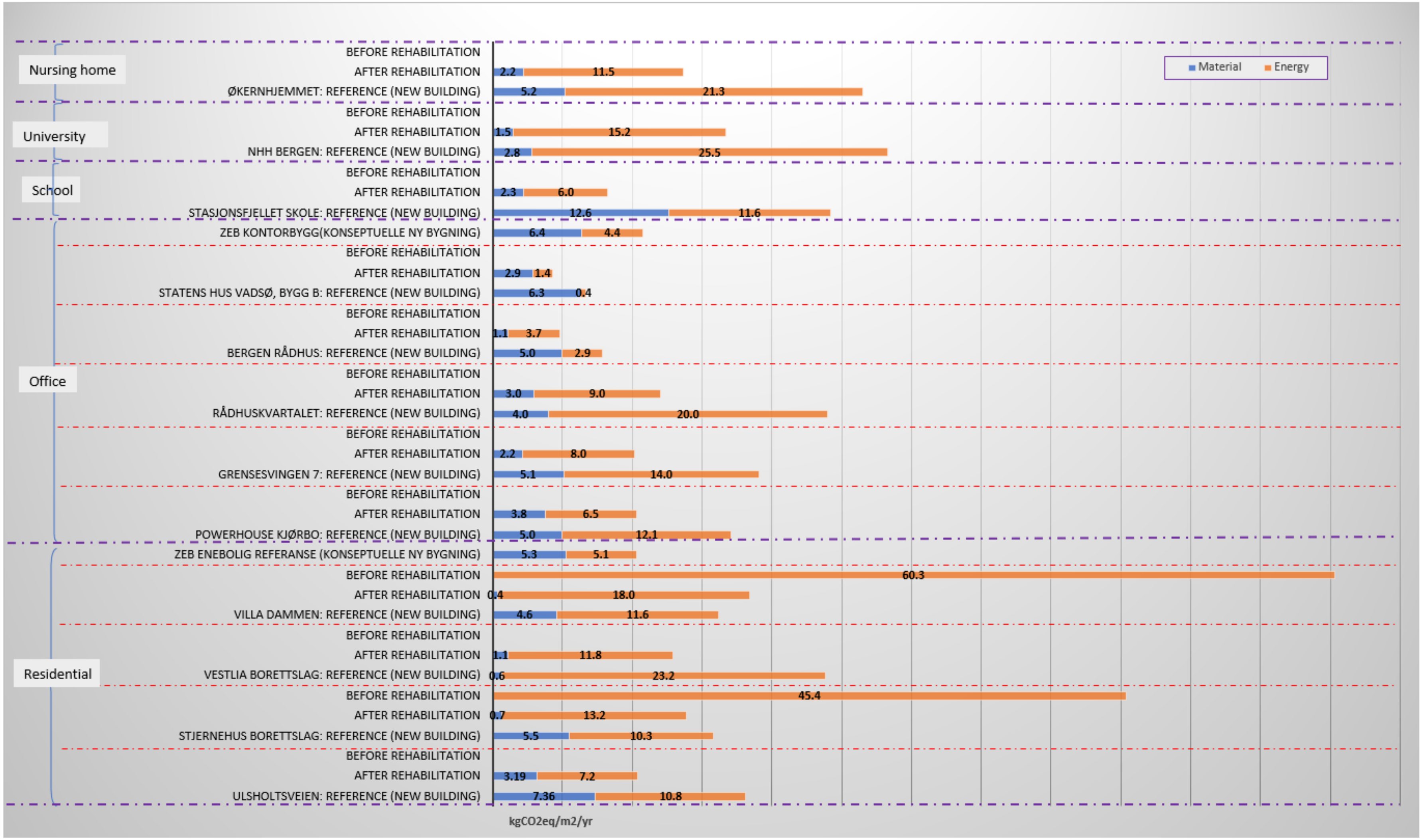


Figure 5.2. Embodied and operational GHG emission (A1-A3, B6) results from the selected case studies

The Ulsholtveien 31 case study contains a project involving a rehabilitated building and two new buildings, and shows the importance of operational energy to the total emissions. The energy performance of the rehabilitated building, Furuhuset, is upgraded to TEK10 standard, with the two new buildings being constructed as passive houses with solar panels (PV). The material emissions from the two new buildings are estimated at 4.88 kg CO_2eq/m^2/year, with the rehabilitated building showing 35% lower material emission at 3.19 kg CO_2eq/m^2/year. As regards emissions from operational energy use, the opposite is the case: the estimated emissions from the rehabilitated building are 7.2 kg CO_2eq/m^2/year, with the new buildings showing 50% lower emissions (3.6 kg CO_2eq/m^2/year). The result is that the emissions from the new buildings are approximately 18% lower throughout their lifetime. It is assumed that 45% of the electricity consumption in the technical installations of the new buildings will be satisfied by electrical generation using PV panels. The data available in connection with the report show that embodied emissions from the solar panels are close to zero. If only electricity from the grid were used (without solar panel generation), the estimated emissions from energy consumption would be around 5 kg CO_2eq/m^2/year. The combined life cycle results with respect to emissions would thus still be around 5% lower per m^2 for the new buildings. In addition to electricity generated by the solar panels, it is expected that 10% of the heating energy will be provided by solar collectors. The report does not state whether the embodied emissions from the solar panels and other technical installations are included in the estimates of material emissions.

Kristjansdottir et al. (2016) found that in the case of the solar panel systems they studied in three residential buildings in the ZEB project, the GHG emissions per generated kWh were around 30–120 g CO_2eq, depending on the system. In the case of electricity generated by the solar panels in the new buildings in Ulsholtveien, the embodied emissions will be around 0.4-1.7 kg CO_2eq/m^2/year. However, we do not know how the embodied emissions for the PV panels are dealt with in these estimates. The Ulsholtveien example demonstrates the importance of transparent, harmonised estimates, as well as a clear description of the results (in accordance with NS 3720). The example also shows that emissions that are omitted from the calculations can have major consequences for the conclusions, and that these sources of uncertainty must be described in the report (emissions from the building activities for modules A4 and A5 were not included, either). The reported emissions per m^2 are lower for the two new buildings than for the rehabilitated building, but there are several assumptions regarding solar energy generation that will satisfy the energy consumption in the new buildings. The results show nevertheless that there is considerable potential for new buildings addressing measures to reduce embodied emissions from materials in combination with energy generation and energy efficiency measures. Similarly, there is potential for energy generation in many existing buildings that can contribute to making those buildings so-called low-emission buildings.

Økernhjemmet Nursing Home is a good example of how such energy generation measures can be implemented in existing buildings, using the roof-mounted solar panels – making an important contribution to reducing emissions from energy consumption. The nursing home achieved a 68% reduction in energy requirements as a result of the upgrade work. The comprehensive rehabilitation led to low added embodied GHG emissions, with the emissions from energy consumption remaining dominant throughout the life cycle at 84% of the total emissions. The total energy requirement of 120 kWh/m^2 is closer to the nZEB scenario than the simple rehabilitation scenario in the Vestlia case study and is low, considering that Økernhjemmet is an energy-demanding nursing home. Data from the operational phase show that emissions increase by 15-20% for energy consumption, compared with the estimated values, which makes this uncertainty alone in the estimated energy emissions higher than the documented, total emissions from materials use in the rehabilitation project.

The project in Grensesvingen 7 was a complete rehabilitation in which only the original foundations and supporting structure were reused. At Grensesvingen 7 the energy consumption in the operational phase can be assumed to be equal to the consumption of a new building (low energy standard). The estimates of GHG emissions from the second year of operation ('in operation' estimates) are higher than estimated for the 'as built' phase, which results in a 29% increase in energy-related emissions compared with those of the estimated building (in the City Hall district there was also an increase, of 23%, from the estimates to the actual emissions). The reduction in emissions as compared with the reference building is 3.7 kg CO_2eq/m^2/year for energy consumption and 2.9 kg CO_2eq/m^2/year for materials. Before the 'in operation' estimates were carried out, the emission reduction for energy was still uncertain, being dependent on user behaviour and an unknown energy emission factor in the next 60 years. The eliminated emissions of 1.33 kg CO_2eq/m^2/year from foundations and building structure represent actual and already eliminated emissions in the rehabilitation phase and represent 46% of the reduction from materials and 20% of the reduction for the combined emissions from materials and energy (compared with the reference building). Although the new building was optimised (without the use of reference values), the emissions from the ground and foundations would probably still have been significant.

In the case of Stasjonsfjellet, the energy consumption is also higher during operation than estimated according to the standards during the planning phase, being about 46% higher than estimated for the building 'as built'. The annual GHG emissions per square metre from energy consumption have increased from 6 kg CO_2eq/m^2/year to 10.4 CO_2eq/m^2/year (a 73% increase). The available results are combined for the 3,600 m^2 original, rehabilitated school building and for the 700 m^2 new building. This complicates the interpretation of the results.

In the case of Bergen City Hall the results of the early phase GHG emission results show that the rehabilitation scenario reduced GHG emissions by 32%, compared with a new building with NO factor (Ulvan, 2019). The new building is based on the reference building in OneClick LCA for materials use, but with more realistic estimates for energy consumption – where it is assumed that a new building would have been constructed as a passive house. The GHG emissions from materials use are reduced by 66%. This is mainly the result of a reduction in materials use and material transport compared with the new building, because of the heavy building elements that are retained. The emission reduction from building site activities is estimated at 39% because of reduced building time. The GHG emissions from energy consumption during operation for the rehabilitation scenario are however about 26% lower than for the new build scenario because the same energy standard is not achieved for the rehabilitated building. The Norwegian Directorate for Cultural Heritage also provided a technical assessment of the cultural heritage value, dealing with the cultural, historical, and architectural value of the existing City Hall (Bergen Municipal development department, 2019). The preservation of the façades was considered particularly important. It was recommended to continue the case study project, incorporating results from the planned building and the 'as built' building, since this may turn out to be an interesting reference case.

The results from the upgrade of Stjernehus Housing Co-operative were to a large extent affected by the change of heating energy source from oil-fired to district heating, as well as the installation of a ventilation system with heat recovery. There was a 70% reduction in energy consumption between the existing building and the rehabilitated building. Emissions from materials originated mainly in the outer walls, including replacement of the façade, doors, and windows, in addition to minor contributions associated with the installation of new balconies. The report compares the rehabilitated building with the existing building and shows that the former 'in operation' shows a 57% reduction in GHG emissions over a lifetime of 60 years, based on the actual measurements of energy consumption and estimated material emissions. Compared with a non-optimised new building, namely the reference building, it is estimated that the emissions from the rehabilitated building will be lower, at 13.9, as compared with 15.8 kg CO_2eq/m^2/year. However, the emissions associated with energy consumption are higher in the rehabilitated building than in the reference building (13.2, as compared with 10.3 kg CO_2eq/m^2/year). The energy requirement of the rehabilitated building is 18% lower than that of the reference building, but the emissions factor used for district heating is higher than that for energy supply in the reference building (using a combination of electricity and heat pump systems). The residents in the housing co-operative were provided with information and instruction in how to reduce energy consumption, and there is only a small increase (3%) from the estimated energy consumption emissions to the 'in operation' estimates (two years after rehabilitation). This indicates the considerable significance of user behaviour for the difference between the estimated and actual values (Gram-Hanssen 2018).

In the case of Statens Hus Vadsø, it is the emission factor used that is decisive in the rehabilitation decision. When the Norwegian emission factor is used, the rehabilitation is clearly more beneficial, whereas when the EU factor is used the new building shows the better result. 82% of the total emissions in the rehabilitation scenario are associated with energy consumption when the EU factor is used, whilst when the Norwegian emission factor is used the relative contribution from energy consumption is lower, at around 31%. When the EU factor is used, the rehabilitation scenario shows 11% higher emissions than the new build scenario, whereas there the Norwegian emission factor gives 40% lower emissions for the rehabilitation scenario. The case study illustrates very clearly how dependent GHG estimates for buildings can be on the choice of emission factor. In the report it is pointed out that 'Statsbygg has decided the European emission factor shall be used' without explaining this choice in the report. Since the decision is to rehabilitate, conservation considerations are weighted heavily. Based on this report on GHG estimates alone it is not clear how the results of the report shall be used for (i.e., the intention of the estimates is unclear). It is of course possible that this has formed the foundation of the further assessment of the complete basis for decision-making.

Even when using the EU factor, the report points out that the rehabilitation scenario will first emerge as the better alternative after 22 years of its lifetime, and that after 22 years the emissions associated with energy consumption will make the new build scenario more beneficial with regard to GHG emissions. Furthermore, it is pointed out that the decision to retain the relatively new electric boilers in the rehabilitation scenario is important, since these are replaced by a combination of 20% electric boiler and 80% heat pump in the new build scenario for energy consumption. This decision is not analysed in detail in the studied report on GHG estimates. In general, one could, for example, have envisaged that installation of heat pumps might also be of interest in one of the rehabilitation scenarios that could have been studied. Alternatively, the electric boiler could have been retained as a theoretical option also in the new build scenario. The choice of energy supply is probably dealt with in another report associated with the project, but it can affect which scenario proves to be most beneficial (even if the EU factor is used). Several rehabilitation scenarios could have been studied. The tender invited options for external insulation and/or replacement of windows and/or external roof covering. This could have been studied as a possible scenario. Considering the significance of retaining the electric boilers, one could also have envisaged that the emissions associated with materials and the installation of a new energy system could have been included (although their importance is possibly low). It is now assumed that emissions per m^2 for the installation of technical equipment are unchanged, but that these emissions are higher for the rehabilitation since the area of the rehabilitated building is greater.

The report on the rehabilitation of NHH Bergen is an internal project report prepared for the planned building (not 'as built' following completed rehabilitation). Only this report was available in connection with work on this study, and it is in the report on the early phase that the reference building is described in detail. The reference building used here is not a new building, but instead an adaptation of a rehabilitated reference building developed using klimagassregnskap.no. In the case of the planned buildings, there is a 50% reduction in the emissions associated with materials use in the low-rise building, while the reduction for the high-rise building is only 23% compared with the reference building. According to the report, steel and other metals contribute most to the materials use emissions for the high-rise building.

The rehabilitation work in the high-rise building is more comprehensive than in the low-rise building. The Norwegian electricity mix is the basis of the energy estimates and energy consumption makes up 91% of the emissions throughout the lifetime.

5.2 Results of case studies in other countries

The results of case studies in other countries are presented below. The findings are divided into two parts: the first presents the principal findings from the Historic England report, which deals with rehabilitation and upgrading of historical buildings. The second part presents the findings of other international studies from the systematic literature study.

The principal findings of the Historic England report

Results for GHG emissions from the Victorian Terrace study showed that the embodied emissions were approximately 2.1% and 27.9% of the total emissions involved in conversion and rebuilding (including demolition), respectively. There are no embodied emissions in the base case scenario. In this scenario no upgrade was carried out of energy efficiency or replacement or upgrading involving materials use. In the case of the rehabilitation scenario, the use of wood fibreboard insulation sheets and carbon storage in the building materials are mentioned as contributing to negative GHG emissions from materials use. GHG emissions resulting from demolition constituted up to 4.1% of the total emissions in the new build scenario. GHG emissions from energy consumption during operation constituted 97.9% and 72.1% of the total emissions respectively for the rehabilitation and new build scenarios.

The authors mention that although the embodied emissions from wood fibreboard and other timber products are low, they emphasise the need to evaluate hygrothermal properties, durability, cost-efficiency and potential technical risks involved in the use of natural products in the rehabilitation of historical buildings. The authors recommend guidelines be developed regarding alternatives for ‘low-emission rehabilitation’ of historical and traditional buildings.

In the results for GHG emissions for the Chapel Transformation project, the embodied emissions are estimated at 10.3% of the total emissions (9.9 tCO2e) for the transformation scenario and 31.1% (18.8 tCO2e) for the new build scenario. These estimates include emissions resulting from demolition. Also in this case the effect of using wood fibreboard insulation and carbon storage in the building materials is deducted, to achieve negative GHG emissions from materials use. GHG emissions involved in demolition constituted up to 6.7% of the total emissions in the new build scenario. GHG emissions from energy consumption during operation constituted 89.68% and 68.87% of the total emissions respectively for the rehabilitation and new build scenarios.

The results show that both for the Victorian Terrace rehabilitation scenario and for the Chapel Transformation scenario, the GHG emissions were relatively lower when a 60-year reference period was used. This is mainly because of the high embodied emissions from demolition and construction of the new building. Energy consumption during operation (from lighting and heating) dominates in both case studies in all scenarios (base case, rehabilitation, transformation, and new build) (Figure 5.3). The authors underline that it is the shorter reference periods that most effectively demonstrate the benefits (of reduced GHG emissions) of the rehabilitation of historical buildings. It is pointed out that it is important to consider indoor temperature variations in future studies, so as to be aware of the actual temperatures found in historical and modern buildings during operation.

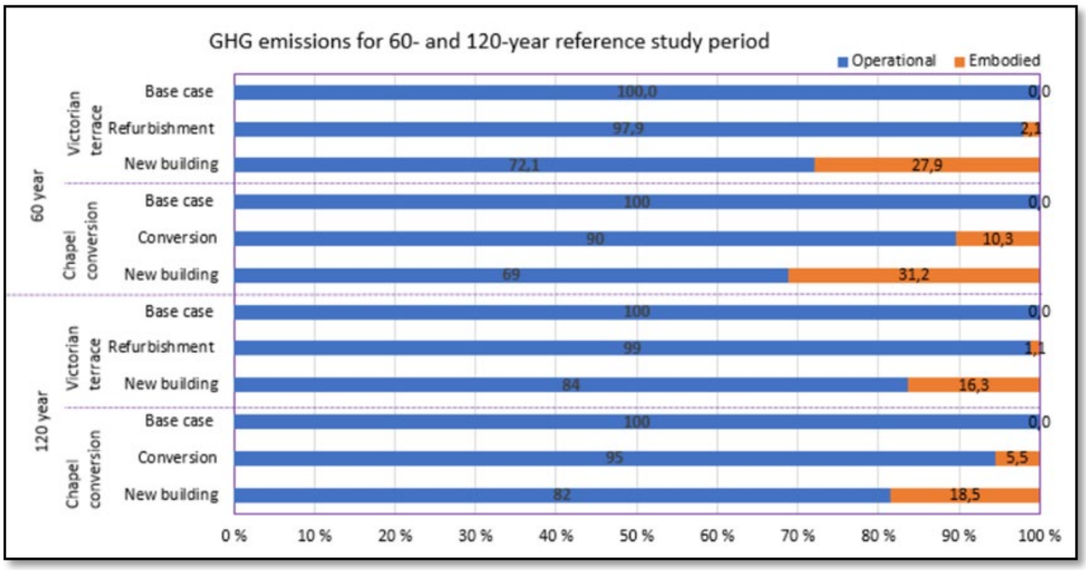


Figure 5.3 GHG emissions for 60-year and 120-year reference study periods for each case study (from Duffy et al., 2019)

Findings from the sensitivity analysis using reference study periods of 60 and 120 years show that GHG emissions from the base case for the Victorian Terrace exceed the new build scenario 10-12 years after the completion of a new building, depending on the indoor temperature used, whilst it is estimated to take 63-74 years (assuming an indoor temperature from 21 °C to 18 °C) before GHG emissions from the rehabilitation exceed those for the new build. For the Chapel Transformation case study, the GHG emissions for the base case exceed those for the new building after 6-7 years, and it is estimated that emissions from the new building exceed those from the transformation scenario after only 13-16 years. The authors therefore point out that the Victorian Terrace rehabilitation scenario compares more favourably with the Chapel Transformation because of the greater focus on improved energy efficiency and lower GHG emissions from the start (in year 0). In the Chapel Transformation, poor insulation of the building and the need for structural modifications resulted in higher embodied emissions.

The estimated results for GHG emissions in 2030 and 2050 for the two case studies are presented in Figure 5.4. This shows the potential for rehabilitation by way of the Victorian Terrace scenario, since this scenario achieves the greatest reductions relative to the GHG emissions targets for 2030 and 2050. In the case of the Chapel Transformation project, it was found that the new building was the best solution and makes it possible to achieve the 2030 and 2050 targets. The results for GHG emissions in the base case scenario are significantly higher for both case studies and for achieving the political targets. For the decision-makers this indicates that continuing to operate buildings with their existing condition and standard does not provide the greatest benefit.

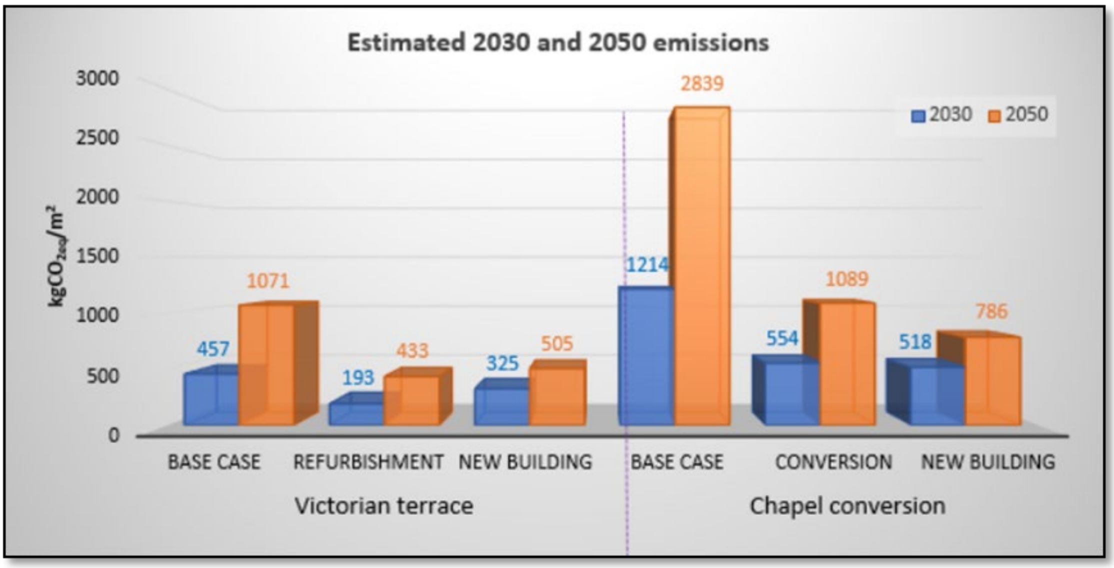


Figure 5.4 Estimated GHG emissions in 2030 and 2050 for the two case studies (Duffy et al., 2019)

In total it is estimated that the two upgrade scenarios in the combined case studies save 266 tonnes of carbon emissions compared with the base case scenarios, and these scenarios are considered worse than both the new build and upgrade scenarios. The authors therefore emphasise the need for energy upgrades of historical buildings, to improve their energy efficiency and enable them to compete with new buildings with regard to GHG emissions throughout their life cycle.

The authors point out that the Victorian Terrace rehabilitation is more representative of rehabilitation projects of historical buildings than the Chapel Transformation project, which is a relatively unusual reuse of a chapel involving significant preservation and repair work.

The limitation of the study as regards the low number of case studies considered is also emphasised, as is the need for additional studies to confirm and support the conclusions. The sensitivity of the LCA results to assumptions regarding construction options and emissions associated with demolition are also factors that should be further assessed. The embodied emissions from the new build scenario are also sensitive to data connected with emissions from demolition, and the authors proposed additional research in this area because of uncertainties and the limited accessibility of data.

Principal findings of international studies
Figure 5.5 provides a summary of LCA results from a selection of international case studies. The intention here is not to make a comparative analysis between the results, but to show the results from the studies in terms of their environmental impact.

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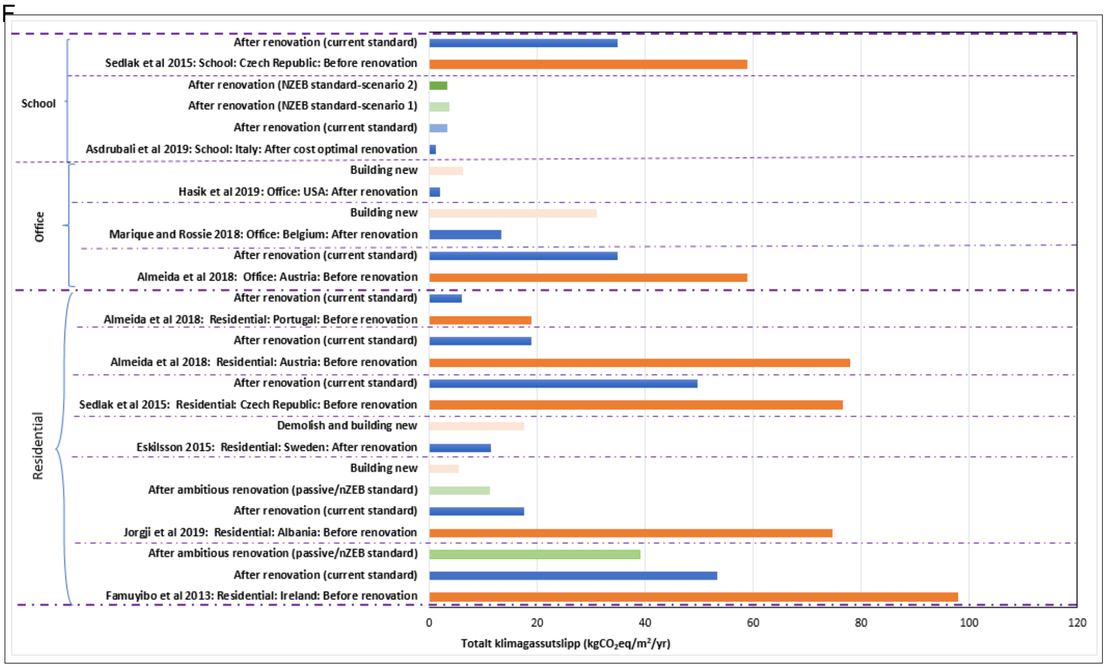

igure 5.5. Summary of GHG emission results of a selection of international case studies

Figure 5.5 shows that there are generally significant emission reductions (up to 70%) in the scenarios after rehabilitation, compared with the situation before rehabilitation. Moreover, there are significant reductions compared with scenarios where new building is considered. Nevertheless, comparisons between different case studies are challenging since the various studies consider very different scenarios. The following sections present some of the findings of the completed case study.

5.2.1 Environmental consequences of rehabilitation projects – contributions of embodied energy

Eskilsson (2015) shows that GHG emissions from energy consumption in the operational phase during the rehabilitation of a Swedish multi-family residence constitute 97% of the total emissions. On the other hand, the embodied emissions constitute about 60% of the total GHG emissions involved in demolition and new building. In this scenario there were relatively high embodied environmental impacts (especially from concrete) and relatively low emissions from energy consumption during operation, using distant heating, mainly based on renewable sources, waste, and surplus heat. They pointed out that the climate impact of the existing building was least in a life cycle perspective, compared with demolition and rebuilding. They also emphasised that it would take around 126 years before the cumulative GHG emissions of the new building were as low as those of the rehabilitated building. They pointed out that in other studies it is the GHG emissions associated with the energy source that have much greater impact in the operational phase and can lead to other conclusions. They discussed the importance of the energy sources to energy consumption during operation and the assumed emission factors.

Almeida et al. (2018) used the method developed by Annex 56 to analyse the significance of embodied energy and embodied GHG emissions to evaluate the cost-effectiveness of rehabilitation work to achieve nZEB standard. The results of six case studies from six European countries show that energy savings in the operational phase for energy-related initiatives are higher than those of the additional embodied energy and embodied emissions during rehabilitation. They pointed out that including embodied energy and embodied emissions in the estimates resulted in a significant reduction (2-32%) of the potential cost savings linked to GHG emissions, cumulative non-renewable primary energy demand (NRPE) and cumulative total primary energy demand (TPE). For countries where all the rehabilitation initiatives were estimated to be cost-effective (for example in the case studies from Austria, Portugal, and Spain), they asserted that including embodied energy and embodied carbon emissions will moderate the achievable reduction in GHG emissions, NRPE and TPE to about 2-15%. They also discussed the fact that there is an increase in embodied energy when the proportion of renewable energy consumption rises as a result of rehabilitation initiatives (for example for nZEB ambitions). Embodied energy is not significant in the scenario in which costs are to be minimised. The findings of the LCA study in Annex 56 (Lasvaux et al., 2017), show that the proportion of embodied energy and embodied emissions are much more significant (compared with energy consumption in the operational phase) in countries and case studies that have a more efficient heating system before rehabilitation, and where emissions in the operational phase are low before rehabilitation. An example of this is Sweden, where distant heating was used, with more than 80% renewable energy. The emissions from the operational phase are more significant in countries and case studies where less efficient systems with high environmental impact were in use before rehabilitation, such as in the Portuguese case study where an oil-fired boiler was used before rehabilitation.

As an example of an energy-efficient upgrade of the Irish housing stock, Famuyibo et al. (2013) demonstrated a potential energy saving in the operational phase of 44% in connection with upgrading to the current national standard and 82% when upgrading to passive house standard, as compared with the base case scenario. They also discussed the importance of assessing initiatives for reducing embodied emissions by means of upgrading and maintenance, since these may potentially increase as the building becomes more energy efficient. They also underlined the importance of an integrated approach and expansion of the system boundaries during the evaluation of rehabilitation of the housing stock.

Hasik et al. (2019) demonstrated a 53-75% reduction in environmental impact in connection with the rehabilitation of an office building, as compared with a new build scenario. Reuse of the supporting structure and parts of the building shell, which often have a lifetime of more than 50-60 years, have considerable effect in reducing environmental impact. Finding a good reference building scenario is challenging. The authors underline the importance of having a database of previously completed projects to be able to compare and ascertain standard reference values.

5.2.2 The importance of erection and demolition of buildings

Jorgji et al. (2019) demonstrate how different approaches in the life cycle assessments provide results that support different (conflicting) decisions. Static analyses favour new build scenarios (because the emissions are reduced in the operational phase), while if one includes statistical uncertainties in the analysis (probabilistic LCA), the upgrade options turn out to be advantageous. Jorgji et al. (2019) consider the probabilistic LCA as a possibility of expanding the existing static approach by assessing different elements of uncertainty in the various rehabilitation initiatives. The method can easily be adapted to varying economic and environmental conditions. Although upgrade initiatives can improve the energy efficiency of a building, it is not certain that upgrading alone is advantageous in the long term: interventions may not mitigate other factors such as weakness of the supporting structure. These may call for major reconstruction during rehabilitation. Such reconstruction is not an optimal solution environmentally and economically, since it may take a long time and involve considerable investments and the disposal of large amounts of waste resulting from demolition of the existing building. Hence it is important to consider innovative technical alternatives in connection with rehabilitation that may extend the building's lifetime and improve overall structural and energy performance.

5.3 Comparison of LCA results

5.3.1 Scenario analysis

Existing studies

Figure 5.6 is a summary of the results collated in Wiik et al. (2020), in which LCA results from more than 120 Norwegian buildings for phases A1-A3 and B4 were analysed. ‘As built 2010-2020’ refers to the statistical analysis of the results for all buildings (new and existing) that were reported at the time of completion of building (referred to as the ‘as built’ results). ‘Rehabilitation’ refers to the statistical analysis of the results of all 13 existing buildings that were upgraded. The assessment considered only GHG emissions and in the production phase (A1-A3) and replacement phase (B4). The 2030 scenario is based on the scenarios in the UNEP Emissions Gap Report, which points out that we must reduce emissions by 7.6% per year from 2020 to 2030 to achieve the 1.5 °C target and 2.7% per year to achieve the 2 °C target, which represent the highest and lowest values respectively in Figure 5.6. For the 2050 scenario, the average emissions were estimated for a reduction scenario of 80% (highest value) and 95% (lowest value) respectively.

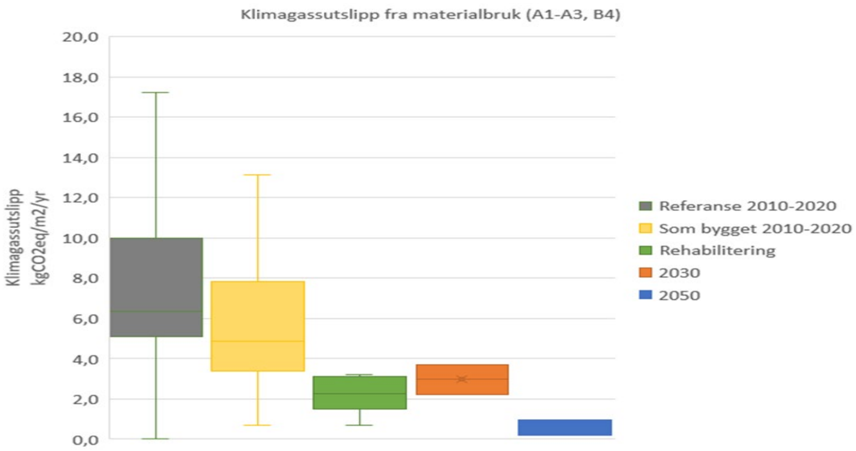

Figure 5.6. Results of measurements of GHG emissions. Source: Wiik et al. (2020)

The results show that upgrading existing buildings made it possible to reduce GHG emissions by an average of 2.3 kg CO_2eq/m^2/year. It is interesting to note that the upgrade strategies are in line with the 2030 target, but that new buildings need to implement additional strategies to cut emissions and close the gap from existing buildings. To achieve the targets for 2050, additional initiatives are needed to reduce emissions from both new and existing buildings. Because the gap for existing buildings is smaller, there is potential in the existing building stock to achieve the 2050 targets. The simplified analysis does not take into account that new buildings will also be needed in coming decades but makes the valid point that upgrading is a better alternative than demolition and rebuilding, as long as this is possible.

The findings of this study

Figure 5.7 presents the results for average GHG emissions (in kg CO_2eq/m^2/year) from 12 Norwegian case studies. For comparison with a new build scenario, the ZEB conceptual new building is used. This is an average emission figure for the two conceptual case studies (one residential building and one office building), developed by the Norwegian ZEB Centre in 2013.

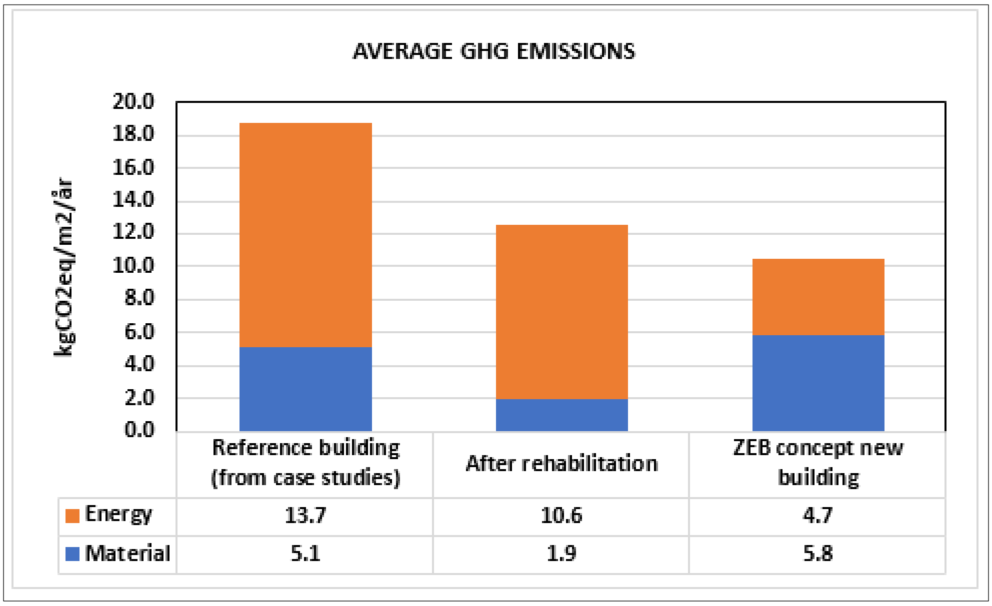

Figure 5.7. Average GHG emissions for Norwegian case studies (in kg CO_2/m^2/year) from materials use (Module A1-A3) and energy consumption in operation (Module B6). ‘Reference building (from case studies)’ represents the average GHG emissions for the reference buildings in the 12 case studies in Norway. ‘After rehabilitation’ represents the average GHG emissions from the existing buildings after rehabilitation in the 12 case studies in Norway. ‘ZEB concept new building’ represents the average for the two conceptual case studies developed by the Norwegian ZEB Centre in 2013 and is used to provide a comparison with a new build scenario.

Figure 5.7 clearly illustrates the potential the rehabilitated buildings represent to be able to achieve the emission reduction targets in 2030 and 2050. In comparison with the ZEB new build and reference building scenarios, GHG emissions from operational energy in new buildings are lower than for the ‘after rehabilitation’ scenario. This also means that the total emissions are somewhat lower throughout the lifetime than for ZEB concept new building (10.5 kg CO_2eq/m^2/year) compared with after rehabilitation (12.6 kg CO_2eq/m^2/year). However, there is a great reduction in GHG emissions for materials use in the ‘after rehabilitation’ scenario, the emissions being a third of those for a new building. The result is that the total average emissions for the reference buildings in the case studies are greater over the lifetime than for the ‘after rehabilitation’ scenario.

For the 60-year reference period we see that the emissions are similar for the ZEB building and the average for the existing buildings ‘after rehabilitation’. Figure 5.8 illustrates the general point that in new build scenario compared with a rehabilitation scenario, a new building will have high emissions before being brought into operation, because of embodied GHG emissions from materials production (Module A1-A3). If one includes the emissions associated with transport of materials and building site activities (Module A4-A5), these emissions before the building is brought into operation will be even greater. However, this analysis only includes emissions from materials use (Module A1-A3) and energy use during operation (Module B6). Lower emissions in the operational phase mean that the overall emissions in the long term may be lower (as for the ZEB scenario), but we see that fairly high reductions in connection with energy consumption in a new building are needed if a new building is to show a better result in 2030 and 2050 than the rehabilitated building. The overall analysis illustrate that the new ZEB concept building does not show lower cumulative emissions until close to the end of the 60-year lifetime. However, such scenarios should be analysed in detail in each individual case.

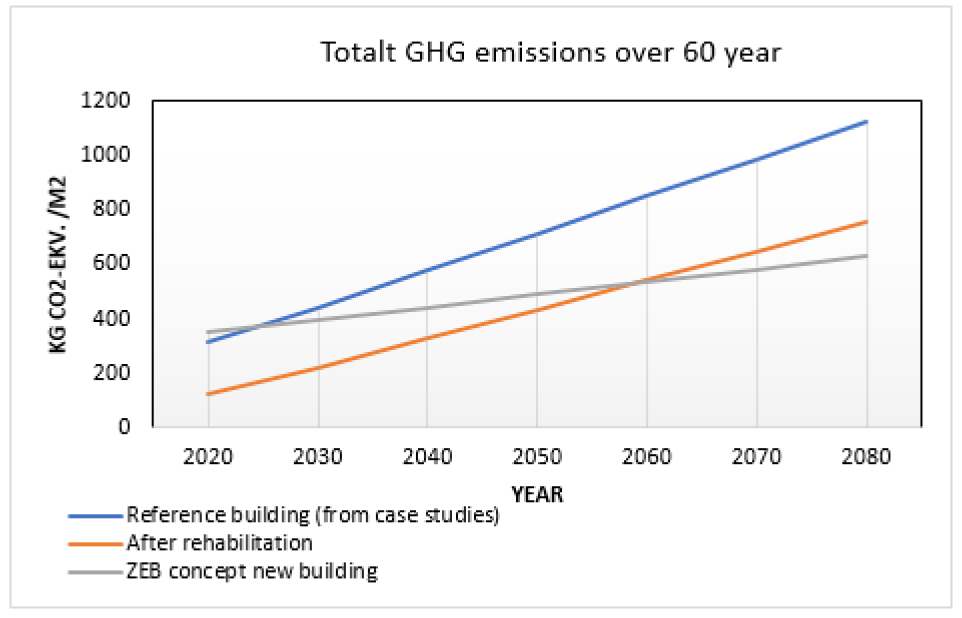

Figure 5.8. Cumulative GHG emissions over 60 years of each of the three scenarios in this analysis. All emissions associated with materials use are allocated to the year of construction (2020), while energy use in the operational phase is distributed equally over the following 60 years.

Since the curve for ‘after rehabilitation’ is based on an average of the Norwegian case studies, which are based on different approaches, it does not consider changes in the energy mix in the years up to 2050. It is assumed that the annual energy-related emissions are equal throughout the 60-year period. The 60-year lifetime is also a general assumption in all scenarios. The analysis only deals with the emissions values for materials use and energy consumption as these are specified in the case studies examined, and because there is a lack of data for other important parts of the life cycle, only these phases of the life cycle are considered.

The findings of the Historic England report emphasise that energy-efficient upgrades of historical buildings are necessary to achieve performance and emissions levels comparable with those of new buildings. Existing statutory regulations, which only consider GHG emissions in the operational phase, put historical buildings and their rehabilitation at a disadvantage as regards assessment of GHG emissions. If embodied emissions are omitted from the LCA studies, the total GHG emissions from new buildings will be underestimated by almost 30%. A sensitivity analysis of reference periods shows that the shorter, 60-year reference period most clearly highlights the advantages (as regards GHG emissions) of the rehabilitation of historical buildings. This period also corresponds closely to that considered in standard construction planning. In the case of the Victorian Terrace houses, it was found that rehabilitation achieved the best results in the years 2030 and 2050 of all the alternatives studied and was also the best alternative economically.

Further studies beyond this simple analysis should consider how the emissions targets in 2030 and 2050 can be used in such a scenario analysis. Our work with the case studies shows that not enough of them provide data for emissions for before rehabilitation scenarios. At the level of individual buildings, it would be interesting to be able to use such ‘before rehabilitation’ data to analyse and compare different rehabilitation scenarios to achieve the emissions targets for 2030 and 2050, for example 40% for 2030 and 95% for 2050, compared with before rehabilitation. Here one can also compare performance with that of a new build scenario. In such scenario analyses of specific individual buildings, one should look more closely at how changes in the energy mix in the years up to 2050 affect and change the analysis. Moreover, it is important to look more closely at the differences for various types of building in those cases where the building type has not been taken into account in the general analysis conducted in this work. There is also a need for more studies of the 2030 and 2050 targets in the scenario analyses of rehabilitation and emissions from the entire building stock, but that is peripheral to the subject of this study, which is at the level of individual buildings.

5.3.2 Reference values in LCA context (Benchmarking)

LCA reference values can be developed using either a top-down approach, in which the reference is based on political targets using statistical data, or a bottom-up approach, using reference buildings (Hollberg et al., 2019). These approaches may also be combined by using reference buildings and statistical data simultaneously (Schlegl et al., 2019). The reference values are often presented using 1) limiting values that specify minimum permitted values, 2) reference values based on existing technical standards ('business as usual' or current 'state of the art'), or 3) deliberately chosen values that make use of best-practice values that can be assumed to be achievable in a medium- or long-term perspective (Hollberg et al., 2019).

Figure 5.9 summarises reference values from different countries, compared with average values from the Norwegian case studies. The results show that materials emissions are lower in the Norwegian case studies involving rehabilitation, compared with the reference values for new buildings in the other countries. The emissions from energy consumption are however greater for the rehabilitated case buildings in Norway, compared with the reference values from Denmark and France. It must be pointed out that the findings of the Norwegian case studies are for after rehabilitation scenario based on a limited number, which makes comparative analysis difficult.

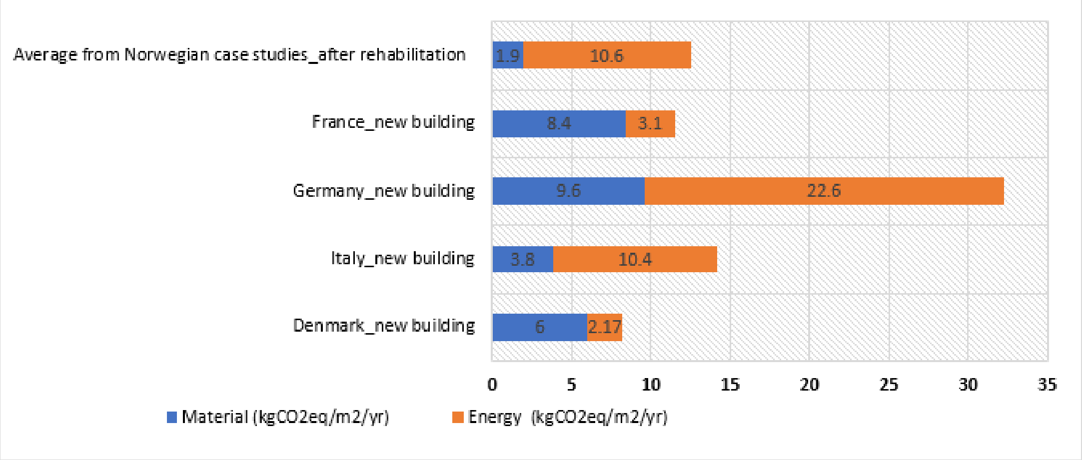

Figure 5.9. Reference measurement (benchmarking) values of GHG emissions from different countries

Although the reference values from other countries are for new buildings, they summarise effectively the challenges of varying approaches in different countries and the challenges associated with reference buildings. The background data used in each study are summarised in Appendix 2.

6 Discussion of findings

The following chapter presents the reflections of the authors on the work involved in the study and discusses the findings described in Chapters 4 and 5. Relevant references are highlighted in support of the discussion. This constitutes the basis for conclusions and recommendations presented in Chapter 7.

6.1 Environmental benefits of rehabilitation

Traditionally, the rehabilitation of older buildings has not been prioritised by politicians, building owners or property developers in the professional construction market, although such work has a potential for increasing energy efficiency and reducing GHG emissions. Instead, the rehabilitation of existing buildings in the commercial building sector has often been considered expensive and not very environmentally friendly because of technical, functional, and economic limitations (Flyen et al., 2020; Höfler et al., 2017).

The results of the meta-analysis show the potential environmental benefits of rehabilitation of existing buildings. The reductions are seen to vary considerably from case to case. The review of international literature also supports this conclusion, with the magnitude of the environmental benefits of rehabilitation and adaptive reuse of the existing building stock varying from 4 to 74%. The meta-analysis in Section 5.3 also shows that upgrading existing buildings, rather than demolition and rebuilding, is the way to proceed to satisfy Norwegian national climate ambitions. The high levels of emissions associated with constructing new buildings today will contribute to increasing emissions, and the gap between the actual emissions and the climate ambitions approaching 2030 and 2050 will widen. The study shows that it will take too long before the benefits of the reduction in annual emissions associated with energy consumption during operation of a new building compensate for the high level of emissions involved in the construction of new buildings. Findings in the literature support this, showing that rehabilitation will be beneficial on the short and medium term (<30 years) (Meijer & Kara, 2012), and that it may take 10 to 80 years before a new building compensates for the GHG emissions involved in the initial building process (Preservation Green Lab, 2011). In the case of Statens Hus in Vadsø it was found that it would take at least 22 years before this point was reached, even assuming the most optimistic scenario. The findings of the sensitivity analysis for the Victorian Terrace case study in the Historic England report highlighted that the shorter reference period (60 years) most effectively highlights the advantages (as regards GHG emissions) of rehabilitation of historical buildings.

The Norwegian case studies, show that GHG emissions associated with materials use in upgraded existing buildings is approximately one-third of those associated with materials use in new buildings. The existing building stock represents a major unexploited potential for reuse as well as recycling of buildings, building components and materials. Circular use will contribute to saving scarce raw materials and reducing GHG emissions associated with carbon-intensive production processes for materials such as concrete, steel, and glass. A combination of effective systems for the selection of environmentally sound materials, energy efficiency measures, and the use of renewable energy resources is important for cost-effective rehabilitation of the building stock.

The Vestlia case study shows that upgrading with high energy-reduction ambitions can also result in reduced GHG emissions throughout the building lifetime. This is also in line with the findings of international studies. Upgrading with lower energy-reduction ambitions results in higher emissions over the entire lifetime than in a more comprehensive scenario (Skaar et al., 2018).

The findings of the Victorian Terrace case study in the Historic England report highlighted the importance of energy-efficient rehabilitation of historical buildings for achieving performance comparable with that of new buildings. However, the level of intervention affects the embodied emissions, with some rehabilitation requiring increased material use to achieve an energy standard corresponding to new buildings. Hence the use of low-carbon materials (such as natural timber products) or recycling and reuse of materials with high embodied emissions is important to achieve emission reductions by means of energy upgrading.

To reduce the impact of existing buildings and improve the environmental soundness of the rehabilitation scenario, several emission reduction and compensation measures should be considered in such an upgrading process. It must be accepted that the resources available will ultimately decide which energy efficiency measures can be implemented. Balson et al. (2014) demonstrate nevertheless that despite the challenges presented by preservation status, costs and time restraints, it is possible to achieve sustainable upgrading of cultural heritage buildings with high BREEAM certification.

6.1.1 Challenges of achieving energy efficiency in existing and cultural heritage buildings

Many older buildings will not necessarily be able to satisfy the GHG emission reduction requirements of the Norwegian Planning and Building Act, even after comprehensive rehabilitation. Since the number of existing buildings is large in comparison with the number of new, energy-efficient buildings, and a large number of the existing buildings have relatively low energy efficiency, there is a need to assess the effect of energy efficiency measures in the existing building stock. Such assessments must be seen in the context of cultural heritage value, other rehabilitation and maintenance requirements, technical factors, change in comfort requirements and the effect of the work as regards cost and emission savings.

Implementation of energy efficiency measures – or the use of concepts intended for modern buildings – in historical buildings may have unintended and undesirable consequences (Agbota, 2014). Meeting the need for sustainable and energy-efficient solutions, while at the same time respecting and safeguarding a building's cultural heritage value, presents a clear technical challenge. Pracchi (2014) concludes that the three key issues when implementing strategies to achieve improved energy performance in cultural heritage buildings are 1) the challenges of balancing between various needs, 2) the limitations of tools for implementing diagnostics of efficiency measures, and 3) inadequate knowledge of historical buildings. It is also pointed out that systematic databases should be developed that provide specific information about energy consumption and upgrade and restoration history in the historical building stock. Such databases may be used to carry out accurate and meaningful simulations of energy efficiency measures using models of the buildings (Pracchi, 2014).

This shows that it is important to understand and respect the era in which the building was constructed and its structural principles, materials use and architectonic and historical value (Fouseki & Cassar, 2014; Crockford, 2014). As described above, even small changes in building structure may have the effect of enhancing both the energy performance of a building and its comfort as experienced from a user perspective (Godbolt et al., 2018).

In the case of protected buildings, the potential emission reduction measures are specific to each individual building. Measures such as change of energy source are almost always of interest, while the possibilities for initiatives such as re-insulation of façades and replacement of windows may be limited. Both for existing buildings in general, and for cultural heritage buildings in particular, there is a need for better, more systematic methods for implementing and evaluating upgrading initiatives – what Pracchi (2014) refers to as efficiency diagnostics for upgrading. Such sophisticated approaches will be capable of fully realising the sustainable potential inherent in the existing building stock.

6.1.2 Increasing knowledge of good rehabilitation measures

It is important to establish an overview of best practices, including specific experiences of rehabilitation projects, to protect and improve the technical, environmental, social, economic, and cultural values inherent in existing buildings. Acquiring an overview of best practice by developing a standard method of data collection, evaluation and reporting will make it possible to close the knowledge gap and promote information exchange between the various actors in the building industry. A rehabilitation passport is a (preferably digital) document are good examples that collects information about building functions and short- and long-term rehabilitation planning by engaging a range of stakeholders in the early phase of the process. Preliminary initiatives are under way in Belgium, France, and Germany, and the introduction of such rehabilitation passports is recommended for buildings throughout the EU (Fabbri et al., 2016). As far as the authors are aware, there has been no recent practical research in Norway into the evaluation and development of rehabilitation passports. Further evaluation of the need for rehabilitation passports and communication of the results in Energy performance certification system, EPCs, and building certification schemes, such as BREAAM-NOR, is important. It is also important to tackle the challenges connected with certification systems (such as including clear explanations and justification of advantages and disadvantages of the various alternative measures in EPCs (Berg & Donarelli, 2019)).

The UN Sustainable Development Goals are useful in the work to develop a forward-looking building and construction sector, and evaluation methods should make use of these to promote reuse of existing building stock. At present it is unclear how the sustainable development goals can be implemented, measured, and monitored in practice in construction projects. Initiatives are in progress to link the sustainability goals to industry requirements and to investigate the potential for using LCA as a tool for simplifying the implementation of the sustainability goals. Cultural heritage also constitutes an element of sustainability perspectives, and it is important that the cultural value of the existing building stock is also assessed and considered in the same way as other sustainability aspects are.

6.2 Challenges and opportunities in LCA studies of existing buildings

The review conducted in this study shows that few LCA studies have been carried out for evaluation of the environmental performance of older buildings, and even fewer for cultural heritage buildings. The focus has been on operational energy saving and energy efficiency measures. This somewhat one-sided focus does not show the full picture. Much of the energy use in operational phase of a building is reduced by energy efficiency measures, but emissions associated with the production of building materials and elements, transport, construction, and replacement and disposal of existing materials and elements are not adequately considered in the basis of evaluation when rehabilitation of existing buildings. It is precisely this that is assessed by means of LCAs, if one implements these while following the ‘cradle to grave’ principle.

In the following sections we have summarised some of the principal challenges we have discovered in LCA studies of existing buildings while working on this report.

6.2.1 Improved transparency using LCA standards and harmonised methods

There is lack of LCA studies that follow standard LCA methodologies for existing buildings, both in Norway and internationally. Although a simplified (screening) LCA is helpful in an early phase, when knowledge is limited, the study should be updated throughout the project period as more detailed data become available, to assess developments and any potential supplementary action.

The results of the meta-analysis also show a lack of consistent, methodical choices and transparency in the background data used, which makes it difficult to use few existing studies. Uncertainty in the use of generic as opposed to product-specific background data (from EPDs) should be clearly described in all reports. As regards materials use, the use of product-specific data will result in lower GHG emissions, compared with the use of generic data (Houlihan Wiberg et al., 2015). LCA studies shall clearly describe the LCA system boundary following life cycle modular principles as set out in standards, such as EN 15978 and NS 3720. The harmonisation of the life cycle description given in the standards and further evaluation of uncertainties in the given description will improve the transparency of LCA studies. A discussion should be included of the uncertainties in the selection of the system boundary (for example the consequences of omitting emissions from construction phases in A4-A5).

Most Norwegian LCA studies describe the physical system boundaries and construction elements included, in compliance with NS 3451:2009 Table of building elements. Many uses two-digit level, meaning that elements are reported in the form: 21 Ground and Foundations, 22 Supporting Systems, etc. This is an important premise for facilitating good, transparent comparisons. However, even here there is no consistent interpretation of the standards among the various LCA experts. Wiik et al. (2018) identified these challenges when comparing pilot studies from the ZEB research centre, where some building elements were placed in different categories. This applied particularly to how energy generation technologies were categorised. A clear description of the building elements and what is included in each category is therefore important for understanding the distribution of materials and emissions among the various building elements. All reports should contain a clear definition and description of the ambition and scope of the rehabilitation measures and a transparent documentation of the LCA results. Powerhouse Kjørbo and Vestlia projects are good examples, where the ambitions, rehabilitation measures, environmental impact assessment calculation and reporting methods were provided according to the Norwegian ZEB centre ambition level definition.

6.2.2 Expansion of the scope of the LCA studies

GHG emissions are the most important indicator considered in the case studies. This may result in a shifting of problems to other environmental indicators. Wang et al. (2015) refer to other potentially important environmental impact indicators, such as human toxicity, mineral depletion, land use change, freshwater toxicity, terrestrial toxicity and acidification of soil and water. Future studies should assess additional environmental indicators.

When studies do not encompass the entire life cycle and do not provide detailed investigation of the embodied emissions, the significance of existing building's environmental benefits may be underestimated. All the studies, apart from Villa Dammen, Statens Hus Vadsø and Powerhouse Kjørbo, considered only life cycle Phases A1-A3 and B6 (in addition to B8 Transport during operation, which was assessed in some of the studies, but is not considered in this study).

The construction phase (A4-A5), activities associated with the erection of the building, is often neglected in LCA studies. Increasing attention is being paid to this aspect in the construction industry, since it is estimated to account for 5-10% of the emissions from cities (about 7% of Oslo's total emissions according to SmartCitiesWorld). The national initiatives for developing fossil-free, emission-free (Fufa et al. 2019a; 2019b; 2018; Selvig et al., 2017) and waste-free building sites (Halogen, 2019) indicate that it is important to consider environmental impact reduction measures from the construction phase to fulfil emission reduction targets.

In the case of the scenario in which a building is demolished and rebuilt, the assessment of the environmental impact of disposal of the existing building and disposal at the end of the new building's lifetime can be important (Marique & Rossi, 2018). For example, the emissions from the disposal of Villa Dammen constitute about 20% of the emissions associated with construction. Lucuik et al. (2010) also demonstrate the importance of the elimination of environmental impacts associated with demolition (by preserving an existing historical building) assuming emissions factors for demolition per square metre of 0.08 tonnes CO_2eq/m^2 (GWP) and 0.14 GJ/m^2 (in terms of primary energy). Thus, considering the entire life cycle of a building will also highlight the emissions in the construction phase (A4-A5), which can be up to 10% of the total life cycle emissions, and in the building's end-of-life phase (C1-C4), which can be up to 5% (which will enable to save ca. 15% of emissions related to construction and end of life). Extending the scope of LCA studies to cover the whole life cycle of existing buildings and using different impact indicators will help to highlight the importance rehabilitation of exiting building.

6.2.3 Limited study at individual building level

The scope of this study is limited to existing buildings at individual building level. At such a micro-level it can be challenging to achieve targets for energy demand and emission reduction with an eye to the implementation of energy efficiency measures, the use of renewable energy and emission reduction measures in individual buildings (Wiik et al., 2018). The Preservation Green Lab study pointed out that the reduction in GHG emissions by means of adaptive reuse and rehabilitation of existing buildings can be significant when the results from individual buildings are scaled over the entire building stock in a city (Preservation Green Lab, 2011). Expanding the scope from focus on individual buildings to include the neighbourhood (meso-level) and city (macro-level) can reduce system-wide energy requirements and increase the availability and use of renewable energy. Such a perspective makes it possible to evaluate the total performance of the building stock, rather than of single buildings.

6.2.4 Service life

The service life of an entire building, building components and materials has a significant effect on the LCA results. A building service life of 50 years has often been used in LCA calculations, while actual data from existing buildings show that an average technical lifetime of 100 years or more would be more correct (Marsh, 2017). In Norway it is normal to use a 60-year lifetime in LCA calculations (NS 3720:2018; Fufa et al., 2017). Marsh (2017) shows that the longer the service life of a building, the lower the environmental impact (with potential reductions in environmental impact of 29%, 38% and 44% if the service life is extended from 50 years to 80, 100 and 120 years, respectively). In the real world, buildings are demolished before they reach their physical end-of-life, mainly because of subjective perceptions and changes in use (Palacios-Munoz et al., 2019). Creating awareness and influencing peoples' behaviour and attitudes towards reuse is important to extend the service life of existing buildings.

Studies of existing buildings also use the term 'residual lifetime' to refer to this reference study period for a building. It is the period between the time of rehabilitation to the end of a building's lifetime. In the Norwegian ZEB definition report (Fufa et al., 2016) and Annex 56 (Ott et al., 2017) it is recommended to use a 60-year reference study period for buildings that undergo comprehensive rehabilitation.

When assessing the residual lifetime of materials in buildings that are to be rehabilitated, there is also uncertainty connected with how to allocate the environmental impact for the existing materials and components that are reused (Fufa et al., 2017). The EN 15978 standard states that the allocation of the total impact shall be based on the percentage of the residual lifetime of materials or components that are reused. At the Norwegian ZEB Centre, the environmental impacts for the residual lifetime of the reused materials or components are excluded from the LCA estimate, on the assumption that these impacts belong to a building's previous life cycle (Fufa et al., 2016).

The results described in Chapter 5 showed that replacement of components of buildings contributed to a significant extent to the total life cycle emissions, where the estimated life cycle data for materials and components added to the building play a significant role. The service life of building materials and components depends among others on physical properties (e.g. moisture resistance), context of use (e.g. whether it is placed in the roof or exterior wall; exposed outside, against ground or interior) and maintenance condition and can be replaced once or several times during the reference study period. The background data for estimating the reference service life for different construction materials varies among different studies and analyses. In Norway, service life data obtained from the manufacturer's technical product documentation, EPDs or technical certification developed by SINTEF are mostly used. However, the service life in an actual scenario may be shorter than that stated in the documentation, and it is therefore important to validate existing data by means of experimental tests (such as accelerated ageing tests), numerical analyses or actual lifetime data.

6.2.5 Emission factors for different energy sources

In general, there is lack of transparency, consistency, and discussion in the reviewed studies of the uncertainties linked to energy emission factors. Although the emission factor used for an energy source significantly affects the results of environmental impact, there are no harmonised methods as regards selecting emission factors to be used. The importance of the various emission factors for energy use is illustrated in the Stjernehuset Housing Co-operative case study. The replacement of the oil-fired boiler permits many scenarios that produce better results. The reference building beats the rehabilitation scenario (using a district heating system) that was selected in the rehabilitation process. However, no discussion is provided of exactly why district heating was chosen, nor of the uncertainty in, or background data for, the chosen emission factor.

The dependence on different emission factors and the different methodology behind them – especially with regard to electricity – means that comparing energy and material emissions is generally challenging. This is illustrated well in the example of Statens Hus in Vadsø, where the determination of whether rehabilitation and rebuilding is most beneficial depends on whether one chooses the Norwegian or European emission factor for electricity. The Norwegian ZEB Centre uses an average electricity emission factor of 132 g CO_2eq/kWh for grid electricity (ZEB factor (Fufa et al., 2016)). This is based on the 'ultra-green scenario', assuming that the Scandinavian and European supply grids will be closely linked, and applies to future estimates of carbon intensity, based on a scenario for the European supply grid that assumes a 90% reduction in GHG emissions in 2050, as compared with 2010 (Figure 6.1).

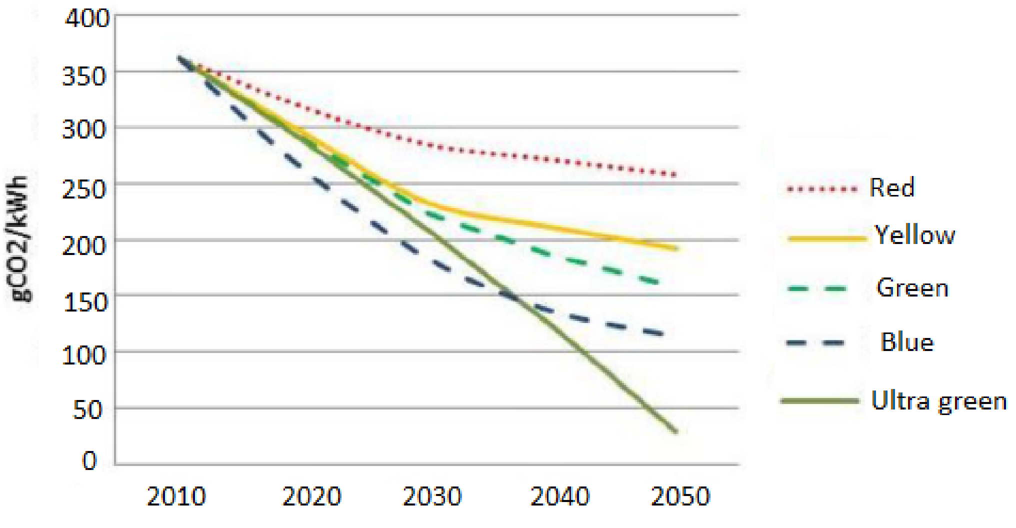

Figure 6.1. Scenarios involving average specific emissions from 2010 to 2050 (Graabak et al., 2014). The five scenarios originate in two important drivers: technological development and public opinion. Red – slow technology development and low environmental focus in the population. Yellow – gradual technology development with positive public attitude with reduced energy demand through changed end-user behaviour. Green – rapid technology development and positive public attitude with many advanced technologies involving the use of renewable energy sources and reduced energy demand. Blue – rapid technology development, but with little focus on the population, with large-scale development driven by governmental regulations and instruments. Ultra-green – more energy-efficient technology development, major increase in transnational exchange capacity and considerable increase in nuclear generation capacity.

Georges et al. (2015) demonstrated that embodied emissions dominate operational energy emissions when low CO_2 factors are used for fully electric ZEB buildings, while high CO_2 factors have the opposite effect. This means that a lower CO_2 factor for electricity in the supply grid (for example when using the Ultra-Green scenario) will favour the reduction of embodied emissions while placing less emphasis on the future reduction in the operational phase. Choice of CO_2 factors will also affect the choice of energy carriers. The findings of the ZEB pilot project show that even though the ZEB factor probably does not favour energy initiatives in ZEBs, as compared with other emission reduction measures, this challenge also presented an opportunity to develop and test new concepts in the research centre's pilot projects (Andresen et al., 2017).

There is a noticeable lack of reporting regarding emissions factors, as in the Ulsholtveien 31 project, where it appears that the emission factor for PV panels (which satisfy 45% of the electricity consumption) is assumed to be zero. The LCA study from the Norwegian ZEB Centre, which was applied to three roof-mounted PV systems for residential buildings, shows that the embodied emissions per kWh for the three different systems vary between 30 and 120 g CO_2eq. On the other hand, the emission factor for solar energy is stated as 13−190 g CO_2eq/kWh in the Norwegian standard for estimates of GHG emissions from buildings (NS 3720). In Villa Dammen, wood-burning heating is deemed to be emission-free. However, in NS 3720 the emission factor for biobased fuel is specified as 8.5–130 g CO_2eq/kWh. In addition to NS 3720, the Norwegian ZEB Centre uses a range of default values for different energy carriers.

As mentioned, different energy sources will impact the environment in different ways, which can result in a shift from one type of environmental impact to another (for example, nuclear power stations, while having favourable GHG emissions, present a higher risk in the form of radiation). It is important that data sources are available to enable such assessment for several energy sources. Moreover, it is important to reach agreement on, develop and to a greater degree put into use reference emission factors from standards, to avoid greenwashing. Hence it is important to provide more information about the emission factor in use, as well as the source of the data. Following this methodology can contribute to improving transparency and make it possible to replicate results.

6.2.6 Comparison of actual and estimated operational energy use

The findings of the case studies show considerable differences between actual (measured) and estimated energy consumption. For the Grensesvingen 7, City Hall district, Stasjonsfjellet og Økernhjemmet projects the operation energy use was (respectively) 29%, 23%, 46% and 15–20% higher than the estimate for the planned or completed building. For Villa Dammen it was seen that consumption was lower than expected, which shows the importance of user behaviour in ensuring that energy consumption is as efficient as envisaged. Changes in user behaviour can potentially have a considerable effect in reducing the environmental impact of energy consumption (as indicated by Fouseki & Cassar (2014) and Gram-Hanssen (2018)). There is also a range of other factors that play a part, where, for example the future climate and other unknowns make energy consumption over the lifetime uncertain.

The uncertainty associated with actual energy consumption, future emission factors for electricity and the use of emission factors for energy make it difficult to compare the total emissions from energy consumption and emissions from materials use. It is important to document the estimates of environmental impacts from operational energy consumption, including imported and exported energy according to the NS 3720 standard.

6.3 The use of scenarios in LCA studies of existing buildings

Alternative scenarios are often used to analyse LCA results. This section discusses the use of these in current LCA studies in the light of the preceding chapters, and includes recommendations based on this work. References are cited where relevant.

6.3.1 Reference buildings

Most of the Norwegian case studies compare emission reductions with a new building represented by a reference building. This makes a comparative assessment of the new build scenario and the rehabilitation scenario complicated. An optimised new build will probably also produce lower emissions than the reference building. Reference buildings are often developed by using existing scenarios, often using generic data without considering optimised concepts and material selection. Schlanbusch et al. (2016) pointed out that setting emission reduction targets based on a poor choice of background data can result in lower ambitions.

Most of the Norwegian case studies compare GHG emission reductions with the new building represented by non-optimised reference building. This makes the comparative assessment of the new building scenario with the rehabilitation scenario complicated. Since the total GHG emissions from energy consumption are higher than from materials in the case studies, the best performers (for GHG emissions) are those that manages to reduce emissions from operational energy use compared with the reference building, namely: Stasjonsfjellet, Ulsholtveien, City Hall district, Kjørbo, Grensesvingen 7, and Økernhjemmet. These reduced emissions related to energy use to half of that of the reference, which also means that they reduce the emissions from the total materials and energy use by about a half. This can be assumed to be better than, or at least equal to, a new, optimised building (without considering the lower emissions from the rehabilitation scenario in the building and construction phase and the disposal phase). In Ulsholtveien, where a new building was erected alongside the rehabilitated building, with the optimised new build producing 18% lower emissions per square metre during its life cycle. In this case, the potential for energy generation favours the new, optimised building (although the emissions from all modules are not included, as is possibly also the case for emissions from technical installations such as PV panels).

Thus, reference scenario shall be clearly described and defined in comparative assessments. This may influence decisions, also towards the avoidance of environmentally preferred measures, and should be discussed carefully in the analyses. The use of more realistic new build scenarios (instead of conceptual reference buildings) that include all relevant modules of the life cycle can provide a basis for further interesting discussions.

6.3.2 Development of national reference values based on existing studies

Hasik et al. (2019) pointed out the challenges associated with developing a new build scenario for comparison with a rehabilitation scenario, and therefore propose a database of previously completed projects, to enable comparison or to develop a standard reference building.

Existing national LCA benchmarks have been developed, but focuses mainly on data from new buildings, since the number of studies of existing buildings is limited. The results of the first LCA reference study in Norway are a good example of this, with only 13 of the 120 LCA studies acquired being for existing buildings (Wiik et al. 2020). Furthermore, only 2 of the 13 studies present results from old buildings. The IEA EBC study shows similar findings, with only 11 existing buildings among the 80 evaluated studies (Moncaster et al., 2019). Such work is important for collecting good reference studies and to approach more closely real reference values. The goal should therefore be the development of a transparent reporting system that can be used by different quality and certification schemes. This necessitates further development of, and focus on, harmonised LCA methodologies and pressure to develop more integrated LCAs of existing buildings.

The comparison of reference values from different countries is difficult, largely because of differences in background data and estimate methodology, as was pointed out in the Round Robin test in the IEA EBC study, in which several LCA experts from different countries performed an LCA for the same building. The work to develop harmonised methods, with a corresponding increased transparency in the LCA results, will facilitate better-informed decisions that are adapted to choices regarding rehabilitation and reuse of existing buildings.

International co-operation in the development of LCA reference values (benchmarking) will enable the Norwegian building and construction sector to examine lessons learnt from existing studies in countries which are more advanced in this field. Government subsidies will play an important role in encouraging reuse of existing buildings, creating awareness of environmental impacts and benefits and their potential contribution to achieving national and international emission reduction targets.

6.3.3 Potential future scenarios

An analysis of the environmental performance of different rehabilitation methods is important for assessing several possible scenarios. Applicable LCA studies mainly base their analyses on scenarios from current best practice or consider future scenarios using present-day data. Pesonen et al. (2000) define LCA scenarios as '*a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future*'. They distinguished between two scenario development approaches: What-if scenarios, which are used to obtain operational information and to compare two or more alternatives in a well-known situation with a short time horizon. Here, hypotheses are defined based on existing data. The other approach is Cornerstone scenarios, which offer strategic information for a longer term, for use in planning and to provide guidelines for further specific research work. Thus, consideration of time perspectives is important methodological aspect.

7 Conclusions, limitations and future research

The principal objective of the project is to establish an integrated picture of, and provide better insight into, the environmental significance of the existing building stock. This is achieved by studying how this is highlighted in the existing literature. The actual environmental benefits, shortcomings, and opportunities inherent in the upgrading of existing buildings are considered from a life cycle perspective. This chapter summarises the findings in the report in the form of some general conclusions, and finally some specific recommendations.

7.1 General conclusions

The main conclusions are as follows:

1. *There exists a major unrealised potential in terms of environmental benefits linked to existing building stock. If possible, rehabilitation should be favoured in preference to demolition and the construction of new buildings, in accordance with Norwegian and international climate change targets.*
2. *When assessing environmentally friendly rehabilitation measures, both cultural and historic conservation considerations should be taken into account.*
3. *Comprehensive life cycle assessments represent key decision-making tools in our efforts to identify the most effective rehabilitation measures.*

The three main conclusions are considered in detail below.

7.1.1 There exists a major unrealised potential in terms of environmental benefits linked to existing building stock

The building and construction sector has a key role to play in the work being carried out to achieve the GHG emission reduction targets set out in the Paris Agreement and the UN Sustainable Development Goals (SDG). The existing building stock represents a major unrealised potential for reuse and repurposing, as well as recycling of building components and materials. Considering that most of the world's building stock in 2050 already exists today, the rehabilitation and adaptive reuse of existing buildings will make a decisive contribution to a sustainable future. In Norway, current building upgrade rates are low (at about 1 to 1.4%). This study demonstrates that, if possible, the environmentally sound upgrading of existing buildings should be favoured in preference to demolition and rebuilding wherever possible. Such upgrading of existing buildings is more in line with the ambitions of the Paris Agreement and the UN Sustainable Development Goals. Clear political ambitions should be established with regard to carrying out rehabilitation of the existing building stock to a far higher degree than is the case today. It takes decades before the benefits of lower levels of annual emissions linked to energy consumption during operation offset the negative impacts caused by the increase in emissions linked to the construction of new buildings. Findings in the literature support the conclusion that rehabilitation of existing buildings is preferable in the 30-year time frame up to 2050, as it can take from 10 to 80 years before the GHG emissions arising in the construction of a new building are compensated for. We may conclude from this that, from an environmental perspective, the rehabilitation of existing buildings will be more beneficial to the environment in the short and medium term.

The research front indicates that the potential environmental benefits of upgrading existing buildings are great compared with new build projects because the emissions generated during rehabilitation represent only a half of those associated with new builds. However, reductions in the environmental impacts depend on various specific conditions. Reductions in GHG emissions in connection with rehabilitation result principally from the extended lifetime of existing buildings, since existing materials are retained and embodied emissions from the use of new materials, waste generation, and energy consumption during building are avoided. The Norwegian case studies reveal that GHG emissions linked to the use of materials for the upgrading of existing buildings amount to only a third of those linked to new build projects.

The minimisation of materials use and energy requirements, the selection of locally-sourced, low-carbon materials, the implementation of energy efficiency measures, combined with the use of renewable energy are the most important ways of reducing emissions, and should be considered during the upgrading of existing buildings. The case studies show considerable variation in GHG emission reductions, which naturally depend on the emission reduction measures mentioned above. In particular, the level of upgrade initiatives –comprehensive rehabilitation or a lower target – is considered important. As shown in the Vestlia case study, comprehensive rehabilitation leading to high energy efficiency is preferable, combined whenever possible with other technological measures such as renewable energy generation. There is wide variation in the energy efficiency potential of the existing building stock, depending on factors such as age, materials, construction elements, conservation value, and current status of preservation. This clearly demonstrates two points. First, that one can specify equal requirements with regard to the degree of energy efficiency to all buildings, since the measures should be adapted to the applicable building type and the specific situation and building. The other point is dealt with in detail in Section 7.1.3: At present, embodied emissions are not considered sufficiently when upgrading is assessed and should be analysed in a more critical fashion when upgrading and new build scenarios are being assessed.

7.1.2 When environmentally sound rehabilitation measures are being assessed, the cultural and historical heritage value should be considered.

In a sustainability perspective, social factors such as local identity and the preservation of cultural assets clearly justify conserving façades, fine details, materials use, etc. This can make comprehensive rehabilitation difficult, but this does not mean that the only alternative is demolition and the construction of sustainable new buildings. The decision cannot be based on assessing GHG emissions alone. This is particularly important as it has not been proven that GHG emissions attainable in a new building are lower than in the case of even simple rehabilitation scenarios, since there is a shortage of studies that consider all embodied emissions. Several factors, such as other environmental consequences and social aspects, should therefore also be included in analyses.

The literature reviewed highlights several challenges connected with interventions aimed at improving the energy efficiency of cultural heritage buildings. It reveals the challenge of balancing various demands, especially between technical interventions and the needs of conservation, as well as the fact that cultural heritage buildings are particularly vulnerable to modern technical installations. A widespread problem highlighted in much of the literature is the pervasive lack of expertise about cultural heritage buildings and historic building stock.

A thorough evaluation is needed of the effects of upgrading initiatives on cultural heritage buildings. The maximum potential of a high ambition level for cultural heritage buildings is not necessarily the same as that for younger existing structures or new buildings. The efficiency enhancement potential of the building stock should be realised by means of an integrated, balanced approach applying to the actual building environment of which each individual building forms a part. If the decision tends towards demolition, this should be based on thorough assessments, rather than superficial and/or inadequate analyses of costs and GHG emissions.

7.1.3 Comprehensive life cycle analyses are important decision support tools

A life cycle approach is key to obtaining more thorough assessments of the sustainability of existing buildings. This study has revealed that few LCA analyses of existing buildings have been carried out. Moreover, there are major uncertainties linked to the studies that have been performed, largely due to variability and deficiencies inherent in the methods applied. To fill the knowledge gap revealed by this study, it will in future be important to carry out the entire life cycle assessment with a clear description of the physical system boundary (for example, a description of building elements and energy supply systems studied) and of the life cycle stages considered in the analysis. This is important because it is the only way to communicate the environmental and social benefits of rehabilitation: *This is precisely where most of the benefits lie*.

Such an analysis becomes more valuable if it includes several environmental indicators and social or societal aspects, because the entire value spectrum of the building is then taken into account. To evaluate the sustainability of existing buildings one should also incorporate social and economic life cycle assessment. Most projects carry out economic analyses in one way or another, to evaluate the profitability of different choices. However, there is a need to incorporate social LCA studies to identify social hotspots. These are points in the value chain throughout the life cycle of the building stock that have the greatest impact on society or other social factors, and measures should be taken to minimise potential negative impacts. The use of sustainable life cycle assessment methods will make it possible to provide a clearer picture of how demolition and rebuilding compares with rehabilitation and reuse of existing buildings as regards impact on the environment and society. In this way the inherent value of the existing building stock in terms of embodied energy is illustrated.

If a scenario is to be used, it should be realistic. Basic uncertainties inherent in the scenarios must be discussed to a much greater extent than is currently the case. Analyses that examine only materials use (A1-A3, B4) and energy consumption while the building is in use (B6) are insufficient to provide us with an informed basis for decision making in a scenario involving the choice between a rehabilitation scenario and a new build scenario, and we must therefore include emissions both in the construction phase (A4-A5) and the end-of-life phase (C1-C4) of the existing building and the new one (A, B and C refer to Figure 2.4 in Chapter 2). Inherent uncertainties in the energy estimates must also be highlighted as part of such assessment. Seen in a life cycle perspective, it cannot be concluded that simple (less comprehensive) rehabilitation scenarios are less effective than demolition and rebuilding scenarios, since this is specific to each case and depends on a range of uncertainties. However, a clear conclusion is that energy efficiency measures and in particular the use of renewable or low-emission energy sources are especially important when rehabilitation projects are to be assessed. A need has therefore become evident for further research to elaborate and establish a knowledge base for decisions regarding demolition and rebuilding as opposed to preservation and rehabilitation.

7.2 Recommendations

Based on the findings in this report, some of the questions requiring additional work are listed below. There is a need for:

Ambitions related to building rehabilitation projects must be clearly defined: A clear definition of the level of ambition and scope of rehabilitation ought to exist at an early stage, with a description of an integrated evaluation of initiatives and a plan for follow-up throughout the project period. If possible, clear goals should be defined for the most thorough (environmentally sound) rehabilitation possible, which can facilitate, as a minimum requirement, meeting prevailing energy requirements as set out in the TEK building regulations. The initiatives should preferably result in a zero-emissions house or 'plus house'. The achievement of such ambitions may conflict with the cultural heritage value of a building and all initiatives or interventions must therefore be carefully assessed.

Comprehensive life cycle assessments should be used as decision support tools: Comprehensive life cycle assessments should to an increasing degree be used to assess the sustainability of rehabilitation projects and the condition before and after rehabilitation and to make informed decisions regarding rehabilitation versus demolition and rebuilding. Arrangements should be made for detailed and transparent LCA studies of existing buildings, with clear ambitions and scope of projects (for example, in the case of rehabilitation type and initiatives, LCA system boundaries according to NS 3720, and physical boundaries according to NS 3451). The studies should encompass the entire life cycle of a building. To enable a comparative assessment of rehabilitation versus demolition and rebuilding, the impact of the demolition of an existing building should be included in the impacts of the entire life cycle of a new building. Uncertainty in the energy estimates and emission factors used for an energy source should be assessed and discussed in reports since these have significant impact on the results (and decisions). The use of a standard evaluation and reporting methodology (in accordance with the NS 3720 standard) is important to improve the availability of data and the comparability and transparency of results, as well as to enable the evaluation and comparison of the results later. The implementation of more transparent and comprehensive life cycle analyses in more projects, with communication of the results by way of quality and certification schemes, will to a greater extent make it possible for different players to make informed decisions.

Integrated thought process: The scope of this study is limited to LCA studies of existing buildings at an individual building level. Environmental LCAs should be combined with Life Cycle Costing (LCC) and Social Life Cycle Analyses (SLCA) in order to obtain more comprehensive and sustainable perspectives for existing buildings. Other aspects than GHG emissions, such as other environmental indicators, cultural heritage value, and life cycle costs, are important in assessing the value of the building stock. Also important is an extensive thought process that expands the scope of individual buildings and assesses different buildings and their varying condition, to contribute to the establishment of neighbourhoods (meso-level) or urban environments (macro-level). Arrangements should be made for broader and more comprehensive analyses to enable better support for decision-making.

All possible rehabilitation measures must be considered when it comes to cultural heritage buildings, provided that these are not implemented at the expense of their conservation value: Many historical buildings are vulnerable to technical intervention, both because of technical conditions (construction, materials use, technology) and with regard to the cultural heritage the buildings represent. Comprehensive upgrading of historical or cultural heritage buildings can therefore be very demanding. However, it is important to review and consider possible measures and interventions that do not compromise cultural heritage value.

A process of gathering documentation related to best practice should be considered: It is important to collect documentation of best practice to obtain an overview, including specific experiences of rehabilitation projects, so as to protect and improve the existing building stock. The collection of case studies involving BREEAM-NOR and BREEAM certified buildings should be commenced. This can be carried out by introducing rehabilitation passports as a standard documentation method and by evaluating building functions and short- and long-term rehabilitation requirements. This should include documentation of life cycle assessments in all phases of a building's life – from construction to end-of-life.

Incentives and subsidy schemes for extensive rehabilitation projects should be evaluated and introduced: The environmental and social benefit of rehabilitation is demonstrated by several life cycle studies. Incentives are necessary in order to develop new technologies, materials and concepts that can be effectively implemented in existing buildings without compromising cultural value. In particular, there is a need for a higher level of knowledge of energy efficiency enhancement and adoption of new technology and innovative concepts in cultural heritage buildings, where there may be considerable potential for the generation, storage and recovery of energy. The incentives may be of both economic and legal nature, for example subsidy schemes that favour reuse and rehabilitation of existing building stock and political ambitions to improve the degree of rehabilitation of the existing building stock.

The UN's Sustainable Development Goals should be used as a tool to influence the sustainable development of existing building stock. Even though the building and construction sector is important in achieving several of the UN goals for sustainable development, uncertainty exists as to how this shall be implemented, measured, and monitored in practice. Ongoing initiatives should be pursued and initiatives for future implementation should be part of all building projects. Cultural heritage is also the focus of sustainability perspectives, and it is important that the cultural value of the existing building stock is also assessed and considered in the same way as other sustainability aspects.

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Appendix 1: References selected for systematic review

From total of 137 studies identified through Scopus, Web of science and Engineering village, the following 83 studies were selected.

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Appendix 2: Background data for LCA benchmarking studies

Country	Denmark			Italy		
References	Rasmussen et al 2019			Rasmussen et al 2019		
Background						
Reference study period	120			100		
Building typology	7 residential buildings (3 multifamily and 4 terraced houses)			28 residential buildings (3 single family and 25 multifamily)		
New/existing	New, constructed between 2014-2018			New, constructed between 2015-2017		
Life cycle stages	A1-A3; B4 (no replacement if the expected service life of replaced material exceeds the remaining SL of the building by 2/3 and no replacement for the last 10 years of a building service life); B6 (dynamic energy scenario with increased use of renewable energy 2015-2050); C3-C4			A1-A3; A4 (assuming transport by lorry for distance of 50km for inert materials and 300km for additional materials); A5 (2% of A1-A3 impact); B4 (no replacement if the expected service life of replaced material exceeds the remaining SL of the building by 2/3 and no replacement for te last 10 years of a building service life); B6 (static energy scenario based on Italian grid mix from Ecoinvent database); B7 (portable water consumption of bathrooms, kitchen and irrigation); C2 (assuming transport by lorry for distance of 20km for inert and non-hazardous waste and 250km for hazardous waste); C3-C4		
Standards	ISO 14040-44, EN15978			ISO 14040-44, EN15978		
Databases	Ökobau 2016 (rmany database)			Ecoinvent 3.3		
Tools	LCAbygg 3.2			Excel		
Benchmark values	Embodied	Operational	Total	Embodied	Operational	Total
GWP (kgCO2eq/m2/yr)	6.00	2.17	8.2	3.8	10.4	13.8
AP (kgSO2eq/m2/yr	0.018	0.008	0.023	0.0189	0.0455	0.0656
PEtot (MJ/m2/yr)	85.1	53.9	132	62.7	207	279

Country/region	DE	FR
References	Schlegl et al 2019	Lasvaux et al 2017
Background		
Reference study period	50	50
Building typology	22 office buildings	40 low energy buildings (with 3 single family and 25 multifamily)
New/existing	New, constructed between 2014-2018	New, constructed 2012
Declared life cycle stages	A1-A3; B4; B6 (including heating, ventilation and cooling, without user's electricity demand); C3, C4, D	A1-A3; A4 - A5; B2; B4; B6 (energy consumption from heating, DHW, lighting, ventilation, and auxiliaries and emission factors for electricity from the grid, natural gas, pellets, on-site renewable energy production from Ecoinvent V2); B7; C2-C4
Declared building elements	Excavation, foundation, external wall, interior wall, ceiling, roof, component, other, technical facilities	External works, foundation, structural element (walls, slab), roof, interior wall, windows and joinery work, interior finishes, HVAC, sanitary facilities, electricity and communication network, Safety equipment, lighting, lifts, on-site electricity generation
Environmental indicators	GWP and 9 other indicators*	GWP, AP, PEnr, WC, non-hazardous and inert waste (NHIW), Radioactive waste (RW)
Standards	DIN EN15978	NF EN15978
Databases	OKOBAU:DAT	INIES EPD (for building products); PEP EPD (for technical equipment) Ecoinvent v2 (for other building products and technical equipment)
Tools	-	Excel

Country/region	DE			FR		
Benchmark values (median)	Embodied	Operational	Total	Embodied	Operational	Baseline (median value)
GWP (kgCO2eq/m2/yr)	9.6	22.6	32.2	8.4	3.1	11.5
AP (kgSO2eq/m2/yr	-	-	-	0.043	0.010	0.053
PEtot (kWh/m2/yr)	-	-	-	37.0	52.1	89.1
NHIW (kg)				35.4	0.3	35.7

Green isn’t just a colour – sustainable buildings already exist

The aim of this report is providing an overall picture of the environmental significance of the reuse of existing buildings. The report focused on addressing the following two main research questions:

- What is the current status of research in terms of the significance of the environmental impact of existing buildings?
- What is the environmental performance of the existing building stock following upgrading/rehabilitation, compared with demolition and new construction?

The approach used has involved a systematic assessment and meta-analysis of life cycle assessments performed in connection with the rehabilitation and upgrading of existing buildings.

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