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Life cycle assessment and historic buildings: energy-efficiency refurbishment versus new construction in Norway

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ABSTRACT

Refurbishment policies for the historic segment of the building stock must be carefully promoted in the process of addressing the transition to a low-emission society to avoid the loss of the values which make this heritage significant. This article presents and the results of a Norwegian life cycle assessment comparing the net climate benefits from the refurbishment of a residential building from the 1930s with the construction of a new building in accordance with modern building codes. The results show that a careful refurbishment of the historic building is favourable in a climate change mitigation perspective over a 60-year period of analysis. For the new building, it takes more than 50 years for the initial emissions from construction to be outweighed by the effects of lower in-use energy consumption. The results underline the significance of emissions from the use of materials in the refurbishment process and that residents play a critical part with respect to realising the expected energy savings. It is concluded that material use and user behaviour have a crucial impact on greenhouse gas emissions in a life cycle perspective and that the continued use of historic buildings should be advocated for in building codes and environmental policies.

KEYWORDS

Life cycle assessment (LCA); energy efficiency; historic buildings; building conservation; climate change

Introduction

As part of the transition to a low-emission society, existing buildings need to be adapted to comply with increasingly strict environmental and energy performance requirements.[1] Historic buildings, in particular, are as a consequence facing scenarios where their cultural heritage significance is impaired in favour of the environmental benefits related to new buildings.[2] With this, the goal of the low-emission society is brought into a supposed conflict with the continued use of historic buildings.[3]

A growing number of studies have on the other hand suggested that safeguarding and upgrading historic buildings could, in fact, contribute to climate change mitigation. This can be achieved by making the historic building more energy efficient, and, indirectly, by taking into account the avoided emissions it represents, as it has already been built.

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Objective

The objective of this paper is to explain general environmental advantages and disadvantages represented by the refurbishment and continued use of historic buildings in the transition to a low-emission society. We will do this by presenting and discussing the results from a Norwegian life cycle assessment (LCA) comparing the net climate benefits from the refurbishment of a historic residential building from the 1930s with the construction of a new building in accordance with modern building codes. As a secondary objective, the results will be used to shed light on the impact of user behaviour on energy consumption and emissions.

Life cycle assessment

A LCA is a systematic evaluation of the environmental impact caused throughout the life cycle of a product or service. An LCA of a building considers the environmental impact caused throughout the life cycle of the building, and not just in the operational phase. This includes material extraction, transport of materials, the construction process, maintenance and eventual demolition and waste management. An LCA, therefore, provides a better picture of environmental performance than operational energy use calculations. By evaluating the environmental impact of buildings solely based on energy use in the operational phase, and failing to account for environmental impact caused throughout the rest of the building life cycle, we run the risk of operating with unsustainable policies. By allowing for justifiable comparisons between specific building scenarios, a broader use of LCA can thus help in rethinking energy and building codes. Accounting for environmental impact from the construction process also enables the evaluation of avoided environmental impacts by not constructing new buildings.[4]

Background and previous research

Sustainability by building conservation

One aspect that distinguishes the historic building (in this article generalised to having been built before 1945) from the modern building is that it has been constructed to fit fundamentally different conditions. The climate and the lesser availability of resources in general, and building materials, in particular, were, for instance, a larger influence on building design than is the case today. The historic building was also designed to meet other demands regarding indoor comfort.[5]

Larsen and Marstein[6] have claimed that – in terms of representing a sound long-term use of resources – sustainability has in fact always been a central concept in building conservation. Or, as Jean Carroon phrased it, 'the history of concern for the environment and the history of concern for the built heritage is interwoven, it emerged at the same time'.[7] With modernism, these characteristics eventually changed, and Northern Europe departed from a thousand-year-long validated building tradition somewhere around the mid-twentieth century.[8] How then, can experience and knowledge from the interaction between managing the built heritage and the environment benefit in the transition to a low-emission society?

Curtis[9] has, on behalf of Historic Scotland, argued that in order to sustainably refurbish a historic building stock, improvements should also consider the embodied energy and long-term life cycle environmental impact of the building. Studies have on the other hand showed that implementing energy-efficiency measures do not always lead to environmental benefit in a life cycle perspective.[10] Thus, in addition to going against cultural heritage aspects, energy-efficient measures may not be environmentally sound, unless a life cycle perspective is considered.

Norwegian codes and subsidy systems

Norway has in light of its partnership in the european economic area committed to reducing its greenhouse gas (GHG) emissions by 60–80% by 2050.[11] National legislation has been set to progressively raise the standards and minimum requirements for energy performance in new buildings and major refurbishment of existing buildings. The national building code document TEK10 aims to realise climate goals by ensuring that all buildings are constructed, maintained and disposed of with as little impact on natural resources and the environment as possible.[12] The legislation does not further address the overall environmental impact construction entails, and it is not flexible in the sense that the use of renewable energy can compensate for stringent energy requirements for existing buildings. It does, however, regulate the maximum *U*-value allowed for different elements of the thermal envelope. For existing buildings, an alternative is provided: when buildings are refurbished, minimum energy requirements can be omitted if they are not acceptable regarding the cultural heritage significance of a building.

To support the transition to a low-emission society and speed up the process of making existing buildings more energy efficient, government bodies such as ENOVA provide incentives and subsidies to homeowners for implementing energy-efficiency solutions if the measures comply with aforementioned energy requirements. The ENOVA grant is in turn connected to the Norwegian Energy Performance Certificate system, which is an energy performance assessment system loosely based on generalised pre-defined data sets. This system is efficient but has the unfortunate consequence that buildings are more broadly categorised rather than assessed on their own individual merits.[13]

Energy efficiency and historic buildings

The growing demand for more research into the energy efficiency and environmental impact of historic buildings is reflected in several recent research calls (NFR 107, Energimyndigheten 3. Etapp, Horizon 2020), policy documents[14] and reports.[15]

A large amount of research has, however, already contributed to defusing the assumed conflict between energy efficiency on one hand and preservation of historic buildings on the other. The FP7 EU project '3encult' contributed, for instance, to the development of passive and active solutions feasible for improved energy efficiency in historic buildings.[16] Within the ongoing Swedish programme for energy efficiency in historic buildings, Spara och Bevara (2006–2018), a method has been developed that systematically weighs techno-economic life cycle optimisation with risk assessments concerning the historic qualities and hydrothermal features of a building.[17] An early study conducted in the SECHURBA project aimed to show how historic districts can be adapted to reduce their carbon emissions.[18] The recently finished EU project 'EFFESUS' developed a decision support system for improving energy efficiency in historic districts. However, as discussed by Fouseki and Cassar,[19] the life cycle approach (via LCA) to energy efficiency and building conservation is still relatively unexplored.

The same goes for the importance and potential of user-driven energy efficiency in historic buildings, i.e. measures that have a significant effect on energy demand, yet have no physical impact on the buildings. Several studies have pointed to the general knowledge gap regarding this and how the users of historic buildings represent an untapped energy saving potential, possibly equivalent to that of some technical measures.[20] The Nordic CERCMA investigation from 2014 acknowledged a similar outlook by concluding that 'the influence of behaviour tends to be more apparent to the user of historic buildings' than buildings in general since older e.g. heating systems such as wood burning stoves require active residents.[21]

Long-term environmental impacts of historic buildings

A new European Standard for improving the energy performance of historic buildings acknowledges the importance of the assessing the whole life cycle of a building by stating that 'historic buildings should be sustained by respecting the existing materials and construction, discouraging the removal or replacement of materials / … / which require reinvestment of resources and energy with additional carbon emissions'.[22]

In terms of previous case-study research, only a few studies have been conducted on the topic. The Empty Homes Agency of England demonstrated for instance in a study the importance of taking into account both the emissions associated with energy use and with material consumption when assessing building rehabilitation, by highlighting the avoided impact that refurbishing represents compared to new construction.[23]

The Green Lab study[24] compared the potential environmental savings offered by reusing or retrofitting historic buildings to replacing them with new buildings over a certain period using LCA. Results showed it can take between 10 and 80 years for a new energy-efficient building to 'pay back' the emissions caused during construction through reduced emissions in the operation phase. The study also pointed out that the benefits of refurbishment can be reduced or negated based on the type and quantity of materials selected for a reuse project. This has also been implied by findings from Vancouver, where it was suggested that upgrading historic buildings can perform on par or better than new houses built following code.[25]

Munarim and Ghisi[26] have contextualised the environmental impacts of buildings and the prospects for the reduction of these impacts by rehabilitating the existing building stock. In their study, they identify a main barrier in the lack of consistent data for life cycle inventories, both temporally and geographically, and seek that the LCA approach is consolidated in refurbishment policies and single building decision-making. They also concluded that the concept of avoided environmental impact is a relevant approach to assess the feasibility of building rehabilitation.

Lastly, two pieces of LCA research commissioned by the Norwegian Directorate for Cultural Heritage in 2011 and 2015 respectively, assessed two traditionally constructed buildings – one historic and one recently built – to a comparable building constructed with materials in common use today in the mainstream construction industry. The first LCA was delimited to include only CO_2 emissions related to material production phase and the operational phase (60 years) (hence excluding emissions related to construction, transportation, demolition, etc.). Information on building material and components for both buildings were acquired from model data sets from the free LCA software 'klimagass-regnskap.no'. Amounts of materials required for the rehabilitation of the existing building was estimated and based on experience. Three different packages of measures with increasing impact on energy saving were modelled to establish a basis for comparison with the new reference building. As the historic building had restrictions for exterior alterations, all measures were designed with respect to the restrictions. The reference building was modelled to have corresponding geometry, size and use to the historic building and ascribed technical attributes in compliance with minimum requirements of TEK07 (predecessor to TEK10). The second LCA aimed to investigate the carbon footprint generated by materials and operation for a traditionally constructed log house compared to a house designed in accordance with the proposed new energy requirements where the exemption for log buildings was removed. The log house was a single-family dwelling from 2006 with a timbered wall and roof construction. The reference building was a modelled modern dwelling of equivalent size and use that reached the proposed new requirement in TEK17. The timbered building used wood burning stoves to supplement its heat pump. Consumption for the stove and the average indoor temperature was not known. Instead, CO_2 emissions were calculated on the basis of acquired data from energy monitoring for the timber building, correlated climatic conditions and pre-defined data sets for building components from klimagassregnskap.no.

The results in both studies showed that the two 'traditional' buildings yielded smaller environmental impact than the new building over their life cycle, despite higher emissions in the operation phase. Furthermore, the studies also concluded on two main points:

(1) Operational energy performance can not necessarily be used as an argument against the conservation of historic buildings.
(2) The reuse and sustainable refurbishment of historic buildings are serious alternatives to the replacement of existing buildings with new low-energy buildings.

A third conclusion to be drawn is that the accuracy of data, e.g. energy consumption and user behaviour, is crucial for comparing two different cases where a reference building is modelled and an existing building per definition is changing with respect to both use and management every so often. Both studies thus illustrate the need to improve existing life cycle inventory data for traditional materials and techniques. In addition, they underline the importance of accurate modelling which requires using other methods then e.g. generalising software such as klimagassregnskap.no.

Method

In 2016, a third LCA was commissioned by the Norwegian Directorate for Cultural Heritage, aiming to measure the net environmental benefit of refurbishing a historic dwelling, Villa Dammen in Moss, Norway, taking into account both energy use and consumption of materials in a life cycle perspective. The study was carried out as a comparative assessment, where the refurbished building was compared to a scenario with no refurbishment and another scenario where the existing building was demolished and replaced by a new house complying with then current Norwegian energy-efficiency requirements (TEK10).

In addition, the study explored how different assumptions for estimating energy use in the operational phase, as well as for calculating GHG emissions from energy use, affect the results. The impact of user behaviour on energy use and emissions was assessed by looking at the consequences of including different assumptions for temperature zoning (i.e.

adjusting temperature to intended use in different rooms). The results were also held up against the actual measured energy consumption in Villa Dammen post-refurbishment.

LCA and calculation assumptions

The LCA was conducted in accordance with current LCA standards NS 14040:2006 and NS 14044:2006.[27] Calculations accounted for emissions associated with the use of construction materials and energy required over the entire life cycle to build, operate, maintain and dispose of the considered buildings. A period of analysis of 60 years was used, in accordance with standard practice for LCAs of buildings in Norway, to ensure comparability with similar studies.

Emissions associated with the use of materials included emissions from the production of materials (extraction of raw materials, energy use and transportation in the manufacturing process), transportation of materials to the construction site, the expected replacement of components during the analysis period (maintenance), as well as demolition, transportation to waste management facilities and final disposal of materials.

The LCA software SimaPro (PRé Consultants, ver. 8.3.1) was used to acquire data from the database Ecoinvent (Swiss Centre for Life Cycle Inventories, ver. 3.1) for the analysis. The ReCiPe Midpoint characterisation method was used to calculate environmental impacts.[28] Only climate change impact, given in CO_2-equivalents (CO_2-eq.) is considered in the analysis.

Operational energy use was estimated for all scenarios using standardised values in the energy calculation software Simien (ver. 6.000), using standardised parameters as prescribed by the Norwegian standard for energy use calculations[29] (NS 3031), and information on the energy sources installed in the buildings. Emissions from energy use were calculated using emissions factors published by the Norwegian research centre ZEB.[30]

Description of case-study Villa Dammen

The case-study building, Villa Dammen, was built in 1936 with an uninsulated timber-frame structure, outside vertical wooden cladding and full concrete basement, see Figure 1. The building represents a common type of building from the 1920s/1930s with cultural heritage significance connected mainly to its visual appearance, shape and materiality. Villa Dammen was up until its refurbishment in 2014 heated with an oil boiler supplemented by electric radiators. Energy-efficiency measures carried out in 2014–15 were chosen with general consideration to the historic qualities, passive design qualities in the construction, as well as the intended use of the building, expectations regarding indoor comfort and so on. This is in line with the procedural approach presented in the standard for improving energy performance in historic buildings.[31] The period of analysis was defined as starting with the refurbishment. Although it might seem counterintuitive to assume a 60-year life span for a building which has already fulfilled its function over a period of more than 80 years, this was done to ensure comparability with similar studies. Emissions associated with the use of construction materials were calculated from information on actual materials and amounts used.

Refurbishment measures included the installation of a large wood stove, which supplies most of the heating required, supplemented by a heat pump. The residents of Villa

Figure 1. Villa Dammen, Moss, was with its steep saddle pitched roof and classical proportions constructed in a slightly obsolete style. The glass veranda is not heated. Photo: Fredrik Berg.

Dammen make use of temperature zoning during heating season as well as reducing the set temperature of the building when they are not at home. Such measures are not considered standard in energy consumption simulations. Consequently, actual measured energy consumption in Villa Dammen over the two years after refurbishment is significantly lower than the estimated energy consumption from Simien simulations which were used as the basis for the LCA. Scenarios, where actual measured energy use was used, were, therefore, also investigated in the study as an additional scenario.

Reference building

The reference building used for calculating emissions in the new construction scenario was based on a building of equivalent construction, size and use as Villa Dammen, built in accordance with the Norwegian building code 'TEK10'. Data on consumption of building materials in the reference building was adapted from another comprehensive LCA study based on an actual dwelling project at Stord in Norway.[32] The reference building has a reinforced concrete slab on ground insulated with expanded polystyrene and a timber-frame construction insulated with mineral wool in exterior walls and ceilings. Materials used for components of energy and ventilation systems in the reference building were acquired from an LCA study conducted in parallel with the original Stord study. Operational energy use for the reference building was estimated by adapting the energy simulations used in the Stord study to the size of Villa Dammen, to ensure consistency. The reference building was assumed to be heated by electricity and a modern wood oven. For more detailed information on the reference building, see original study.[33]

Results

Life cycle environmental performance

The results show that the refurbishment of Villa Dammen causes a reduction in total GHG emissions over 60 years of approximately 295 tonnes CO_2-eq, amounting to a 67%

reduction, compared to the scenario without refurbishment. Consumption of construction materials during refurbishment causes some emissions, but these are dwarfed in magnitude by a 70% decrease in emissions from energy use.

Despite energy-efficiency measures, a new building constructed according to modern standards will be significantly more energy efficient than Villa Dammen. Thus, emissions from operational energy use are 40% lower for the new building. However, due to the large amounts of construction materials needed to construct the new building, the difference in net life cycle emissions between the scenarios is small. Over 60 years, net life cycle emissions for the new construction scenario are only some 8% lower than for the refurbished Villa Dammen scenario.

Figure 2 shows the total GHG emissions for the three scenarios accumulated over the 60-year period of analysis. The intersection between the curves representing Villa Dammen with and without refurbishment is difficult to discern, as it occurs in less than a year (ca. 6 months). The environmental pay-back time of the refurbishment, meaning the time needed for avoided energy emissions due to energy-efficiency measures to equal emissions incurred in the upgrade process, is thus very short in this case. Correspondingly, the time needed for the effect on emissions of lower annual energy consumption in the new building to outweigh the emissions caused in the construction process, when compared to the upgraded Villa Dammen, is around 52 years.

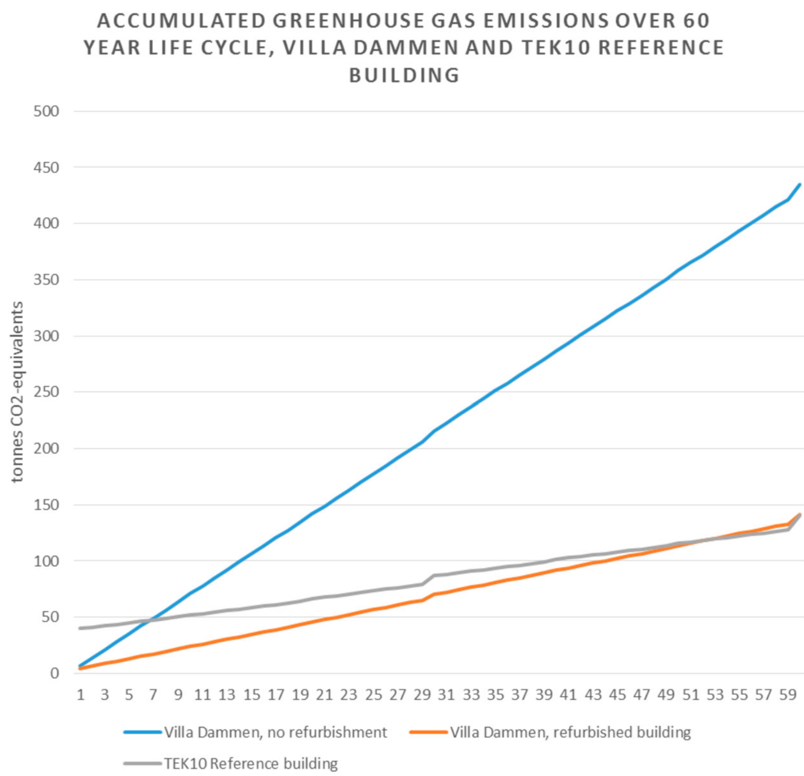

Figure 2. Accumulated GHG emissions over a 60-year life cycle for Villa Dammen with and without refurbishment, and for scenario with new construction.

Emissions related to energy use

Figure 3 shows that emissions related to energy account for the largest share of total emissions for all three scenarios. The proportion of total emissions associated with energy use is largest for Villa Dammen without refurbishment (97%). Emissions from energy use account for 89% of the life cycle emissions for the upgraded building, and 60% for the reference building.

The energy-efficiency measures implemented in Villa Dammen are estimated to reduce operational energy use by ca. 30%. The corresponding reduction in energy-related emissions is much greater (70%), due to the transition from using an oil boiler in the no-refurbishment scenario, to a wood burning stove as the main heat source in the refurbished building. As wood is considered a renewable energy resource, the incineration of wood is assumed to cause no net climate change impact. There is increasing scientific debate regarding the effect of biomass-based fuels on climate change mitigation, and the implications of the assumption of climate change neutrality for biomass combustion are investigated comprehensively in the study. However, for the sake of brevity, they are not elaborated upon here.

Emissions related to electricity consumption account for a very large share of total energy use emissions – ca. 40% for Villa Dammen without refurbishment, ca. 87% for the refurbished building, and ca. 97% for the new building. The reference building is assumed to use electricity to cover a large part (80%) of its heating demand, as is the

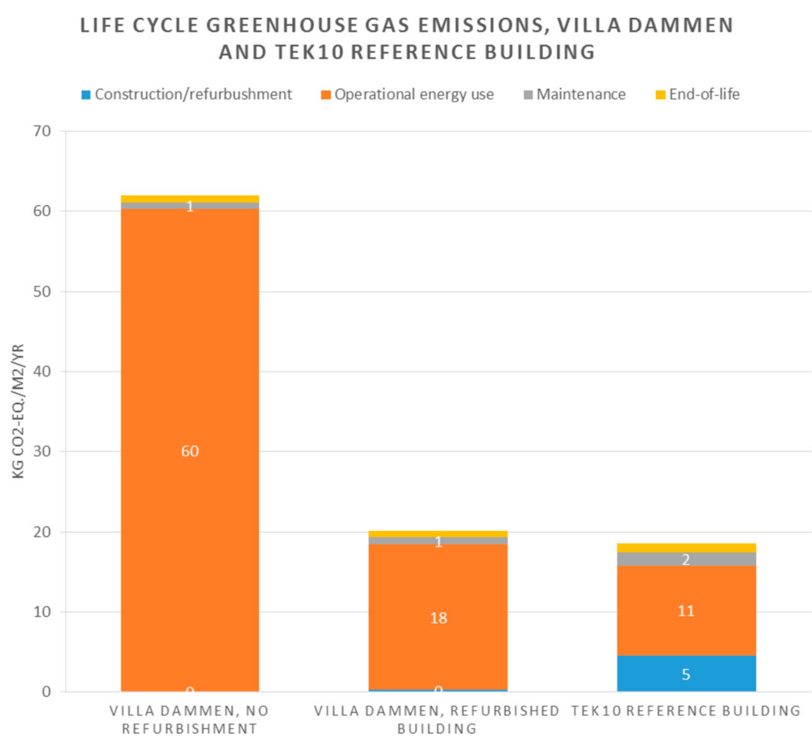

Figure 3. GHG emissions related to the production, operation and maintenance, and end-of-life for Villa Dammen with and without refurbishment, and for scenario with new construction, per m^2 heated indoor area per year, over a 60-year life cycle, per life cycle phase.

case for the majority of Norwegian dwellings. Under the assumption that biomass combustion is net climate neutral, the emissions from operational energy for the reference building are thus dominated by emissions related to electricity consumption. The impact of assumptions regarding energy supply is investigated in the study by considering additional scenarios for Villa Dammen before and after refurbishment. If the pre-refurbishment building is assumed to be heated using a combination of heat pump, direct electricity and wood stove, energy use emissions for the scenario with no refurbishment are almost cut in half. Correspondingly, a shift from mainly using biomass combustion to a mix of heat pump, electricity and biomass for the refurbished building increases the energy-related emissions for the refurbished building by some 40%, so long as electricity is assumed to cause higher emissions per kWh than biomass combustion.

Actual measured energy use in the refurbished building is, as previously noted, much lower than the energy use estimated using Simien – almost 50% lower than the estimated energy use for the scenario without refurbishment, as a consequence of the systematic energy conserving behaviour of its inhabitants. If actual measured energy use is used as the base for comparing the refurbished Villa Dammen with the new building, as opposed to standardised energy use estimates, net life cycle emissions are 10% *higher* for the new building over the 60-year period of analysis.

The gap between energy simulations based on standardised user profile data (NS 3031) is a key issue investigated in the study, as the analysis results point to a larger discrepancy between actual and estimated energy use for older buildings than new ones.

Emissions related to use of materials

Emissions from use of materials in the upgrade process account for only 2% of total lifetime emissions for the refurbished building. Emissions related to the construction phase are 12 times higher for the new construction than the refurbishment scenario. This reflects the difference in the amount of materials required, the emissions associated with the demolition of the existing building in the new construction scenario, and the type of materials used.

Emissions caused by materials for operation and maintenance account for 1–9% of total emissions over 60 years, while emissions from the demolition phase represent only 1.6% of the total.

Life cycle emissions related to the use of construction materials in the three scenarios are shown in Tables 1 and 2. Demolition of Villa Dammen accounts for ca. 20% of emissions from the construction process for the new building. However, if emissions from demolition are excluded, the construction of the new building still causes 10 times more emissions than the refurbishment of Villa Dammen. As seen in Tables 1 and 2, emissions from the operation and maintenance phase are higher for the reference building than the scenarios for Villa Dammen. This is because the materials used in Villa Dammen have a very low climate change footprint, whereas standard building materials (with higher climate change footprint) are used in the reference building. Thus, replacement of materials within the period of analysis causes higher emissions for the reference building. This is seen as a fair assumption, as, historically, simpler and more durable construction materials were used in dwellings.

Table 1. GHG emissions related to the production, operation and maintenance, and end-of-life for materials used in Villa Dammen with and without refurbishment, and for scenario with new construction, over a 60-year life cycle.

Life cycle phase	GHG emissions (tonnes Co_2-Eq.) Villa Dammen, no refurbishment	Villa Dammen, refurbished building	TEK10 reference building
Construction/refurbishment	0.0	2.6	32.4
Operation and maintenance	6.1	6.3	12.1
End-of-life	5.9	6.1	7.4
Sum	12.0	15.0	51.9

Table 2. GHG emissions related to the production, operation and maintenance, and end-of-life for materials used in Villa Dammen with and without refurbishment, and for scenario with new construction, per m^2 heated indoor area per year, over a 60-year life cycle.

Life cycle phase	GHG emissions (kg CO2-EQ./m^2/yr) Villa Dammen, no refurbishment	Villa Dammen, refurbished building	TEK10 reference building
Construction/refurbishment	0.0	0.4	4.6
Operation and maintenance	0.9	0.9	1.7
End-of-life	0.8	0.9	1.1
Sum	1.7	2.1	7.4

Discussion

The primary objective of this paper has been to explain environmental advantages and disadvantages represented by the refurbishment and continued use of historic buildings in the transition to a low-emission society.

First, principally, how may we generalise from the case? The limitations of the study are reflected on the one hand in how well-informed the decision-making was when refurbishment measures were planned in Villa Dammen. The energy-efficiency process was a model performance with a less-is-more approach followed up by relatively aware and motivated users. Not unlike the model performance scenarios that new buildings which have yet to be constructed often show in concepts. On the other hand, rather than criticising Villa Dammen for being advantageous compared to a new building, it can be viewed as an example of good practice. Both in respect of how it helps problematise LCA when comparing historic to new buildings, but also regarding the effective technical and non-technical measures it uses. In other words, Villa Dammen is perhaps an *atypical* case, but important nonetheless when moving forward to other studies that produce similar or contrasting results. The energy regime of Villa Dammen is based on active users that know how to adapt to and optimise the thermal characteristics of the building. This is an essential element in the energy-efficiency process, it applies to all historic buildings where non-intrusive are favoured and is similarly crucial in reducing emissions when using existing buildings (which we, of course, will be doing).

The results are thus also relevant on a more general level, especially considering how national and global policies stress the importance of rapid reductions of GHG emissions if the most severe consequences of global climate change are to be avoided. This calls for adopting emission reduction measures that provide results within a short time-frame, i.e. prioritising energy-efficiency measures with a short pay-back period. Extrapolation of the numbers thus makes a strong case for the environmental benefit of upgrading historic buildings, considering that the environmental pay-back time of replacing Villa Dammen with a new, more energy-efficient building is over 50 years. Moreover, as the historic building stock in many ways represents a finite (cultural) resource, any situation involving demolition should preferably be avoided, given that is an irreversible action.

The results of the LCA also confirm that the amount and type of materials used in energy-efficiency refurbishment and new construction have a decisive impact on the total emission rates, both in the short and longer term, i.e. the less-is-more approach demonstrated in Villa Dammen pays off. Measures tailored to reduce infiltration, improve insulation and shift energy systems are transferrable to most other historic buildings. The results, therefore, agree with similar findings presented in chapter 2, and echo what Larsen and Marstein[34] labelled as a 'central concept' in building conservation; 'sound resource management implied by regular maintenance instead of periodic replacement'. This is also tied to the advantage of the *avoided environmental impact* gained or saved by refurbishing rather than replacing, which Carl Elefante[35] once managed to concisely describe by stating that 'the greenest building is the one that is already built'. On district scale, it should be fair to require a life cycle approach for 'both parties' when assessing densification or revitalisation strategies where historic buildings are affected.

As a secondary objective, we aimed to shed light on user behaviour and the impact it has on energy consumption and emissions. As emissions from energy use account for a major part of life cycle GHG emissions from buildings, accurately estimating annual energy consumption is critical when comparing the environmental benefit of refurbishing vs. new construction. We, therefore, used a revised set of user profile data that better reflects likely energy use behaviour of residents in historic buildings. The results showed that user behaviour has a critical effect on the outcome and reliability of energy modelling which, as stressed by Yu et al.[36] and Delghust et al.,[37] has implications for expected energy and emission savings and underlines the importance of equivalency of case and reference study data.

A new low- or passive energy building will, under the condition that it outlives the historic building, inevitably recoup its environmental investment costs and overtake the historic building in environmental performance due to its lower operational emissions. This is perhaps, except for an increasing demand of domestic floor space, the strongest argument for constructing new buildings and, from a theoretical point-of-view, a disadvantage for the comparative case of Villa Dammen. Yet the argument only holds provided that the new building is maintained and used in accordance with its original design and purpose. It will, in addition, depend on the rather uncertain expected technical lifetime and maintenance intervals of a (new) building.

It is important to point out that, while the LCA of a building concentrates on its environmental impact and provides an opportunity to identify the building phase or modelled scenario with the largest impact,[38] it does not take into account sustainability in a broader sense.[39] When a building has a proven lifetime exceeding by far the standard LCA practice of 60 years, it surely represents more than an environmental investment. Indeed, other aspects of sustainability, such as social and cultural values, can be problematic to analyse on similar premises due to the lack of agreement on how to estimate their values,[40] although there are examples of models with sets of sustainability indicators, such as those adopted in Building Research Establishment Environmental Assessment

Method and Leadership in Energy and Environmental Design. There are indicators in these models that refer to reuse existing materials,[41] but it is with the purpose of reducing waste and emissions from materials production – not for assessing heritage values. Including simultaneous assessments of energy savings, economic aspects, heritage values and building physics in the decision-making process for any single building is, however, a relatively comprehensive undertaking. The complexity of carrying out such assessments can be reduced by the development of new multi-criteria toolkits and decision guides. A supplemental and perhaps more proactive approach would be to improve datasets for structures and material emissions in existing toolkits, e.g. the Norwegian energy performance certificate system, in order better to pass on information about environmentally acceptable measures and materials.

The theoretical implications of the results suggest that the current policy system for energy refurbishment might not be appropriately aligned with climate change mitigation goals. TEK10, for instance, has disadvantages with its focus on technical performance measured in kWh and *U*-values, although it has shown remarkable sophistication with its exception for log building constructions. This further suggests an untapped potential in tailoring flexible (or at least more dynamic) subsidy systems with respect to supporting both optimal environmental consequences and materials compatible with the cultural heritage values' historic buildings.

Conclusion

The main knowledge brought forward by this paper is that emissions related to the use of construction materials in an energy-efficiency process is not only important but can, in fact, be decisive when it comes to the net climate benefits of upgrading a historic building. We can also see that users and residents play a critical part with respect to realising the expected energy savings related to upgrading and that modelling user behaviour in LCAs is demanding.

More importantly, we see that a careful energy-efficiency refurbishment of Villa Dammen is favourable from a climate change mitigation perspective and that it takes more than 50 years for an equivalent new building to recoup its environmental investment. Our study thus also confirms what previous studies also have indicated, that the refurbishment of historic buildings can make them perform on par, or even better, with respect to reducing GHG emissions compared to constructing new buildings. This indicates that the continued use of historic buildings should be better advocated for in building codes and environmental policies and that the notion of building conservation has a research role in translating climate change policy into strategic options for decisions makers.

Certainly, the increasingly improving energy performance of new buildings is an essential part of reducing total GHG emissions. While the historic segment of the building stock might not be a large contributor to GHG emissions, compared with other sectors, it is more vulnerable to hastened decisions and should, therefore, be handled with care.

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Notes

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