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Review

How Can Existing Buildings with Historic Values Contribute to Achieving Emission Reduction Ambitions?

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Abstract: In line with the Paris Agreement, Norway aims for an up to 55% reduction in greenhouse gas (GHG) emissions by 2030 compared to 1990 levels and to be a low-emission society by 2050. Given that 85–90% of today's buildings are expected to still be in use in 2050, refurbishment and adaptive reuse of existing buildings can help in achieving the environmental goals. The aim of this work is to provide a holistic picture of refurbishment and adaptive reuse of existing buildings, including buildings with heritage values, seen from a life cycle perspective. The methods applied are a literature review of LCA studies and experiences from quantitative case study analysis of selected Norwegian case studies. The findings show that extending the service life of existing buildings by refurbishment and adaptive reuse has significant possibilities in reducing GHG emissions, keeping cultural heritage values, and saving scarce raw material resources. The findings show limited LCA studies, uncertainties in existing LCA studies due to variations in case-specific refurbishment or intervention measures, and a lack of transparent and harmonized background data and methodological choices. In conclusion, performing a holistic study covering the whole LCA and including socio-cultural values and economic aspects will enable supporting an argument to assert the sustainability of existing buildings.

Keywords: embodied emission; existing building; LCA; heritage value; socio-cultural value

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1. Introduction

Adopted by 195 countries in December 2015, the Paris Agreement was a major step forward for a global action plan in mitigating climate change [1]. The agreement aims to keep global warming below 2 °C above pre-industrial levels, and to continue efforts to limit global warming to below 1.5 °C to prevent the adverse effects of climate change. The EU has been at the forefront of international efforts to fight climate change by setting ambitious energy and climate targets towards 2020 and 2030, and by progressively working towards a climate-neutral EU by 2050 [2]. The climate ambitions for 2030 have been revised in line with the Paris Agreement goals, with an ambition of cutting GHG emissions by at least 55% compared to 1990 levels [3]. The previous EU target was a 40% GHG emission cut while improving energy efficiency by at least 32.5% and the share of renewable energy by at least 32%. The EU Green Deal, proposed by the EU Commission in December 2019, sets a road map on how to achieve the newly set climate goals [4].

Despite the progress in climate policy and ambitions in many countries, global GHG emissions continue to grow to the highest ever, as recorded in 2019 [5]. Buildings are responsible for about 40% of the EU's total energy consumption, and for 36% of its greenhouse gas emissions from energy [6]. More than 220 million building units (85% of the EU's building stock) were built before 2001, and 85–95% of existing buildings today will still be standing in 2050 [6]. However, almost 75% of those existing buildings are energy-inefficient, and the annual energy renovation rate is lower than 1% [6]. The Norwegian building stock is expected to follow the same trend. The construction industry is seen as essential in the transition to a circular economy, as it consumes around 40% of the total material resources and generates over one third of the total waste in the world [7]. The Norwegian national statistical data show that waste from construction, refurbishment, and demolition (1.95 million tons in 2019) represented around 26% of the total national waste, an increase by 5.6% from 2018 [8]. Of this, about 76.3% of the waste is from demolition and refurbishment activities, and only 46% of the total waste was recycled in 2018, which is a decrease of 8% from the previous year.

To achieve the 55% emission reduction target by 2030, the EU should reduce buildings' greenhouse gas emissions by 60%, their final energy consumption by 14% and energy consumption for heating and cooling by 18%. The COVID-19 crisis has clearly demonstrated the importance buildings play in our daily life, and also the unique opportunities that lie in refurbishment in terms of rethinking, redesigning, and modernizing existing buildings into more energy-efficient and less material-intensive buildings and sustaining economic recovery [6]. Further, this is sustainable from a holistic and cultural heritage perspective, due to upholding and continuing the socio-cultural values the existing buildings, in general, and heritage buildings, specifically, represent.

With the growing carbon spike and climate change impacts, refurbishment and adaptive reuse of existing buildings, and heritage buildings, can be conducive to taking immediate action and achieving various emission reduction goals. The EU Green Deal started a new renovation initiative in 2020, the "renovation wave", with a target to doubling the current public and private renovation rate in the next 10 years [9]. Applying circularity principles would help conserve scarce raw material resources, reduce GHG emissions associated with carbon-intensive production processes (i.e., cement, steel, and glass), and boost economic crises resulting from the pandemic. The evaluation of the environmental performance of existing buildings in a life cycle perspective, using transparent and harmonized methods, will enable avoiding problem shifting, and evaluating and following up the fulfilment of emission reduction ambitions.

This paper presents a summary of the main lessons learnt from the life cycle assessment of four Norwegian case studies to shed light on the gaps in the above-mentioned challenges and opportunities. This paper begins by outlining the state-of-the-art literature, followed by a short description of four case studies and the methodology used for evaluating and discussing these. The LCA results of the case studies are presented, and the findings are discussed, in order to provide background for lessons learnt from each case study. After highlighting the needs of future research activities, final remarks are drawn in the conclusion.

2. Literature Review

This section provides relevant studies focusing on definitions of terminologies (to avoid misinterpretation), and refurbishment and adaptive reuse of existing buildings and life cycle assessment are presented.

2.1. Definitions

The terms renovation, refurbishment, restoration, retrofitting, upgrading, and adaptive reuse are often used interchangeably and inconsistently. Shahi et al. [10] conducted a literature review of terminologies related to building adaptation and developed a framework by summarizing the definition of terminologies into two main categories:

- Refurbishment: The process of improvement or modification of an existing building, through maintenance, repair, improvement/upgrading of existing systems, and incorporation of energy efficiency measures, in order to make it fulfil current building standards for existing use (without change of use). Refurbishment is categorized into the following:

    - Retrofitting: addition or upgrading of building envelope, HVAC systems, energy efficiency, and renewable energy sources to improve the energy use and efficiency of an existing building.
    - Renovation: replacing or fixing old components to increase energy efficiency or remodeling of the interior layout of an existing building to improve the esthetic appearance or interior design.
    - Rehabilitation: repairing, changing, or adding to damaged structures, deteriorating envelopes, openings, and HVAC systems.

- Adaptive reuse: Extending the service life of historic, old, obsolete, and abandoned buildings through reusing an existing building for a different use or reusing the building materials and structures for a different use. The two aspects of adaptive reuse of existing buildings are described as follows:

    - Conversion: adaptive reuse of obsolete and abandoned buildings, which are not used anymore or do not satisfy their users, through retrofitting, renovation, and rehabilitation of the building envelope and structures by changing the original function of the building partially or entirely.
    - Material reuse: recover and reuse of materials from an existing building through partial repair or refurbishment.

In this paper, the terms refurbishment, when discussing rehabilitation, retrofitting, renovation, and upgrading, and, accordingly, adaptive reuse, when discussing conversion and material reuse, are considered. Historic buildings, or heritage buildings, are referred to as buildings with heritage significance (not necessarily considered as listed or protected) due to their historical, architectural, symbolic, social, or cultural values [11].

In this paper, a historic building is referred to as an existing building, not necessarily listed or protected, but worth saving. Within the preservation of cultural heritage, renovation measures generally entail interventions that undermine heritage values. Thus, measures incorporating changes in construction details, materials, and appearances of the façades are most often not allowed, or wanted, by heritage authorities [12].

2.2. Refurbishment and Adaptive Reuse

Traditionally, considerate refurbishment of existing buildings, and historic and heritage buildings in particular, has not been a priority. Decisions to keep or demolish existing buildings often lead to several uncertainties as summarized by the Norwegian Green Building Council [13]: (1) refurbishment is more costly than demolition and constructing new buildings; (2) only new buildings can be environmentally certified; (3) existing buildings are not area-efficient; (4) refurbished buildings have difficulties in satisfying modern indoor climate requirements; and (5) refurbished buildings often have poor daylight qualities. The level of the refurbishment is also dependent on the building's historic and heritage values.

Refurbished buildings do, however, provide huge immediate environmental benefits [14,15]. Refurbishment of cultural heritage buildings, with the use of existing resources where possible, rather than dependence on new resources, is the most sustainable course of action. Foster [16] pointed out how multiple analyses in recent research concur that adaptive reuse of existing buildings is beneficial for the environment, and, further, that current research upholds the environmental benefits from adaptive reuse of buildings. In addition, refurbishing and adaptively reusing under-utilized or neglected buildings can revive neighborhoods whilst achieving environmental benefits, and such buildings embody the local socio-cultural and historic characteristics that define communities [16]. Foster [16] does, however, maintain that such benefits are not widely adopted in practice.

Energy efficiency measures in the transformation and reuse of heritage buildings might also lead to increased energy needs, due to a change in use and user needs [17]. Fouseki and Cassar [18] proved that user behavior is often more important than the type of technological selection in energy efficiency measures, both considering the amount of energy spent and the way the building is used. Most of such studies have mainly targeted modern buildings, materials, and constructions. Policy measures for cultural heritage and sustainability should be communicated to achieve public understanding concerning user behavior, energy efficiency measures, and heritage values [19]. Berg et al. [20] highlighted the significant impact and potential of non-intrusive energy efficiency measures and integrated bottom-up refurbishment processes providing for better management.

The building stock represents an important cultural and material resource, where some buildings are of heritage significance due to their, e.g., historic, architectural, social, and cultural values [11]. Many buildings subjected to upgrading or restoration may have been built for other purposes, and for other comfort requirements, which is presently the case. Often, such requirements will conflict with preserving inherent heritage values [19].

The Paris Agreement and the United Nations' Sustainable Development Goals (SDG) provide explicit recognition of the role of cultural heritage in promoting climate change mitigation and adaptation measures [21]. Meeting the need for environmental impact reduction and cost-effective energy-efficient solutions while, at the same time, safeguarding a building's cultural heritage value does, however, present a clear technical challenge [22]. Challenges of balancing different needs, limitation of tools for investigation of energy efficiency measures, and a lack of knowledge of historic and heritage buildings are considered as key challenges when implementing energy efficiency strategies in such buildings [23].

Nastasi and Matteo [24] argued that focusing on incorporating a renewable energy supply system instead of modification of the building envelope or installation of a new HVAC system is a possible solution for preserving existing buildings with historic significance. Studies have shown the possibilities of functional improvement in historic buildings due to technological evolutions, such as a district heating system dominated by biomass [25], integration of hydrogen into natural gas as a partial fuel substitution [24], and HVAC systems [26].

Development of best practice methods, tools, and guidelines with quantitative analyses which support qualitative study of existing buildings with historic values at a large scale (districts and cities rather than the individual building level) will enable filling in the current knowledge gap in this area [22]. Ruggeri et al. [27] developed a score-driven decision making model which can be used to plan and manage energy retrofitting measures applied to cultural heritage and historic buildings. The model is described as a combination of quantitative and qualitative parameters, including energy savings and costs, building conservation aspects measured as a restoration score, and their impact on indoor comfort. Bertolin and Loli [28] developed a zero emission refurbishment (ZER) tool to support decision-makers on maintenance and adaptive intervention principles, and to analyze potential emissions and energy consumptions (that should be compensated with onsite renewables) of interventions of historic buildings.

Since the proportion of existing buildings is large in relation to the number of new, energy-efficient buildings, and, furthermore, since many existing buildings have lower energy efficiency, there is a need to assess the effect of energy-efficient measures in the existing building stock. Such assessments must be viewed in the context of the value added, other upgrading and maintenance needs, changing comfort requirements, and the effect of the measures in relation to cost and emission savings. This demonstrates that there is a need to develop strategies addressing both emission and adaptation considerations for historic and heritage buildings, regardless of ownership. EN 16883 [11] states the importance of evaluating the environmental performance of heritage buildings from a life cycle perspective when making a decision on energy performance improvement measures.

2.3. Life Cycle Thinking

Life cycle assessment has been used as a decision support tool to evaluate the environmental performance of buildings. It enables identifying hot spots, avoiding problem shifting, and making informed decisions. There have been many advancements in developing and harmonizing building LCA standards (e.g., ISO 21931 [29] for LCA principles and framework for assessment of environmental performance of construction works, EN

15897 [30] for the assessment of environmental performance of buildings, and the national Norwegian standard NS 3720 [31]), and in LCA results communication methods (e.g., EPDs, and green building rating systems such as BREEAM) and international research activities (such as the International Energy Agency's Energy in Building and Communities program (IEA EBC) Annex 57 [32], Annex 72 [33]) on assessing and communicating life cycle-related impacts of buildings.

Life cycle-based national GHG emission benchmarks or reference values are receiving more attention in different countries, and there are on-going discussions on the possibility of legal bindings [34]. The lack of harmonized background data and methodology choices used in different studies is considered as a major challenge in the utilization of LCA studies to establish benchmarks [34–36]. Most existing benchmarks also provide aggregated values for both new and existing buildings, mainly due to a lack of LCA studies from existing buildings and heritage buildings.

As with other Nordic countries, in Norway, there is no specific legal requirements for building LCA in the national legislation yet [37]. However, public building owners (e.g., the Norwegian government agency for administration of public buildings in Norway, Stastbygg), large municipalities (e.g., Oslo), initiatives, and projects (e.g., Futurebuilt, FME ZEB, FME ZEN) have been actively promoting the use of building LCA in Norwegian buildings for the past 15 years [37,38].

Stricter legislation towards the implementation of energy efficiency measures and decarbonization of national energy mixes (through use of renewable energy sources) leads to a reduction in operational energy use [39]. However, these measures also increase the embodied emissions from: the initial embodied emissions (from manufacturing (A1–A3 life cycle stages)), transport to construction site (A4), construction installation activities (A5), recurrent embodied emissions (from use phase activities, B1–B5), and end of life embodied emission (C1–C4) (Figure 1).

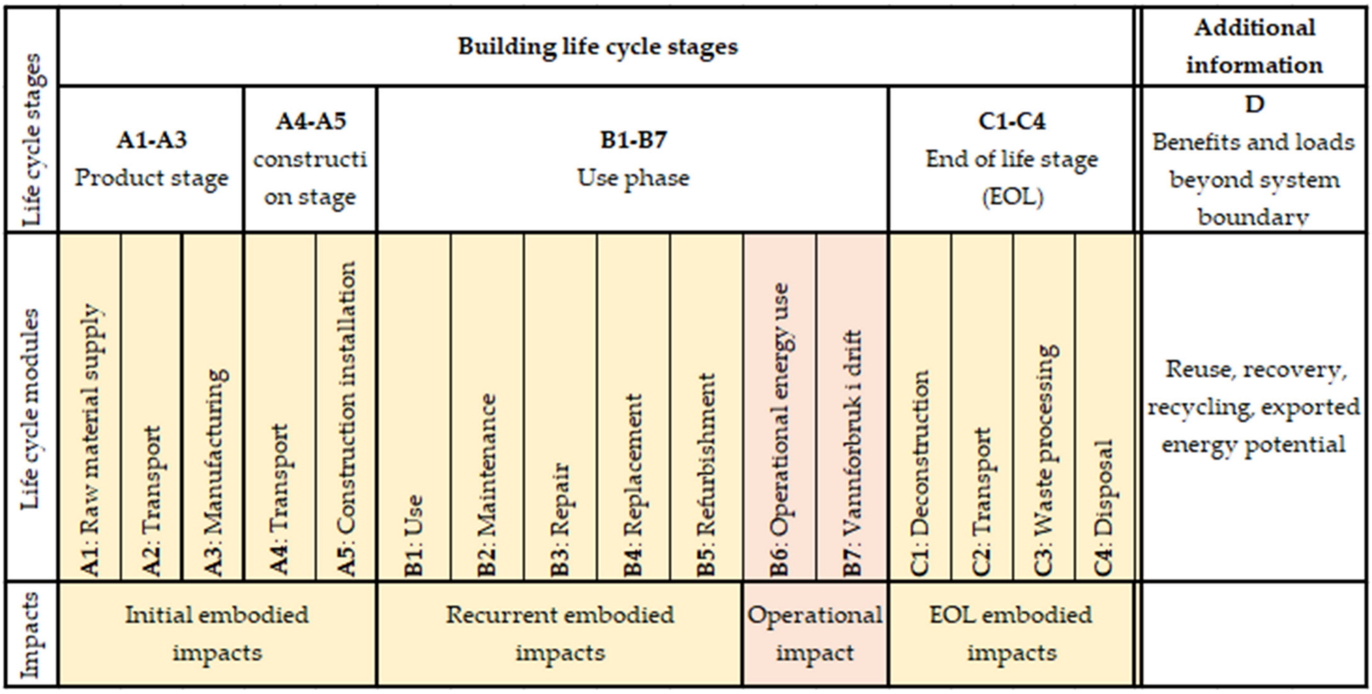

Figure 1. System boundaries in building LCA in relation to life cycle stages, modules, and types of impacts (embodied and operational). Adopted from EN 15978 [30] and Moncaster et al. [40].

Most existing studies mainly cover the production (A1–A3), replacement (B4), and operational energy use phases (B6) [40–42]. The embodied impacts from the transport (A4), construction installation (A5), and end of life (C1–C4) phases are often considered as low, and those life cycle stages are either excluded or calculated based on very rough assumptions. However, on-going fossil-free, emission-free, waste-free, reuse of building products, and other circular economy activities show the importance of those phases. For example, the GHG emission from construction site activities is estimated to be 5–10% [43]. A recent report from Bellona estimated that construction-related transport accounts for 1% of Norway's total emissions [44]. The report also shows a potential GHG emission reduction by up to 50% by efficient transport of goods to and from Norwegian construction sites through better planning and higher utilization of the vehicle capacity. Adding the impacts from the construction use phase (B2–B5) and end of life stages can help to demonstrate the significance of the emission reduction potential from refurbishment of existing buildings.

The findings from the Norwegian ZEB case studies (four new buildings, two concept studies, and one refurbishment building) showed that the embodied impact of ZEBs ranges between 55 and 87% from A1 to A3 and B4, 2 and 15% from A4 to A5, and ca 8% from C1 to C4 [42], whilst the operational impact represented 14–42%. The LCA study from the IEA EBC Annex 57 (Annex 57) on 80 building case studies (where 11 refurbished buildings were included) found that the production phase dominates total GHG emissions, with 64% of GHG emissions, followed by replacements at 22% and end of life at 14% [40].

Existing studies also indicate the potential environmental benefits from refurbishment of existing buildings in the range between 4 and 74% depending on the scenarios considered in the studies. Assefa and Amber [45] indicated a 28–33% impact reduction from the selective deconstruction and reuse of a thirteen-story library tower at the University of Calgary, in Western Canada, in seven environmental impact categories assessed (eutrophication potential, smog potential, global warming potential, fossil fuel consumption, human health criteria, acidification potential, and ozone depletion). Assefa and Amber also pointed out the importance of comparative assessments for reuse vs. new construction regardless of the challenges due to the uniqueness of different buildings and their locations.

Hasik et al. [46] showed 36–75% impact reductions across six environmental impact indicators (acidification potential, eutrophication potential, global warming potential, ozone depletion potential, smog formation potential, and non-renewable energy demand) when refurbishment of an office building was compared to new construction. Hasik et al. [46] also addressed the challenges related to the lack of a clear system boundary description regarding life cycle modules included in existing buildings and refurbishment projects. The study performed by Preservation Green Lab [47] on six building typologies from four US cities showed about a 4 to 46% environmental impact saving from renovation and reuse of existing building rather than demolishing and constructing new buildings. Preservation Green Lab [47] discussed the potential dependency of impacts from the energy performance of upgrading associated with material choices. Eskilsson [48] discussed the dependency of operational energy use on the sources of energy and the associated emission factors and highlighted the importance of embodied GHG emissions.

Even if refurbishment and adaptive reuse of existing buildings have been suggested for reducing embodied impacts [46], only a few LCA studies focus on the evaluation of the environmental performance of refurbishment and adaptive reuse of the existing building stock [49], and even fewer studies consider embodied impacts and evaluate the contribution of cultural and heritage values [16,22,46,50]. For example, from the 80 studies evaluated under Annex 57, only 11 were existing buildings [40]. The results from the first LCA benchmark study conducted in Norway also show similar findings, as from over 120 studies collected, only 13 were for existing buildings, and only 2 of the 13 studies presented the results from a historic building. The results in both Annex 57 and the Norwegian studies indicate the impact from refurbishment projects, which is under half that of new building projects. Developing LCA benchmarking for existing buildings, based on a harmonized methodology, will increase the transparency and repeatability of LCA results and enable different user groups to make informed decisions.

Interventions to reduce emissions will often affect heritage values if special considerations are not taken into account [20]. When restoring or preserving legally protected buildings in Norway, value assessments always form the basis for measures permitted by the cultural heritage authorities [12]. In Norway, the cultural heritage authorities also want buildings without formal protection to be treated in accordance with their heritage values [51].

3. Case Studies

The methodology in this study includes a quantitative review used to critically evaluate and analyze different Norwegian case studies to provide a quantitative answer to research gaps identified under Chapter 2. Four Norwegian case studies, all refurbishment projects where LCA studies were conducted, were selected for the analysis. The calculation was performed using a functional unit of 1 m^2 and a building lifetime of 60 years. LCA practitioners have used either klimagassregnskap.no (KGR.no, the previous Norwegian GHG emission calculation tool, using the Ecoinvent database and EPDs as background data), SimaPro (commercial LCA software using the ecoinvent database), OneClick LCA (commercial LCA tool which replaced KGR.no in 2018), or the ZEB tool (Excel-based GHG emission calculation tool developed by the Norwegian ZEB Centre, using the Ecoinvent database and EPDs as background data) for GHG emission calculations. The calculations follow the LCA methodology outlined by LCA standards, NS 3720, EN 15978, and/or ISO 14040/44.

The Norwegian case studies consist of one residential building: Villa Dammen, and three office buildings: Powerhouse Kjørbo, Bergen city hall, and Statens bygg Vadsø, bygg B. Villa Dammen, Bergen city hall, and Statens bygg Vadsø, bygg B (herein referred to as Statens bygg Vadsø) are buildings with heritage significance. The heritage values were not considered directly in the LCA model when assessing the life cycle analysis as this type of value is not possible to consider in the existing models. However, heritage values were considered when choosing measures to reduce emission values. Powerhouse Kjørbo, an office building from the 1980s, was selected as a case study as it was the first refurbishment project in the world which produces more energy than it consumes. The summary of the general information about the case studies and the results from the life cycle assessment is shown in Table 1.

Table 1. Summary of case studies considered in this study.

General Information				
Name of the building	Villa Dammen	Statens hus Vadsø	Bergen city hall	Powerhouse Kjørbo
References	[52,53]	[54]	[55]	[56]
Typology	Residential	Office	Office	Office
Location	Moss	Vadsø	Bergen	Sandvika
Heated floor area, BRA (m^2)	117	3460 (for new building scenario) [1] 4297 (for refurbishment scenario) [1]	10,756	5180
Service life (year)	60	60	60	60
No. of floors (no.)	2	4	14	4–5
Construction period (year)	1936	1963	1974	1980
Renovation period	2014–2015	2021–2024	2019	March 2013–February 2014
Emission factor for electricity and for other energy sources ($kgCO_2eq/kWh$)	0.132 (ZEB factor), 0.321 (for paraffin), 0.014 (for biofuel)	0.13 (EU factor)	0.195 (EU factor) 0.11 (for district heating)	0.132 (ZEB factor)
Building phase	As-built phase	Design phase	Design phase	As-built phase
Refurbishment or adaptive reuse	Refurbishment	Refurbishment	Refurbishment	Refurbishment
Parts of the building rehabilitated	Sealing around windows and doors, floor and roof insulation, heating system	Interior walls, floor, ceiling, insulation of roof (300 mm) and outer wall (150 mm), and scenarios for technical installation	Interior walls, floor, ceiling, façade, and concrete elements	Outer laminated glass façade was recycled and used internally, and the exterior walls were replaced, re-insulation of roof and exterior walls of the basement
Life cycle modules covered (reported)	A1–A3, B4, C1–C4 (material use), and B6 (operational energy use)	A1–A5, B4, C1–C4 (material use), A5 (installation), and B6 (operational energy use)	A1–A5, B4–B5, C1–C4 (material use), B6 (operational energy use), B8 [2], D [2]	A1–A5, B4, C1–C4 (material use), B6 (operational energy use)
LCA tool	SimaPro	OneClick LCA	OneClick LCA	ZEB tool
Emission factors for electricity considered for scenarios analysis ($kgCO_2eq/kWh$)	0.132 (ZEB factor [3])	0.13 (EU28 + NO factor) 0.0128 (NO factor)—both factors calculated following NS3720, production from 2015–2017	0.195 (EU28 + NO factor) 0.024 (NO factor)—both factors calculated following NS3720	0.132 (ZEB factor [3])
Scenarios used in the analysis and (codes)	(1) Without refurbishment (without refurb.), after refurbishment (Refurb.), demolition and building new (New) (2) Measured and calculated operational energy use	(1) New building as reference (New) and after refurbishment (Refurb.), (2) EU factor vs. NO factor for electricity, (3) With and without technical installation (tech. install.)	(1) New building as reference (New) and after refurbishment (Refurb.), (2) EU factor vs. NO factor for electricity	(1) Measured and calculated operational energy use

Table 1. *Cont.*

<table>
<tr><th colspan="9">GHG Emission Results of Case Studies Per Life Cycle Module ($kgCO_2eq/m^2BRA/yr.$)</th></tr>
<tr><th></th><th colspan="2">Villa Dammen</th><th colspan="2">Statens Hus Vadsø</th><th colspan="2">Bergen City Hall</th><th colspan="2">Powerhouse Kjørbo</th></tr>
<tr><td></td><td>Refurb.</td><td>New</td><td>Refurb.[4]</td><td>New [4]</td><td>Refurb.</td><td>New</td><td>Calculated</td><td>Measured</td></tr>
<tr><td>A1–A3</td><td>0.40</td><td>4.60</td><td>2.74 [5]</td><td>6.24 [5]</td><td>1.10</td><td rowspan="3">5 [6]</td><td>3.77</td><td>3.77</td></tr>
<tr><td>A4–A5</td><td></td><td></td><td rowspan="2">0.11 [5]</td><td rowspan="2">0.28 [5]</td><td>0.20</td><td>0.25</td><td>0.25</td></tr>
<tr><td>B4</td><td>0.90</td><td>1.70</td><td>0.40 [6]</td><td>1.82</td><td>1.82</td></tr>
<tr><td>B6</td><td>18.00</td><td>11.60</td><td rowspan="2">13.21 [5]</td><td rowspan="2">7.85 [5]</td><td>19.00</td><td>18.30</td><td>6.54</td><td>5.82</td></tr>
<tr><td>C1–C4</td><td>0.90</td><td>0.70</td><td>0.03</td><td></td><td>0.74</td><td>0.74</td></tr>
<tr><td>D</td><td>NA [7]</td><td>NA [7]</td><td>NA [7]</td><td>NA [7]</td><td>NA [7]</td><td>NA [7]</td><td>−5.82</td><td>−5.70</td></tr>
<tr><td>Total GHG emission (($kgCO_2eq/m^2BRA/yr$)</td><td>20.2</td><td>18.6</td><td>16.05</td><td>14.37</td><td>20.73</td><td>23.3</td><td>7.30</td><td>6.70</td></tr>
</table>

[1] The GHG emission results given per gross floor area of new (3680 m^2) and refurbished (4555 m^2) buildings are recalculated to per heated floor area (BRA). [2] The results from B8 (transport in use phase, according to NS 3720) and D are not included in this paper. [3] This is the emission factor used in the Norwegian ZEB pilots [57]. The emission factor is yearly averaged based on an assumption of a future scenario of a fully decarbonized European grid by the end of 2050. [4] The results include A1–A5, B4–B5, and C1–C4 values. [5] The results include A1–A5, B4–B5, and C1–C4 values. [6] The result of B4 also includes B5 values. [7] Not Available (NA).

4. Lessons Learned from Norwegian Case Studies

This section presents and discusses the findings from the LCA results of each case study focusing on the share between operational and embodied emissions and factors affecting the LCA results. Moreover, the limitations and topics for further research are discussed.

4.1. Embodied and Operational GHG Emissions

Figure 2 shows the embodied and operational GHG emission results from the four case studies. The results show that the operational GHG emissions of the refurbishment range from 50 to 91%, whilst the operational GHG emissions from new buildings range between 55 and 79%. For the refurbishment, the lowest value (50%) is from Powerhouse Kjørbo, where the ZEB factor is considered. The highest value (91%) is from Bergen city hall, where the EU factor is used. For the new building, the lowest operational GHG emission (55%) is from Statens hus Vadsø, where the EU factor and the impact from the technical installations are considered. Meanwhile, the highest operational GHG emission (79%) is from Bergen city hall.

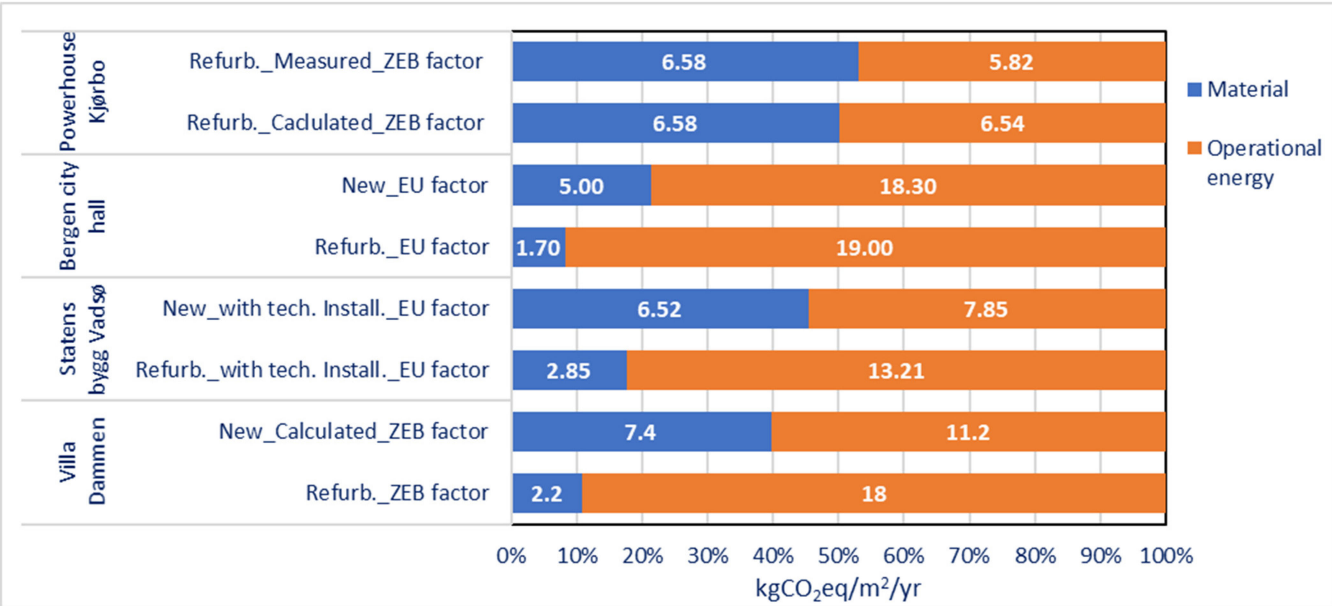

Figure 2. Embodied and operational GHG emission results.

The embodied GHG emissions of the refurbishment range from 8 to 50%, whilst the embodied GHG emissions from new buildings range between 21 and 45%. For the refurbishment, the lowest value (8%) is from Bergen city hall, where the operational GHG emissions dominated due to the use of the EU factor. The highest value for the refurbishment (50%) is from Powerhouse Kjørbo, where the energy efficiency measures were aiming at refurbishing the building to ZEB-COME. For the new building, the lowest embodied GHG emissions (21%) are from Bergen city hall, where the EU factor is considered. Meanwhile, the highest embodied GHG emissions (45%) are from Statens hus Vadsø, where the EU emission factor and impact from technical installations are considered.

The overall results show that the lowest embodied GHG emissions originate from the refurbishment of existing buildings compared to new buildings. A Historic London study [50] showed that the embodied GHG emissions from a new building accounted for 30% of emissions in comparison to 2% from the refurbishment of a Victorian terraced house from 1891 (which is representative of a large number of British homes). Thus, by conserving existing buildings, the embodied GHG emissions that are inherent in the generation of waste during the demolition of old buildings can be reduced. Furthermore, the materials used and waste generated in the construction of new buildings and other emissions associated with transport and energy consumption linked to the construction of new buildings can be reduced.

4.2. Influence of Emission Factors

The refurbishment scenarios have lower embodied GHG emissions in Bergen city hall (8%), Villa Dammen (11%), and Statens hus Vadsø (18%), but the higher operational energy consumption leads to higher total GHG emissions from refurbishment scenarios in comparison with the new buildings. Different scenarios were considered to evaluate the influence of the emission factor, technical installations, and without refurbishment results (Figure 3).

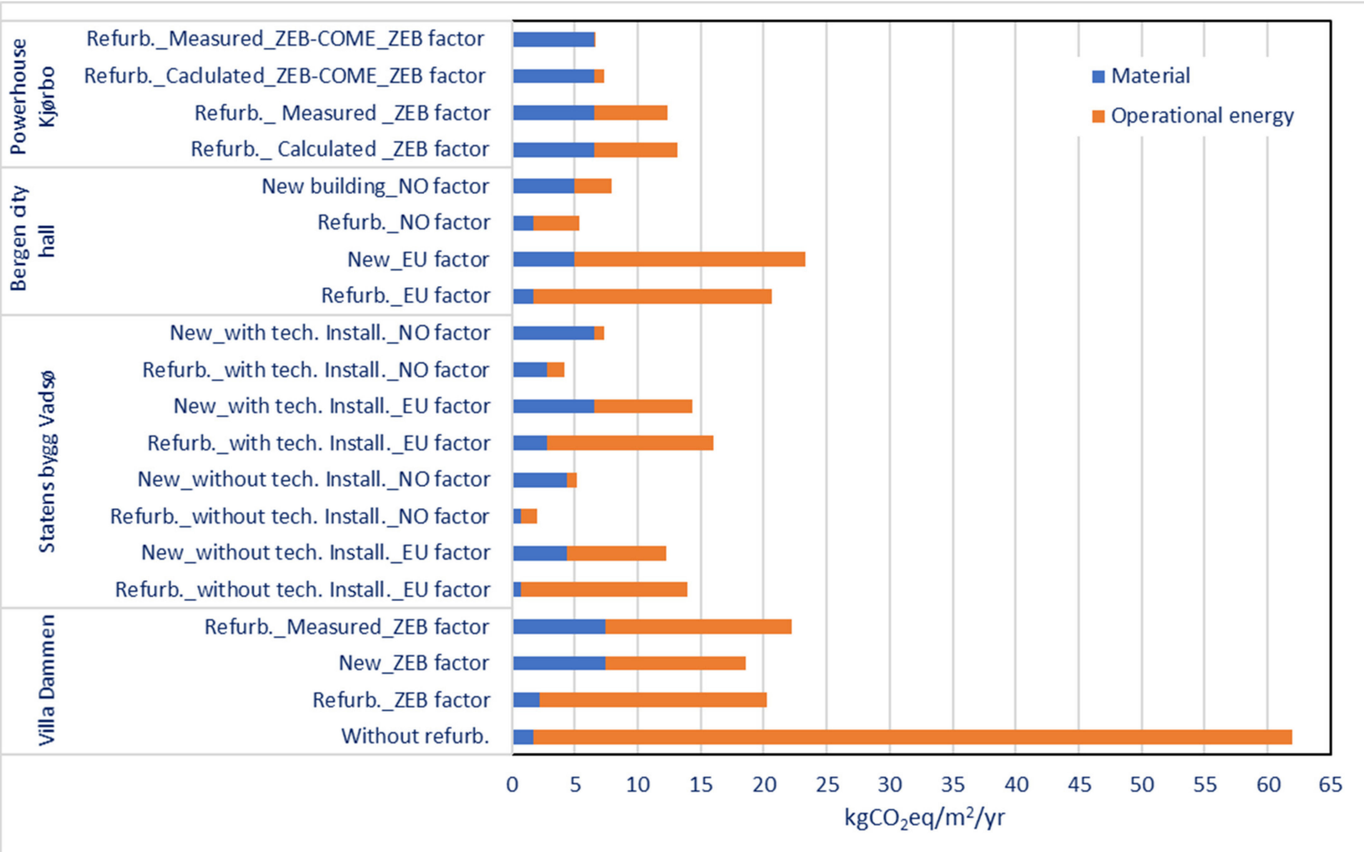

Figure 3. Scenario analysis.

In Villa Dammen and Powerhouse Kjørbo, the influence of the calculated and measured energy consumption was considered, whilst in Statens hus Vadsø and Bergen city hall, the NO and EU emission factors were considered (Figure 3). The change in these scenarios did, however, not have any impact on the embodied GHG emissions.

The operational GHG emissions from the measured energy consumption values were lower than the calculated values both in the Villa Dammen (14.8 $kgCO_2eq/m^2/yr$) and Powerhouse Kjørbo (5.82 $kgCO_2eq/m^2/yr$) refurbishment scenarios. The user's energy use behavior was considered as one of the reasons behind the lower energy consumption in the actual measured values. NS-EN 16883 [11] emphasized the importance of raising users' awareness on the influence of their behavior on energy consumption and associated costs.

Powerhouse Kjørbo is a pilot project of the Norwegian ZEB Research Centre, setting an ambition of achieving the ZEB-COME ambition level, following the step-wise Norwegian ZEB ambition level definition [57]. ZEB-COME means all emissions related to construction (C), operation (O), production and replacement of materials (M), deconstruction, transport, and disposal at end of life (E) shall be compensated for with onsite renewable energy generation. The result for the ZEB-COME scenario shows that the onsite energy generation (-5.82 kgCO_2eq/m^2/yr for calculated and -5.7 kgCO_2eq/m^2/yr for measured) compensated for 44 (for calculated) to 46% (for measured) of the total GHG emissions.

The comparative assessment of the refurbishment vs. new building scenarios in Statens hus Vadsø and Bergen town hall shows the influence of the scenarios for the choice of CO_2 factors on the operational and embodied GHG emissions. When using the EU emission factor, the newly built project has the lowest emissions, and when using the NO emission factor, the refurbishment project has the lowest emissions. The potential environmental benefit of refurbishment is more than half compared to a reference new building scenario. This is also in line with the findings from the IEA EBC study on 11 renovated buildings [40].

The results demonstrate that the lowest GHG emissions from operational energy are found for scenarios when the NO emission factor (lower emission factor, because of electricity generated by renewable resources) is considered. The results from Statens hus Vadsø show that when including the impacts from technical installations, the embodied impact of the new building is further increased by 67% in comparison with the refurbishment (Figure 3). Most studies excluded technical installations; however, Moncaster et al. (2019) estimated the impact of technical installations as being between 9 and 45% of the total life cycle emissions.

In addition, using the EU emission factor resulted in increasing the significance of the emissions from operational energy in comparison to embodied GHG emissions. Thus, considerations of measures that reduce operational energy demands increase the energy efficiency, and the use of renewable energy sources can lead to increases in embodied impacts. Georges et al. [58] demonstrated similar findings in the Norwegian ZEBs where the embodied GHG emissions dominate the operational energy emissions when a low emission factor is considered. The choice of emission factor for electricity affects the contribution of the embodied GHG emissions. Andersen et al. [59] argued that lower emission factors can lead to yielding more weight on embodied emission reduction measures and lower weight on operational energy reductions, and vice versa for higher emission factors. It is important to note that even if both case studies (Statens Hus Vadsø and Bergen city hall) claim to have used the EU28 + NO factor, and that the NO factor was calculated based on NS3720, the emission factors used in the two projects were different. Providing additional information about the calculation method would have increased the transparency of the scenarios. However, such detailed information was not available.

The lessons learnt from the Norwegian ZEB pilots identified the importance of implementation of energy efficiency measures, use of renewable resources, considerations of efficient materials, area reduction measures, prioritizing the use of reused and recycled materials, and the use of long-lasting, low-embodied carbon, and locally available materials to reduce potential embodied GHG emissions [42,60]. Similar findings were obtained through the analysis of IEA EBC Annex 57 case study collections [40]. This is also in line with the three core elements of circular economy and the 10R circular economy framework, which make up the core elements: (1) prioritize regenerative resources (refuse, reduce, rethink), (2) service life extension (reuse, repair, refurbish, remanufacture), and (3) use waste as a resource (repurpose, recycle, recover) [61].

4.3. Time Aspects

The most common LCA method (attributional LCA) uses static calculation perspectives assuming that the emissions occurring today have the same impacts as the emissions in the future. Considerations of emission reduction measures today and in the near future are important to limit the effects of global emissions over time. Evaluation of the time it takes for new buildings to become less carbon-intensive than refurbished buildings, the payback time, is thus the way of showing the importance of refurbishment to make informed decisions. However, the length of the payback period can vary based on several factors including depth of energy efficiency refurbishment measures, emission factors for operational energy use, carbon intensity of materials, and systems used for refurbishment and demolition [50].

Even for the EU factor, which leads to higher operational energy compared to the NO factor, the GHG emissions from the Statens hus Vadsø refurbishment scenario were lower than the new building for up to 22 years (for emissions including the technical installation) and 24 years (for emissions excluding the technical installation) of the building lifetime. This means that after 22 years, the associated lower operational energy GHG emissions will make the new build scenario more beneficial than refurbishment. On the other hand, for the NO factor, the refurbishment has lower GHG emissions than the new building (for both emissions with and without technical installation scenarios) over 60 years of the building lifetime.

In Villa Dammen, the GHG emissions for the refurbishment scenario were lower than for the new building for up to 52 years. This means that in Villa Dammen, considering the operational GHG emissions can only lead to underestimating the GHG emissions from new buildings by up to 40% over 52 years and make refurbishment a less attractive option for emission savings.

From an environmental goal perspective, refurbishment of the Statens hus Vadsø and Villa Dammen buildings will be a better option to achieve the 2030 and 2050 environmental goals. The Historic London study [50] results showed a lower GHG emission from the Victorian terrace refurbishment for up to 60 years and also showed refurbishment as the best option to achieve the 2030 and 2050 lower GHG emission goals compared to demolition and new building scenarios. The results from a Norwegian study [62] noted that refurbishment strategies are in line with the 2030 goals; however, new buildings need to implement more climate mitigation strategies to close the gap. To reach the 2050 climate goals, much more is needed to be conducted for both new and existing buildings.

This demonstrates that refurbishment of existing buildings with historic/heritage values should be favored over demolition and new buildings to achieve short- and medium-term environmental goals.

4.4. Cultural Values and Storytelling Potential

The cultural values of a building often limit the scope of the energy efficiency measures. In Villa Dammen, very few energy efficiency measures have been considered in both the interior and exterior parts to preserve the cultural and historic/heritage value of the building. Thus, there was no re-insulation of external and interior walls, and the original windows were maintained and preserved. Gentle energy efficiency measures through the use of low-carbon materials (wood fiber insulation) (which do not affect the original materials), reducing heat loss in the hot water system (by insulating the water pipes), sealing windows and doors, re-insulating floors, and installing a heat-storing mass furnace in the bricks with reheated tap water have been considered to reduce the operational energy use. Villa Dammen highlighted the importance of considering heritage, cultural, and esthetic values, in addition to energy efficiency and carbon footprint targets. Duffy et al. [50] argued the need for improving the energy efficiency of historic buildings through deep energy-efficient refurbishment to enable them to compete with new buildings from their potential life cycle emissions savings.

In Bergen city hall, the Norwegian Directorate for Cultural Heritage provided an assessment of the cultural heritage value, dealing with the cultural and architectural aspects prior to intervention. The preservation of the façades was considered particularly important. It was recommended to continue the case study project, incorporating results from the planning and as-built phases, since this may turn into an interesting reference case.

In heritage buildings, the GHG emission reduction measures are specific to each individual building. Measures such as change of energy source are often of interest, while the possibilities for re-insulation of façades and replacement of windows may be limited. Even when implementing measures specifically adapted to heritage values, such as in Villa Dammen, it is important to allow for reduced emissions and, at the same time, take care of heritage values. Both for existing buildings and historic/heritage buildings, there is a need for more systematic methods for implementing and evaluating refurbishment measures, which Pracchi [23] refers to as efficiency diagnostics for upgrading. Such approaches will enable realizing the sustainability potential inherent in the existing building stock.

4.5. Scope, System Boundary, and Methodological Choices

Performing cradle-to-grave life cycle assessment from the early design phase through the construction process and the as-built phase of the building, including all building elements as much as possible, will enable supporting informed decision making. Both Statens hus Vadsø and Bergen city hall studies were conducted in the early planning phase of the projects. Such kind of early phase studies, when knowledge is limited, will enable evaluating the potential of refurbishment in comparison to new buildings, identifying the hot spots, and implementing design strategies and energy and material efficiency measures during the construction and as-built phases. However, these life cycle assessments do not allow considering heritage values.

In Villa Dammen, the scenario where the building was assumed to continue to operate as normal without refurbishment (without refurb.) shows the highest operational GHG emissions (97%). By refurbishing the building, up to 70% of these emissions could be saved. This shows that adding "without refurbishment scenarios" would further support the decision-making process.

The building physical system boundaries often vary but determine the emission results. The results from Statens hus Vadsø show that by including the impacts from the technical installation, there is a further increase in the embodied impacts of the new building by 67% in comparison with refurbishment (Figure 3). Moncaster et al. (2019) estimated the impact of technical installations as being between 9 and 45% of the total life cycle emissions. However, most studies excluded technical installations mainly due to a lack of data. In NS 3720, it is stated that building products that present in small quantities can be excluded, but the total excluded product within at each two-digit building element level must not exceed 5% of the total weight [37].

The LCA methods follow an internal baseline scenario approach for the reference buildings [37], where a simplified building model is developed as a reference building (using existing scenarios and generic data) in the early design phase of a project. The reference building is used as a baseline to LCA calculations during the construction and as-built phases to evaluate measures considered to improve the environmental performance of the building (such as design and energy efficiency strategies and material choices). This might lead to setting lower emission reduction targets based on a poor choice of background data [63]. The reference building from OneClick LCA is often used in LCA studies (as in Statens hus Vadsø and Bergen city hall case studies); however, the creditability of the reference building in the tool is under question [37]. External references or benchmark values can be used as good references instead of initial baseline values. Hasik et al. [46] also pointed out the challenges related to reference buildings used for comparative assessment with rehabilitation scenarios and proposed establishing a database of previously completed projects to use as reference buildings. Further works following the first LCA reference study conducted in Norway [62] for existing building LCA case studies are important to collect good reference values.

For the life cycle system boundaries, life cycle modules A1–A5, B4, B6, and C1–C4 are included in the analysis (except in Villa Dammen where A4-A5 is not included). Including the impact from the construction (A4–A5) and end of life (C1–C4), which are often excluded in LCA calculations, will enable pointing out the environmental benefits from refurbishment. The national fossil or emission-free [64–66] and waste-free initiatives [67] showed the importance of construction site emission reduction in achieving environmental goals. The findings from the Norwegian case studies showed 2–15% GHG emissions from the construction phase (A4–A5) and up to 8% from the end of life (C1–C4) phases of the Norwegian ZEBs [42]. The construction and end of life calculation in Powerhouse

Kjørbo was based on some assumptions, whilst in Statens hus Vadsø and Bergen city hall, the calculations were based on the background data from OneClick LCA. The data from OneClick LCA, especially for the construction phase, are described as uncertain and to be lacking transparency [37]. As the results of LCA are dependent on the background data, using transparent background data is useful. The LCA studies performed based on actual construction data collected from Norwegian construction sites can be used as an example [64,66,68].

The results exhibit the effect of case-specific factors, such as refurbishment measures, and methodological choices on GHG emission reductions. Conducting comprehensive LCA studies will enable identifying environmentally preferable refurbishment measures. However, heritage value considerations are most often lacking in such studies.

5. Future Research Perspectives

There are several aspects that need to be covered in future research activities addressing the role of existing buildings.

- Even if improving the energy efficiency performance of historic/heritage buildings is challenging, a thorough assessment is needed. Setting ambitious refurbishment targets to fulfil the current energy performance regulation as minimum ambitions, focusing on achieving zero emissions or plus house by incorporating energy efficiency and renewable energy measures, is important. The uncertainties of future energy mixes and user behavior should also be taken into consideration. Further studies should perform scenario analyses to evaluate different realistic refurbishment measures addressing the uncertainties in background data, assumptions, and methodological choices. Creating awareness and developing expertise to fill in the knowledge gap in this area are also needed.
- A life cycle assessment should be used as a decision support tool to assess the sustainability of refurbishment measures, assess the performance before and after refurbishment, and make informed decisions regarding refurbishment vs. demolition and new building scenarios. Further studies should consider performing detailed and transparent LCA of existing buildings, including both refurbishment and adaptive reuse of existing buildings with historic/heritage values. The study should provide a clear description of the ambitions (for, e.g., achieving TEK 17, ZEB, passive house, plus house) and scope of the study (for, e.g., level of refurbishment, LCA system boundaries following EN 15978 or NS 3720, building physical boundaries in accordance with NS 3451) including the whole life cycle of the building (modules A1–D). Cultural heritage values and different environmental indicators than GHG emissions should also be considered in the analysis.
- Implementing refurbishment and adaptive reuse measures to achieve reduced emission values can be difficult without affecting the heritage values. This calls for a system that systematically considers the role of cultural heritage, and the development of refurbishment and adaptive reuse measures that attend to the socio-cultural values. Further, such systematic evaluation and measures for attending to socio-cultural values should be incorporated into methods such as BREEAM and equivalent systems.
- This study was conducted based on the results of only a few LCA studies on existing buildings with historic/heritage values. It is challenging to conduct a comparative assessment of LCA studies of refurbishment projects due to different refurbishment measures, background data, and methodological choices considered in the LCA calculation. Collecting best practices will enable gathering lessons learned from the technical, environmental, and historic/heritage performance of existing buildings. Futurebuilt is a good example where basic information and the LCA results of the pilot projects are reported in a standardized format. Collection of those documents from Futurebuilt pilots and case studies from BREEAM NOR for BREEAM-certified buildings in a type of database or renovation passport can be a way forward for collecting best practices for rehabilitation and adaptive reuse of existing buildings

with historic/heritage values. This can also support incorporating refurbishment and adaptive reuse projects in the on-going work on setting national GHG emission requirements and reference or benchmark values in Norwegian building codes (TEK) [62].
- The scope of the current LCA studies is limited to environmental impact assessment. Further studies should consider incorporating the economic, social, and historic/heritage aspects to widen the scope of LCA and provide a more holistic view. It is important to include other indicators such as resource depletion and toxicity to avoid problem shifting from one indicator to another. In addition, incorporating the dynamic LCA approach will provide a better understanding of time aspects of refurbishment and adaptive reuse.
- Investigation of potential environmental, economic, and social strains and benefits by using a dynamic input–output analysis method is essential. This enables evaluating the supply chain effects caused by the current and future changes in demand and technological developments at different levels (building, neighborhood, city, region, country, global).
- Activities related to refurbishment and adaptive reuse of existing buildings, with environmental and social benefits proven by LCA studies, should receive financial support, incentives, and subsidies to support and emphasize the role of historic/heritage buildings in climate change mitigation.

6. Conclusions

Given most of the world's building stock for the next 30 years already exists today, consideration of refurbishment and adaptive reuse of existing buildings, in general, and historic/heritage buildings, in particular, is considered as the way towards a sustainable future. This paper presented, evaluated, and discussed the lessons from the GHG emission results of Norwegian case studies. The results show that refurbishment of existing buildings has up to 50% lower GHG emissions compared to a reference scenario, mainly due to the lower embodied GHG emissions. It takes decades before the benefits of lower levels of annual operational GHG emissions offset the negative impacts caused by the increase in embodied GHG emissions linked to the construction of new buildings. Findings in the literature support the conclusion that refurbishment of existing buildings, including buildings with historic/heritage values, is preferable in the 30-year time frame up to 2050, as it can take from 10 to 80 years before the embodied GHG emissions arising from a new building are compensated for. Thus, from an environmental perspective, the refurbishment of existing buildings and buildings with historic/heritage values will play a major role in achieving short- and medium-term environmental goals. This study also highlighted the limited LCA studies on refurbishment and adaptive reuse of heritage buildings, uncertainties in existing studies, and the lack of consideration of socio-cultural values. Thus, performing a holistic LCA study covering the whole life cycle, including socio-cultural values and economic aspects, will enable demonstrating the benefits of refurbishment and adaptive reuse of existing buildings, including buildings with historic/heritage values, in order to fulfil emission reduction ambitions.

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