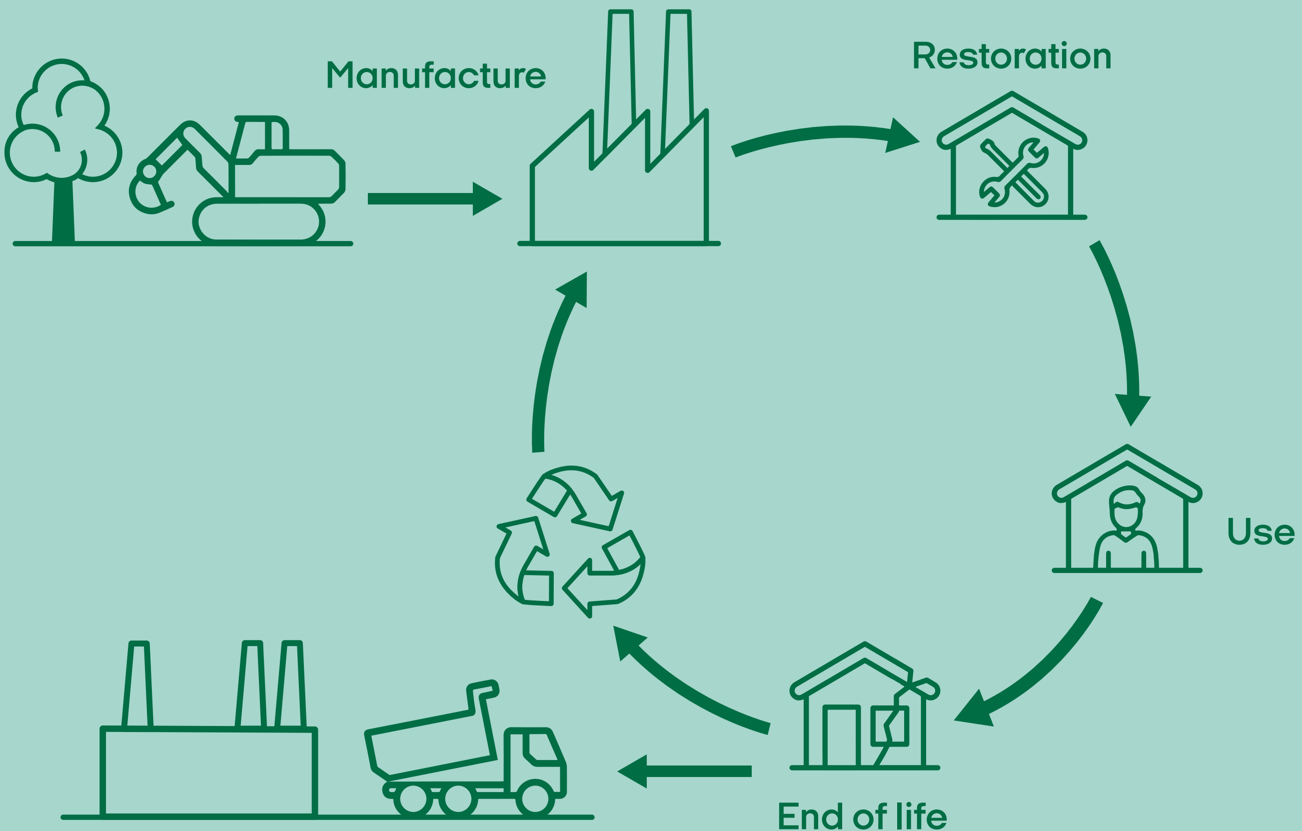
# Life cycle assessment for historic buildings

– Realdania By & Byg's experience with LCA in restorations and transformations




Realdania | Realdania By & Byg

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# Contents



# Preface

Restoring a historic building is a balancing act under which preservation values, aesthetics, present use, finances, the climate and the environment have to be weighed against each other.

As part of its action plan for corporate social responsibility for 2019-2021, Realdania By & Byg launched a number of initiatives, of which several have aimed at exploring ways to reduce the carbon footprint of work on the company's portfolio of historic properties.

The experience gained from implementing retrospective life cycle assessments (LCA) in restoration and transformation projects is the subject of this publication. As the use of life cycle assessments in the construction sector and research has hitherto primarily focused on new building, this work started with a close collaboration with the Department of the Built Environment (BUILD) at Aalborg University to develop an appropriate method that suited a portfolio of historic properties, and that could inspire other owners who share the ambition to help reduce carbon emissions.

The mission and primary objective of Realdania By & Byg are still to secure the preservation values in the properties, but in future with the smallest possible carbon footprint as well.

Over the past almost 20 years, Realdania By & Byg has acquired and restored or transformed around 60 historic buildings, and most recently completed LCAs of the majority of these projects on the basis of data from the company's own files and from the environmental product declarations.

This publication focusses on how LCA is used to analyse the climate footprint of restoration and transformation projects run by Realdania By & Byg, and how learning from this work can be included in new projects.

There is also a presentation of eight historic properties and their preservation values, how they have been restored for modern use and, in some cases, how they have been transformed to entirely new functions. Taking outset in specific LCAs, focus is on some of the elements emerging from carbon-footprint data that owners should consider.

An overall conclusion is that it is more climate-friendly to restore or transform an older building than to construct a new building, and with increasingly carbon-neutral energy supplies, it will also be difficult for an energy-efficient new build to recoup this difference through lower energy consumption during the use phase.

However, even though restoration is generally climate-friendly, it is still worth using LCA to cast a critical eye at individual choices in restoration projects.

**Realdania By & Byg**
**June 2022**

INTERVIEW


**"If you can extend the life of a building component just through good craftsmanship, you can make a big difference from the overall climate perspective."**

# LCA is now integrated in the working methods of restoration

**INTERVIEW**
with Anne Mette Rahbæk, head of development at Realdania By & Byg

**Realdania By & Byg's work on retrospective life cycle assessment (LCA) of historic buildings means that, in future, contractors and consultants will face specific requirements from Realdania By & Byg. Furthermore, LCA will be a fixed part of the restoration practice.**

LCA is now a permanent element when Realdania By & Byg restores historic buildings. The decision follows in the wake of retrospective LCAs of up to 50 historic buildings that clearly document the climate benefits of restoring buildings instead of building new.

LCA work on the existing properties has helped shed light on a previously somewhat murky area in terms of data.

"The use of LCAs and other methods of analysis currently included in most certification schemes in the construction sector has been highly focused on projects for new buildings," says Anne Mette Rahbæk, head of development at Realdania By & Byg.

"If a building owner wants to be climate-friendly with regard to existing building stock, until recently there hasn't been much data on what it's best to do in terms of the carbon footprint. As our portfolio of historic properties is so varied, with buildings from different periods and with different combinations of materials, we thought it would be interesting and appropriate to generate data on the carbon footprint of different types of restoration and transformation," the head of development explains.

**Assessments reveal carbon-intensive initiatives**

The properties in the Realdania By & Byg portfolio have all undergone restoration and, in some cases, transformation into new functions. They include Poul Henningsen's family home, Hindsgavl Castle, Odense Secular Convent for Noblewomen and Arne Jacobsen's private holiday cottage.

Realdania By & Byg has run restoration and transformation projects since the founding of the company in 2003. In transformation projects, the use of the building is changed, while a restoration project retains the original function. In both cases, the building is brought up to good condition.

The LCAs were carried out following a process with strong focus on learning from the results of the assessments across the organisation. In order to integrate the results in the working methods of restoration, this was supported by internal workshops. Staff could share knowledge and experience during the LCAs and discuss the carbon footprint of the individual buildings. LCA work is an extension

of Realdania By & Byg's strategy for sustainability and corporate responsibility action plan. It will also affect Realdania By & Byg's future restoration and transformation projects in several ways.

"It is now possible to identify the carbon-intensive building components from our preliminary analyses. The floor and roof usually stand out. This means that if you are considering breaking up the concrete floor slab as part of the restoration of a building, the retrospective assessments shows that this would be very carbon-intensive, and therefore it may be better from a climate perspective to repair the existing floor if possible," says Anne Mette Rahbæk.

**New expectations of the construction sector**
run should be considered very carefully in future work. This is important from a wider perspective, in which the carbon footprint of a building material should always be assessed against its lifetime in relation to the 50-year reference period in an LCA.

"If the lifespan of piping is lower than the flooring slab in which it is cast, is it then a good solution? This also applies for cable conduits," says Anne Mette Rahbæk. She points out that, like many other sectors, the construction sector is in a period of transition, driven forward by the global focus on climate change.

Realdania By & Byg now asks that consultants and contractors submit documentation for the carbon footprint of the building materials they use and of the quantities they use during construction.

"We expect the construction sector and contractors to relatively quickly fall in with procedures to manage and supply information, as environmental product declarations on building materials (EPD) from material manufacturers become more widespread. As well as contractors have become very clear about the volumes of materials in their tenders," says Anne Mette Rahbæk.

**Wastage and sloppiness cost money and $CO_2$**
The clear indications of volumes and quantities of materials from contractors contribute in themselves to reducing wastage on construction sites - both when materials such as plasterboards are left over, and when wastage is caused by sloppiness, which is yet another point that been highlighted in the retrospective lifecycle assessment.

The data from the lifecycle assessments of the many historic buildings will be used in future restorations, for example of the architect Poul Erik Thyrring's private home in Herning (previous pages), Gelsted Station (left) and Ejner Ørnsholt's private home in Nakskov (below).

"$CO_2$ calculations suddenly make it very clear just how expensive sloppiness is in terms of $CO_2$. One thing is that it costs money, but there's also a sort of double bottom line that seriously impacts the $CO_2$ accounts. This underlines the importance of good craftsmanship, and it also applies for maintenance. If you can extend the life of a building component just through good craftsmanship, you can make a big difference from the overall climate perspective," says Anne Mette Rahbæk.

Overall, construction is a significant element in the global $CO_2$ accounts. According to the World Green Building Council, 39% of climate impacts come from construction. This also applies in Denmark, where 10% of carbon emissions originate from the construction process, while 20% come from energy consumption in buildings. Data on ongoing maintenance of the properties will soon be part of LCA calculations by Realdania By & Byg, together with carbon emissions from heating, which over time will provide a more complete picture of the carbon emissions from the portfolio of historic buildings.

Therefore, in future Realdania By & Byg will also focus on operation and energy management.

"It's necessary to focus on embedded carbon in buildings, but it's also crucial to consider energy-efficiency improvements in historic buildings. In this context, we've gathered experience across our portfolio, and in future we'll follow up more on which solutions work best, and whether they do so in all aspects. The energy reports will enable us to act if a building exceeds the expected energy consumption," says Anne Mette Rahbæk.

INTERVIEW

**“There was an awareness of the resources in the old building processes that we can take with us moving forward."**

# Historic buildings required adaptation of methods

**INTERVIEW**
with Freja Nygaard Rasmussen, post.doc, BUILD, Aalborg University

**An adapted approach to LCAs with a few well-considered adjustments of the scientific LCA method was the key to calculating the carbon footprint from restorations and transformations of the historic buildings in the Realdania By & Byg portfolio.**

How do you distinguish between an LCA for restoration of a building and an LCA for a new building? What can you exclude and which reservations are required when trying to calculate the carbon footprint of restoring or transforming existing buildings compared with new building from scratch?

These were some of the questions Freja Nygaard Rasmussen, a post.doc at BUILD at Aalborg University wanted answered in order to establish the methodology and model behind LCAs for the historic buildings in the Realdania By & Byg portfolio.

"A restoration is a special case, because you are bound by various overall architectural factors that simply cannot be changed. Therefore, part of the work has involved mapping the different restoration initiatives that have been taken after the purchase of the properties, and their significance compared with typical climate impacts from new construction," says Freja Nygaard Rasmussen.

The 60 properties represent a historical range of about 500 years, with corresponding differences in their architecture and construction techniques. Many of the properties are listed. Freja Nygaard Rasmussen completed her work in 2019-20, and she took her outset in four specific cases from the portfolio of historic buildings. Her work formed the basis for the LCAs that Realdania By & Byg has subsequently carried out for the majority of the properties. The LCAs have confirmed that, to a large extent, existing buildings can be restored and transformed before the carbon footprint reaches the same level as a new building.

During LCA work by Realdania By & Byg, each property was thoroughly analysed for the quantity and type of materials used in the restoration or transformation of the property. After this, the carbon footprint was calculated using the LCAbyg program, which contains environmental data on a large number of different building materials.

**Adapting LCAs**

LCAbyg was developed by the Department of the Built Environment at Aalborg University, and the program includes all phases of a building's life cycle in its calculations. These include extraction, transport and production of building materials and onwards to con-

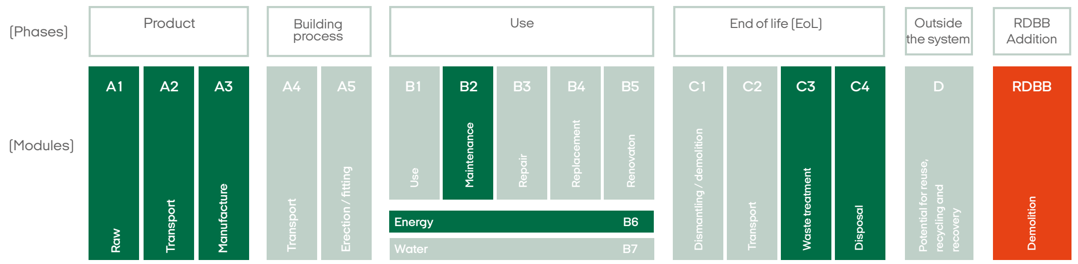



Figure 1: Realdania By & Byg's LCA model includes the dark green and red modules, shown here on the basis of the general LCA model. B2 "Maintenance" was chosen instead of B4 "Replacement", which is used for new building, and red module "Demolition" [of old materials] is Realdania By & Byg's own addition to the model. The modules under the "Use" phase have been included in the LCAs from the start as they require data collection on an annual basis, but they will be incorporated regularly in the future.

struction of the building itself, to the operation phase, to disposal and possible reuse or recycling of materials. In general, the format follows the LCA method in the DGNB certification system [Deutsche Gesellschaft für Nachhaltiges Bauen], which is often used in the Danish construction sector. The method has many similarities with the method in the climate requirements in the Danish building regulations applicable from 2023.

**"It quickly became clear that restoration and maintenance are more cost-intensive in terms of labour hours than in terms of the climate."**

"The DGNB method has been the most commonly used by the construction sector in Danish practice. It's a good compromise between what is practicable in an LCA, and a more comprehensive version of an LCA that follows the standards to the letter," says Freja Nygaard Rasmussen.

There have been several adjustments to the content of some of the modules in the phases that are usually standard in an LCA. This is partly to ensure that they suit LCAs of restorations and transformations instead of new building, and also to reflect the fact that Realdania By & Byg will be owning, maintaining and operating the buildings in the future. For example, there is an adjustment in the use phase such that module B4 "Replacement" is replaced with B2 "Maintenance".

This choice was made because Realdania By & Byg will continue to own the building in the future and therefore can monitor what happens with it. The company itself is responsible for the facades and other maintenance and therefore can be certain that this will actually be done. If buildings are properly maintained, they can last for much longer and for this reason, the two modules were exchanged.

**Challenges with niche products**

Consideration for the original architecture and building style of the historic buildings has meant that many of the restoration measures focusing on the energy efficiency of the building have aimed at less visible features such as insulating attics or basement floors. It has also been considered whether it is best to replace a window or instead preserve an old hardwood window and fit new secondary glazing.

As several restoration measures on the buildings are unique, much of the exercise has involved accepting that it is not always possible to obtain precise sector data on the carbon footprint of them all.

"There are figures for many common industrial products such as mineral wool, concrete, bricks, etc., but it is difficult to find data at component level for many niche products. This applies for very close copies of windows in very old buildings, for example, as not many of these will be produced in large numbers," says Freja Nygaard Rasmussen.

Freja Nygaard Rasmussen completed the first four LCAs for Realdania By & Byg, including Bakkekammen 40 in Holbæk [top] and the Harboe Widow's Convent in Copenhagen [below].

The first LCAs produced by BUILD included the Harboe Widow's Convent, Erik Christian Sørensen's private residence in Gentofte and Meldahl's Town Hall in Fredericia.

**Demolition added to the $CO_2$ bill**

The LCA model phase "Outside the system" has the module for the potentials for reusing building components after their end-of-life, which, although it can be calculated and reported, it cannot be included in the final LCA. This is because there is a risk of double counting if a future contractor also includes the benefits of reuse, and because, by its very nature, you cannot be certain of obtaining a potential $CO_2$ saving in the future. Another module reported separately is demolition of older building components during restoration or transformation of the building. The module is an addition by Realdania By & Byg to adapt the LCAs to the historic buildings. The specific changes to the standard LCA are shown in Figure 1 (page 14).

Demolition of all the materials removed as a consequence of a restoration has a double role in the $CO_2$ accounts.

For example, wood that is disposed of and incinerated during a restoration will emit $CO_2$ to the atmosphere, and the current owner is responsible for this.

"In reality, the $CO_2$ emissions associated with disposal are linked to the previous owner, but it ends as a question of the division of responsibilities. You could consider whether it is reasonable that the current owner is penalised for both carbon emissions from what is being disposed of and for future disposal of the new components being fitted. But on the other hand it's a genuine decision made by the current owner and therefore the current owner should take full responsibility," says Freja Nygaard Rasmussen.

**Original building process excluded**

The carbon footprint of this "double demolition" is included In LCAs by Realdania By & Byg to help emphasise that, even with the extra costs in the $CO_2$ accounts, restoration and transformation can be better for the climate than new construction. However, the LCAs also show that the climate benefits largely depend on how the building is heated.

In order to complete LCAs of the historic buildings, the actual construction of the buildings is excluded from the model, as obtaining valid data on a construction process that in some cases took place several hundred years ago is a cumbersome process. This is a conscious decision, rather than trying to include estimates of the original owner's emissions during construction of the building.

"You could argue that it's possible to make assumptions about the carbon emissions from construction in order to gain the full picture of a building's carbon footprint. But how can information on emissions hundreds of years ago help our decisions today? That's why we decided to focus on the measures in the restoration itself, in order to learn from other similar projects," says Freja Nygaard Rasmussen.

**Energy management included in plans**

Even though the work began by mapping the carbon footprint of different restoration measures, over time focus has shifted to include the energy use of the buildings.

"It quickly became clear that restoration and maintenance are more cost-intensive in terms of labour hours than in terms of the climate. On the other hand, energy use means a lot for the carbon footprint of the buildings. It was obvious that more focus should be on energy management as part of the future maintenance plans, and that energy use should be monitored closely to find out where to take action to reduce the carbon footprint from the heat supply system without compromising comfort or the architectural expression," says Freja Nygaard Rasmussen.



The review of the buildings has given the researcher insight into earlier building practices, and in some ways, these can inspire owners and contractors of today.

"Today, labour is the costly item, not materials. In the past, the opposite applied, and this can be seen in the different building designs that were conceived to protect the vulnerable parts of buildings so that they lasted for many years, provided they were well-maintained. This is a huge difference compared with the present day, where focus is on minimal maintenance, and where buildings are not generally designed for materials and elements to be reused directly in a subsequent building. This was an awareness of the resources in old building processes that we can usefully take with us in the future."

INTERVIEW

"A new brick emits about 56-times more $CO_2$ than it costs to clean an old brick and reuse it."

# LCA emphasises the climate benefits of restoration

**INTERVIEW**
With Troels Frey Andersen, project manager at Realdania By & Byg

**Life cycle assessments of restorations and transformations of Realdania By & Byg's portfolio of historic buildings have demanded a good deal of detective work in interviews and by delving into the archives. The results confirm that it is climate-smart to preserve as much as possible instead of building new.**

So many bricks in this old manor house. So much paint in that architect-designed house.

Scrutinising the archives was the first time-consuming task for project manager at Realdania By & Byg, Troels Frey Andersen, when he began work on LCAs of around 60 historic buildings in the Realdania By & Byg portfolio.

The objective was to map the carbon emissions arising as a consequence of each restoration or transformation project. Work on the LCAs began in September 2020, initially focusing on the actual restoration, but later also on maintenance and ongoing heating of the buildings.

"I had a list of around 60 buildings, the majority of which had been restored; some more than 15 years ago. Therefore, the first step was to look through our tender lists, descriptions of processes and drawings to identify the quantities of materials used in a building component, for example one cubic metre of insulation and square metre roofing felt. This helped me form an overview of all the materials added to the building. That was the most time-consuming part of the LCA," says Troels Frey Andersen.

LCAs of buildings usually have five phases: extraction of mineral resources and manufacture of building materials; the construction phase; the use of the building; end-of-life; and finally a phase considering factors outside the system. There have been a few adjustments to the content of some of the modules in the phases in order to suit life cycle assessments of restorations and transformations instead of new building, and also to reflect the fact that Realdania By & Byg will own, maintain and operate the buildings in the future. However, apart from the adjustments, Troels Frey Andersen has used the same approach as for a standard LCA.

The carbon footprint of a building material such as a brick is listed in an Environmental Product Declaration (EPD). Finding the correct EPDs was yet another part of the time-consuming preliminary detective work. EPDs are found in varying levels of detail, and this can give rise to a little uncertainty in the LCAs. We will get back to this.

**Uncertain quantities of materials**

If you have the EPD for a specific building material, e.g. insulation, and you know the quantity used during the restoration or transformation, in principle it is simple to find the total carbon footprint of the material. However, up to 50 properties have been restored and transformed since 2003, and in practice, Troels Frey Andersen had to be critical of the information from the archives to take into account uncertainties.

"Some changes may have been carried out that have not been documented, e.g. a different type of insulation may have been used. I have had to interview all the project managers on the individual restoration projects to find out whether anything was done that was not recorded. For this reason, there may be uncertainties regarding the materials and the quantities for individual buildings, although overall they should even out across the whole portfolio," says Troels Frey Andersen.

As mentioned, another uncertainty is with regard to the EPDs, as these can be product-specific, sector-specific or generic. Product-specific EPDs contain the most accurate information about the carbon footprint of a product or material and they are prepared by the manufacturer of a specific product, e.g. tiles.

Sector-specific EPDs are less precise, but still represent a relatively accurate carbon footprint because a part of the building sector have agreed on them jointly on the basis of an average. Finally, there are generic EPDs, which are the least accurate, although they may sometimes be all that is available for a product or material.

**Environmental product declarations are getting better**

If Troels Frey Andersen was unable to track down Danish product-specific or sector-specific EPDs, he resorted to the German Ökobaudat database, which includes generic EPDs based on data from Germany. This type is sometimes the best alternative possible.

"Producing EPDs entails costs for manufacturers, and therefore often only the bigger players on the market have them for their products. However, a lot has happened since I started on the LCAs, and more players are joining. This means that the construction sector has moved ahead, because it is one of the few sectors with $CO_2$ labelled products," says Troels Frey Andersen.

LCAs are performed using the program LCAbyg, and this makes it possible to develop and calculate the different scenarios - e.g. the carbon footprint of using used bricks instead of new bricks. The calculations focus exclusively on global warming potential stated in $CO_2$ equivalents. Environmental impacts such as degradation of the ozone layer are not taken into account.

**Climate-friendly reused bricks are expensive**

The LCAs consider the $CO_2$ accounts for a building over a period of 50 years. This may initially be a little surprising, as Troels Frey Andersen explains.

"It may seem a little misleading, because we all know that buildings aren't usually torn down after 50 years, and in some cases they can remain standing for several hundred years. However, you have to make the cut-off somewhere, and setting a period of 50 years signals that it's about getting people to reduce $CO_2$ levels now," says Troels Frey Andersen.

"This isn't surprising in itself. However, what's new now is that it's been put into figures so we can see the difference. This confirms that it's common sense to preserve as much as possible in a building."

One specific experience from LCAs is that, even though there are huge benefits in terms of the climate, reusing bricks instead of building with new may be hard to justify in terms of budgets.

"A new brick emits about 56-times more $CO_2$ than it costs to clean an old brick and reuse it. So why don't we do it more often? Partly because it's much more expensive than buying new bricks, and partly because it requires the use of lime mortar instead of cement, because the latter cannot be cleaned off without ruining the stone. However, if it is possible, there's a big saving in the $CO_2$ accounts," says Troels Frey Andersen.

**Large climate penalty with new buildings**

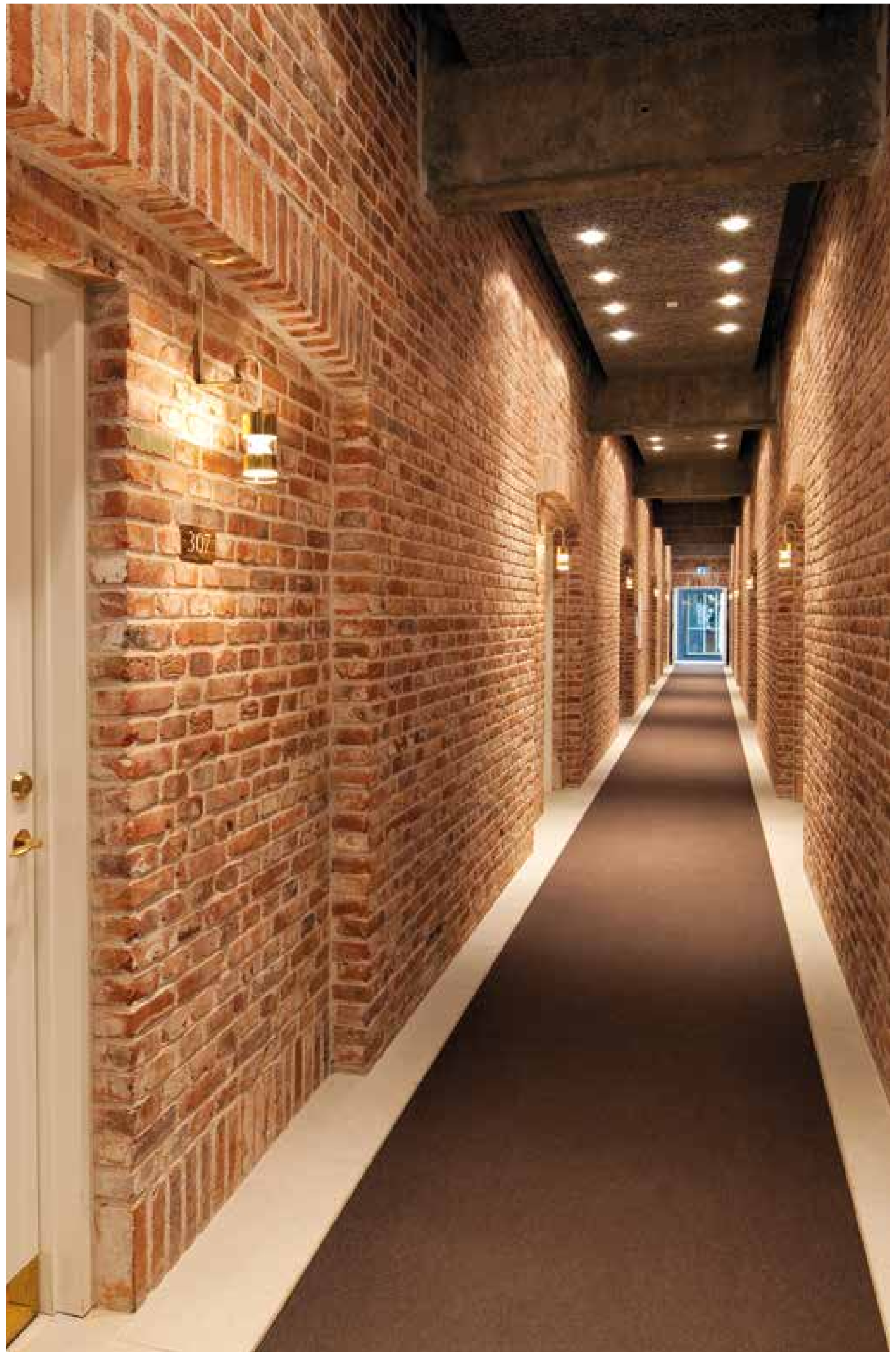
Overall, the LCAs are very clear with regard to the comparison between restoration and transformation.

"Transformations generally emit more $CO_2$ than restorations because more work needs to be done. For example, this applies for the old stables at Hindsgavl Castle, which have been restored and transformed into a hotel wing. This costs a lot in terms of $CO_2$ because we have changed the use of the stables so drastically," says Troels Frey Andersen.

The result shows a distinct line between restorations, transformations and new buildings. Whereas a transformation emits an average of almost twice as much $CO_2$ per square metre as a restoration, the carbon footprint of a new building is on average almost four-times higher.

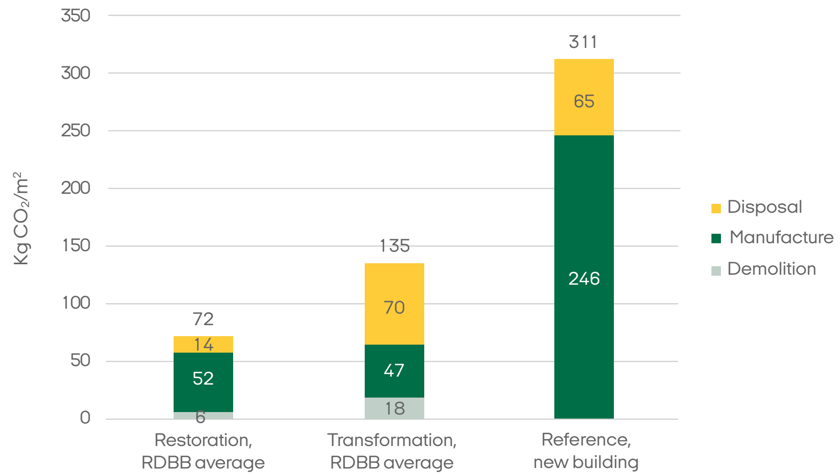
"This isn't surprising in itself. However, what's new now is that it's been put into figures so we can see the difference. This confirms that it's common sense to preserve as much as possible in a building," says Troels Frey Andersen.

Reused bricks in the “Kostalden” hotel wing, which has been transformed from its previous agricultural function at Hindsgavl Castle.





The diagram shows average $CO_2$ emissions from materials for restoration, transformation and new building, respectively.




**Environmental product declarations**
An Environmental Product Declaration [EPD] is a type of LCA for a single building material, and it includes $CO_2$ emissions from production and transport of the material, for example. Valid EPDs are verified in accordance with the international standards EN15804 and ISO14025.
Read more at www.epddanmark.dk.

# Restorations

Restoring a preservation-worthy building, and making it suitable as a framework for present-day use is a balancing act, whereby the climate and the environment have to be weighed against other considerations such as preservation, aesthetics, interaction with surroundings, function, comfort and finances. In this context, LCAs can sharpen focus on the climate dimension by clarifying the total carbon emissions linked to the restoration, with the specific individual choices and with the alternatives.

The following pages present some of Realdania By & Byg's historic buildings, their restoration, and some of the experience and considerations arising from the recently completed LCAs.

CASE 1

## The Roman House:
# Restoration of Utzon's patio home in Elsinore

**Restoration of Jørn Utzon's Roman House included recreating the experience of a coherent spatial passage with uniform floor covering. New insulation was also laid, and this led to considerations about the climate impact of the insulation material; both the material itself and how it will affect heating consumption in the long term.**

The Roman House on Baggesensvej in Elsinore is part of a site of 60 patio homes designed by the world-famous Danish architect, Jørn Utzon, and built between 1957 and 1961. The houses became known colloquially as the Roman Houses, as their design is reminiscent of an ancient Roman atrium house, and they are a good example of the experimental building that inspired many of the houses built for Danish families in the 1960s and 1970s.

Through the Roman Houses, Utzon created a Nordic patio house that broke with the usual conception of the family home as a detached house on its own site. The houses were built in a continuous row, but staggered, so that a Roman House seems more like a detached house than a terrace.

Realdania By & Byg purchased the house in 2011 to secure and preserve it as an important example of the distinctive style that characterised post-war Denmark, and to restore it to preserve the original qualities of the building for posterity.

### Continuous floor slabs

The restoration focused in particular on restoring the Roman House's original spaciousness, because a number of interruptions built into the house later had impaired the experience of the house. Not least the arrival at the house, and thus the first impression was disturbed by the flooring, which was a mottled mosaic of different materials such as linoleum, vinyl, cork, parquet, concrete and yellow-brown tiles.

The individual restoration initiatives aimed at streamlining the expression of the inside surfaces, striving for extremely simple and repeated solutions. In order to take the Roman House back to Utzon's original design, the very diverse floor surfaces were replaced by coherent flooring that underscores the original spatial passage of the house.

The flooring in all rooms except the shower and utility room is linoleum like the original floor covering. Extensive work on the structure of the floor was required before the new floor surfacing could be laid.

The Roman Houses were one of the first housing developments in Denmark built with underfloor heating using copper pipes embedded in the concrete floor. The copper pipes run in an unbroken line straight through all the rooms so, in principle, they all have the same temperature. However, when Realdania By & Byg took over the house, after it had been empty for five years, it turned out that there were rooms that could not be heated, indicating that some copper pipes had eroded and were leaking. Therefore, there was not really any choice, and because it was also necessary to underpin some outer walls, dividing walls and the concrete floor, it made sense to break up all the floors.

**Small differences in insulation materials**
Replacement of the floor of the house and under-floor insulation, with improvements to underfloor heating and electric installations, were the most carbon-intensive parts of the restoration of the Roman House.

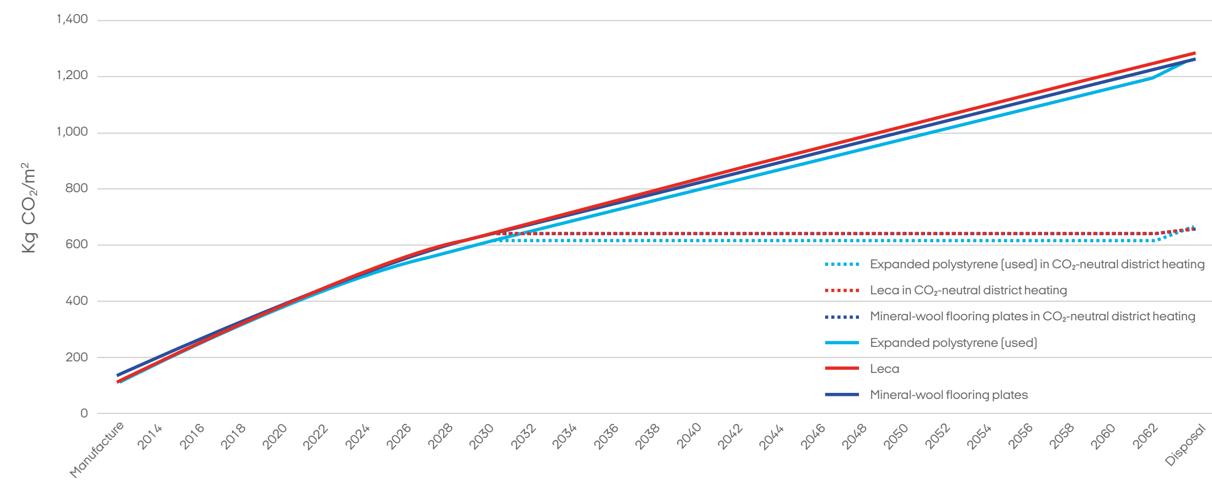
Concrete for the floor cost 29.3 kg $CO_2$ per m², while the polystyrene insulation (EPS) cost 64.5 kg $CO_2$ per m², corresponding to more than one-half of the total carbon footprint of the restoration. Polystyrene is less carbon-intensive in production, but more carbon-intensive at end of life than Leca and mineral wool, but the material is well tried and tested and it also protects against damp. In the long term, in the operating phase, the different methods of insulation are closer to each other, because polystyrene also insulates the most effectively.

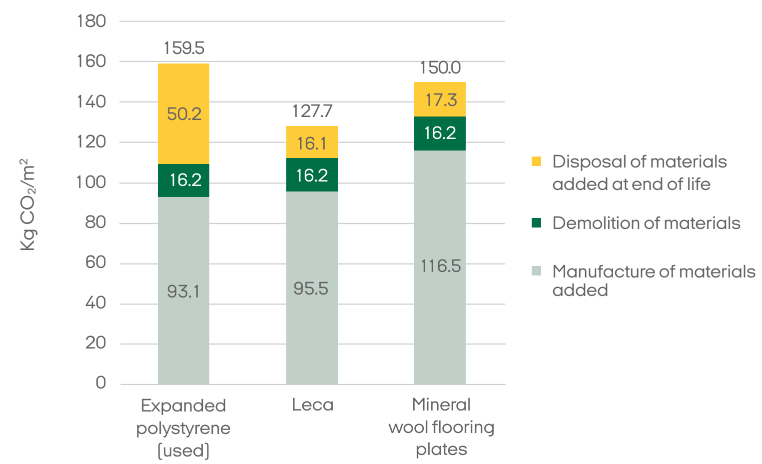
However, the differences are marginal, and if, in the future, it is possible to find a carbon-friendly way to dispose of the material, polystyrene may turn out to be the best choice.

The restoration of the Roman House by Realdania By & Byg included re-establishment of a hallway and garage, which had been converted to a spare room, restoration of the patio garden to its original appearance, replacement of all electrical installations, removal of unoriginal fittings, and modernisation of the bathroom with white surfaces to suit the rest of the house. The original kitchen fittings have been preserved and restored.



← Before and after: A key factor in the restoration of the Roman House was to restore the experience of one large, coherent floor surface that emphasises the overall spatial passage of the house.




↑ Bottom: Carbon emissions per square metre of the total restoration of the Roman House and future disposal using different insulation materials in the flooring, broken down by phases. Polystyrene is "best" in the manufacture phase but loses in the long term with disposal, particularly if ongoing heating of the house is not included.

↑ Top: Carbon footprint of the restoration of the Roman House and many years of operation with the different insulation alternatives: Expanded polystyrene is the best choice until the day it has to be disposed of. Mineral wool is then slightly better. The dotted line shows the change with possible carbon-neutral district heating from 2030. After 50 years, the solution with polystyrene has emitted approx. 1 tonne of $CO_2$ more than mineral wool.

CASE 2

State-guaranteed smallholding in Skovbølling:

# Modest and beautiful time warp

**State-guaranteed smallholdings offered an opportunity to forge a better life between the wars for people in Denmark of modest means, and the property at Haderslev is a very well-preserved example. The two different roofs on the house were the most carbon-intensive part of the restoration; one material was more so than the other.**

In Skovbølling, north of the town of Haderslev, stands a well-preserved smallholding where time stands still. Very few changes have been made over the years, and the smallholding, which was built in 1934, appears in the original style, without the modernisation that otherwise often impedes preservation of this type of building. The original owner, Christian Mink, lived in the house right up until Realdania By & Byg acquired the property in 2010.

Realdania By & Byg purchased the listed smallholding because it is a typical example of the type of smallholding built with state aid in the interwar period. The idea was that the state would provide financial help and architectural expertise to help people in rural areas of modest means to enable them to make a better life for themselves, with their own home, and living off their own plot of land.

**Better Building Practices and Danish identity**

The design and the materials used are characteristic for this type of smallholding and for the time when they were built. It was built in the Better Building Practices style, which aimed at improving and developing general Danish building culture. In southern Jutland, the Better Building Practices style was also a way of introducing a local Danish style, thereby underscoring independence from Germany after the reunification with Denmark in 1920.

Realdania By & Byg restored the property from 2011 to 2012, with focus on demonstrating how it is possible to balance preservation and modern requirements for comfort to secure the house and cultural heritage for posterity.

Work included renovation of the farmhouse, rebuilding the linking building, fitting new electricity, water and heating installations, and establishing geothermal and bio wastewater treatment solutions. The garden was also restored as an example of a Danish peasant garden with ornamental, vegetable and fruit gardens.

**Roof restoration was the most demanding**

Restoration of the roof was the most carbon-intensive part of the project at about 26.7 kg $CO_2$ per m², out of a total 87.4 kg $CO_2$ per m² for the whole restoration. Next came the floor slab at about 17.5 kg $CO_2$ per m².

The roof of the farmhouse was finished with new cement wing tiles with the same profile as the original. The original plan was to reuse the old tiles as far as possible and purchase recycled tiles if necessary, but during demolition it became apparent that the tiles were not suitable to be cleaned and relayed. Had it been possible, relaying the roof with only recycled tiles would have saved almost 4.2 kg $CO_2$ per $m^2$.

An old cement foundry nearby that still had the old moulds was tasked to produce new tiles for the roof. They were formed and coloured with red dye so that they resembled the original red tiles.

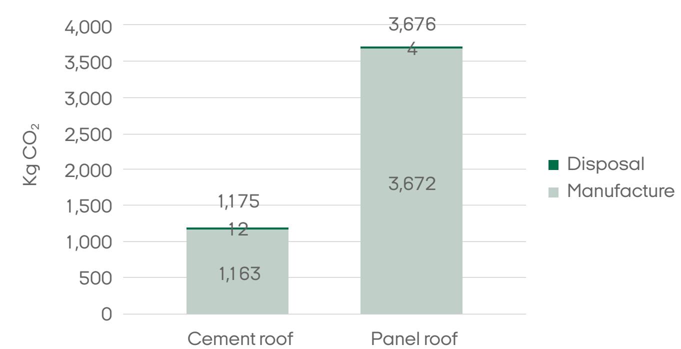
The roof was fitted with roof boarding with roofing felt on beams, and the boarding was laid on the old rafters, which were in good condition, so there was no need to repair or replace these. The roof was insulated with mineral wool to meet modern comfort requirements.

The sheet-metal roof on the linking building and the breeding barn also required renovation, and new panels were laid on the renovated roofing.

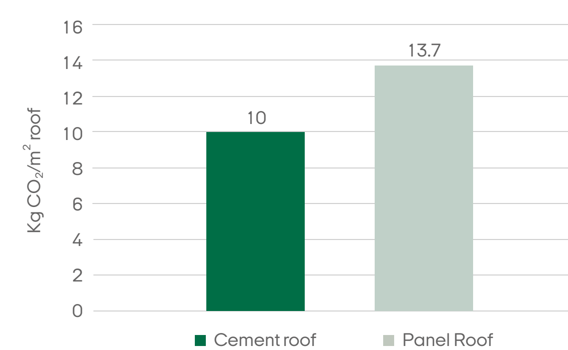
**Roof panels emit most**

The restoration of the roof of the smallholding entailed examining the climate impact of different types of roof. The panels are 37% more $CO_2$-intensive for a given area than cement roof tiles, and in both cases the actual manufacture of materials costs by far the most in the climate accounts compared with subsequent disposal of the materials.

Because of the need to preserve a unique example of building heritage, the new roofs on the buildings corresponded to the original. However, if it had been possible to choose between different materials with priority for the climate, it is worth noting that there can be large differences in the carbon footprint of the materials.




↑ $CO_2$ emissions for the 118-square-metre tile roof on the farmhouse and 268-square-metre panel roof on the other buildings. Only the two materials are included here, and not the underlying roof structure with the rafters, roofing felt, etc.




↑ The difference in $CO_2$ impact for the two types of roofing per square metre of roof.

CASE 3

## Poul Henningsen's Family Home:

# Super insulating material enables preservation

**The restoration of Poul Henningsen's family home in Gentofte involved examining how to heat the house within a normal budget without destroying the preservation values of the house. One possible solution was a material called aerogel, which is $CO_2$-intensive in manufacture, but which only requires a thin layer to insulate effectively.**

Poul Henningsen's family home in Gentofte, north of Copenhagen, was built in 1937 as a rebellion against the norms of the day in terms of architecture, layout and materials.

The well-known Danish architect, light maker, scriptwriter and provocateur designed his house to use pre-fabricated concrete building blocks with iron doors and windows painted with red lead paint. The house was built on a steeply sloping site, and eleven levels inside are joined by short open stairways that stood in sharp contrast to the traditional homes of the day, which were clearly divided into separate rooms and functions. Even though the building still seems unconventional today, it was a precursor of what was to become the Danes' favourite family home.

When Realdania By & Byg acquired the house for restoration and preservation in 2014, not least the insulation demanded radical attention so that the house could be lived in by a family on an average budget. The challenge was to do this with due regard for the preservation values of the house. The solution was untraditional insulation in combination with secondary glazing and a more modern heating installation.

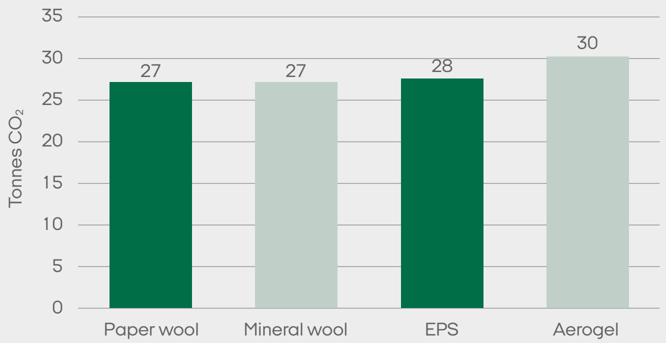
### Aerogel

The outer walls of Poul Henningsen's house were only insulated with two-centimetre cork, and with the iron-framed windows and their single glazing, this meant that it was hard to keep the heat inside and there were cold bridges and draughts. However, replacing the thin cork with a suitable thickness of mineral wool would impair the interior proportions of the house.

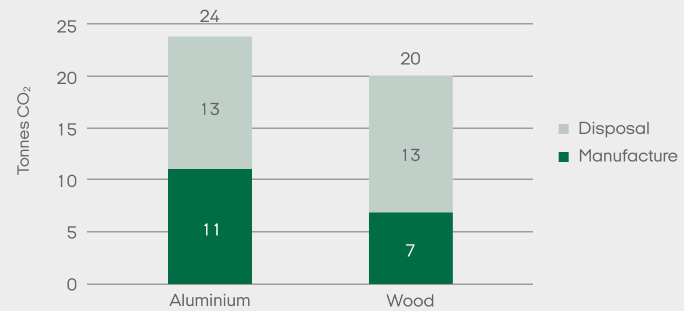
The solution to this dilemma was a special, super-insulating material called aerogel, which is also used in the space industry. Two layers of aerogel measure 2 cm; the same thickness as the cork in Poul Henningsen's house, and as a 2 cm layer of aerogel insulates just as well as 15 cm of mineral wool, it was possible to insulate the house without disturbing the architecture.

Not only is aerogel significantly more expensive than other insulation materials, it also emits considerably more $CO_2$: in fact about 30-times as much as mineral wool. On the other hand, it requires much less energy to later heat the house because of the good insulation properties, and for this reason things quickly turn around given the requirement that, irrespective of the material, the insulation had to have a specific thickness to maintain the preservation values of the building. This meant that the choice of aerogel in Poul Henningsen's house had already shown improvements in the $CO_2$ accounts just two years after the restoration.

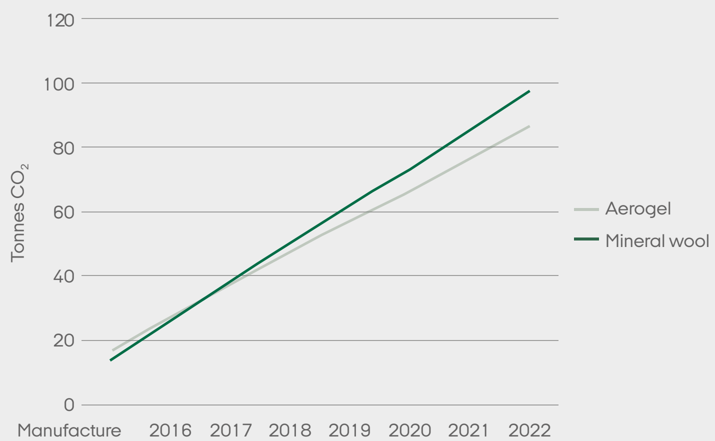
However, it will take more time to make up for the $CO_2$ loss with a more sustainable energy source than natural gas, but such an energy source is on the way, and in 2024, the property will have district heating.



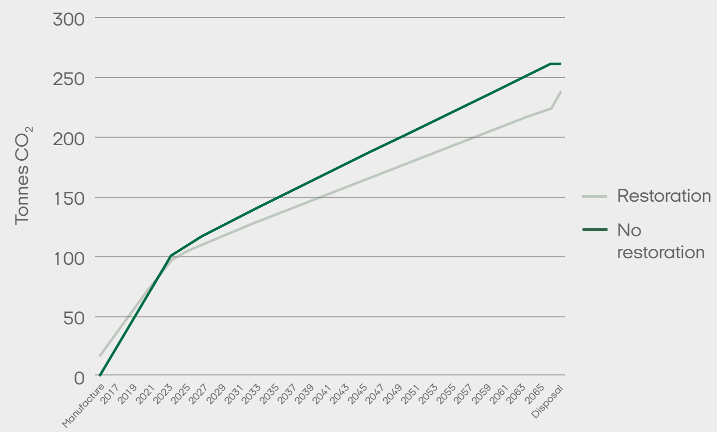

↑ **$CO_2$ emissions from the restoration of Poul Henningsen's house based on a life cycle assessment.** The "Aerogel" bar reflects the actual restoration, while the other bars show what the carbon footprint would have been if 2 cm of another insulation material had been fitted.




↑ **$CO_2$-emissions of the full restoration of Poul Henningsen's house using aluminium window frames compared with wood window frames.** This grap shows the difference between aluminuum-framed secondary glazing and, as another option, wood frames.




↑ **$CO_2$-emissions using 2 cm aerogel vs. 2 cm mineral wool**
Using aerogel has paid off in terms of $CO_2$ arund two year after restoration of Poul Henningsen's house, because the house is better insulated and therefore emits less $CO_2$ for heating.




↑ **$CO_2$-emissions during and after the restauration vs. no restauration**
The graph shows how the overall restoration of Poul Henningsen's house generates long-term $CO_2$ benefits compared to no restoration (the break in the curves marks the transition from natural gas to direct heating in 2024).

**Restoration of windows and underfloor heating**
Another important part of the restoration was about the characteristic iron windows. They only had single glazing and no secondary glazing, and they were included with consequential condensation and rust.

Restoration of the windows included both replacing some later panes of glass with the addition of secondary aluminium glazing on the interior side of the windows. Similarly, Poul Henningsen's windows are prefabricated secondary glazing, and they help reduce heat loss significantly.

In terms of $CO_2$, wood secondary glazing would have been better than the aluminium glazing chosen, which emit around four-times as much $CO_2$. Aluminium windows cost approx. 4.7 kg $CO_2$ more per m$^2$ floorspace.

Finally, energy renovation of Poul Henningsen's house entailed insulation of floors and ceilings with mineral wool, and that underfloor heating was laid with new electrical installations which are accessible via the small boxes in the floor. The existing radiators were restored and equipped with modern thermostats controlled via tablets in the individual rooms.

← **Fixing aerogel insulation sheets to the walls in Poul Henningsen's house.**

↑ **Poul Henningsen's family home on the sloping plot in Gentofte.**

CASE 4

## Højgården on Sejerø:

# A thatched roof is attractive but not necessarily the most climate-friendly

**The traditional farm of Højgården on Sejerø has been extensively restored, among other things with a new thatched roof. Natural materials such as reeds are in principle $CO_2$-neutral, but transport of the material from where it is cultivated to the thatcher means that thatch is not always the most climate-friendly choice.**

Højgården dates from 1873 and is beautifully located on a ridge on the island of Sejerø in the southern part of the Kattegat. The farm is a very rare example of a distinctive local half-timbered building style - *sidebåndsbindingsværk* - which was dominant in western Zealand up until the twentieth century. Højgården also represents a special local variant with internal timber fillets, which make the farm look as if it only was built with posts and infill. This half-timbering technique is the oldest of its type in Denmark and has its origins as far back as the Viking Age.

Realdania By & Byg acquired Højgården in 2017 and started to restore the building in order to preserve the local building traditions. The approach entailed as much reuse and repair as possible, and it was important to preserve everything that could be preserved. Otherwise, the farm could have ended up looking like a newly constructed building. Reuse is usually a climate-friendly choice.

Unfortunately, however, almost all of the original half-timbering could not be saved. Around 10% of the original woodwork was reused, and the remaining around 90% that had to be disposed of, was replaced with pine like the original. The larch lining between the half-timbering had to be replaced, and was daubed with a mixture of clay, straw and organic buttermilk. According to the LCA, this method is not only as faithful as possible to the original, it is also a much more climate-friendly choice because the normal brick infill between the half timbering would emit almost 20-times as much $CO_2$.

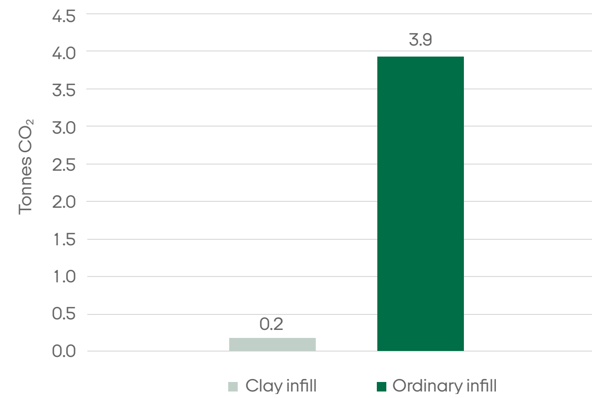
### The thatched roof

In addition to restoring the half-timbering as a unique piece of local craftsmanship, the new thatched roof laid on Højgården also adhered to local building traditions. The original thatched roof had been replaced with sheet metal and fibre cement roofing. This was returned to a thatched roof, with large flat surfaces consisting of reeds with an eelgrass ridge held together with oak bracing. The 384 $m^2$ roof is also held together with 16 kg of steel wire.

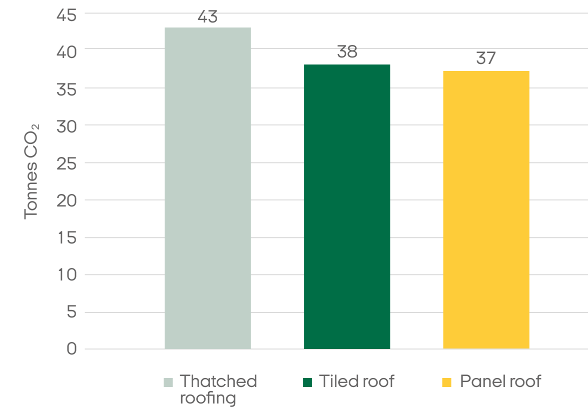
As the reeds and eelgrass are nature's own materials, production caused no carbon emissions. In fact, the reeds are behind significant negative carbon emissions, because while the plants are growing they are absorbing $CO_2$. However, the straw in the roof emits a lot of $CO_2$ as it decays in the use phase, and in final disposal. More or less all the $CO_2$ absorbed by the straw will be emitted back into the atmosphere.

→ Thatched roof on Højgården – with eelgrass ridge held together by oak bracing.

↓ Højgårdens characteristic half-timbering.




The difference in the carbon footprint using clay infill between half timbering and using ordinary infill consisting of bricks and lime mortar. The calculation is based on the 42 m² infill it was necessary to replace at Højgården.




LCA for the whole restoration of Højgården on Sejerø with thatched roof compared with other types of roof. According to the LCA, five tonnes $CO^2$ more is emitted from a thatched roof than a tiled roof using the generic German EPD for tiled roofs. However, there can be great differences between the different types of roof, and using other, product-specific EPDs could turn things around completely.

**Transport means a lot**
However, the LCAs show that a thatched roof is not necessarily the most carbon-friendly choice. An EPD (environmental product declaration) of thatched roofs points in another direction. Among other things, this is because of the high carbon emissions in transporting the reeds, as they come from other countries. The reeds at Højgården come from the Black Sea region of Romania, and in other cases reeds come from Denmark, other eastern European countries, or even from China. There may also be additional carbon emissions from the supplementary materials, especially fire protection for the roof.

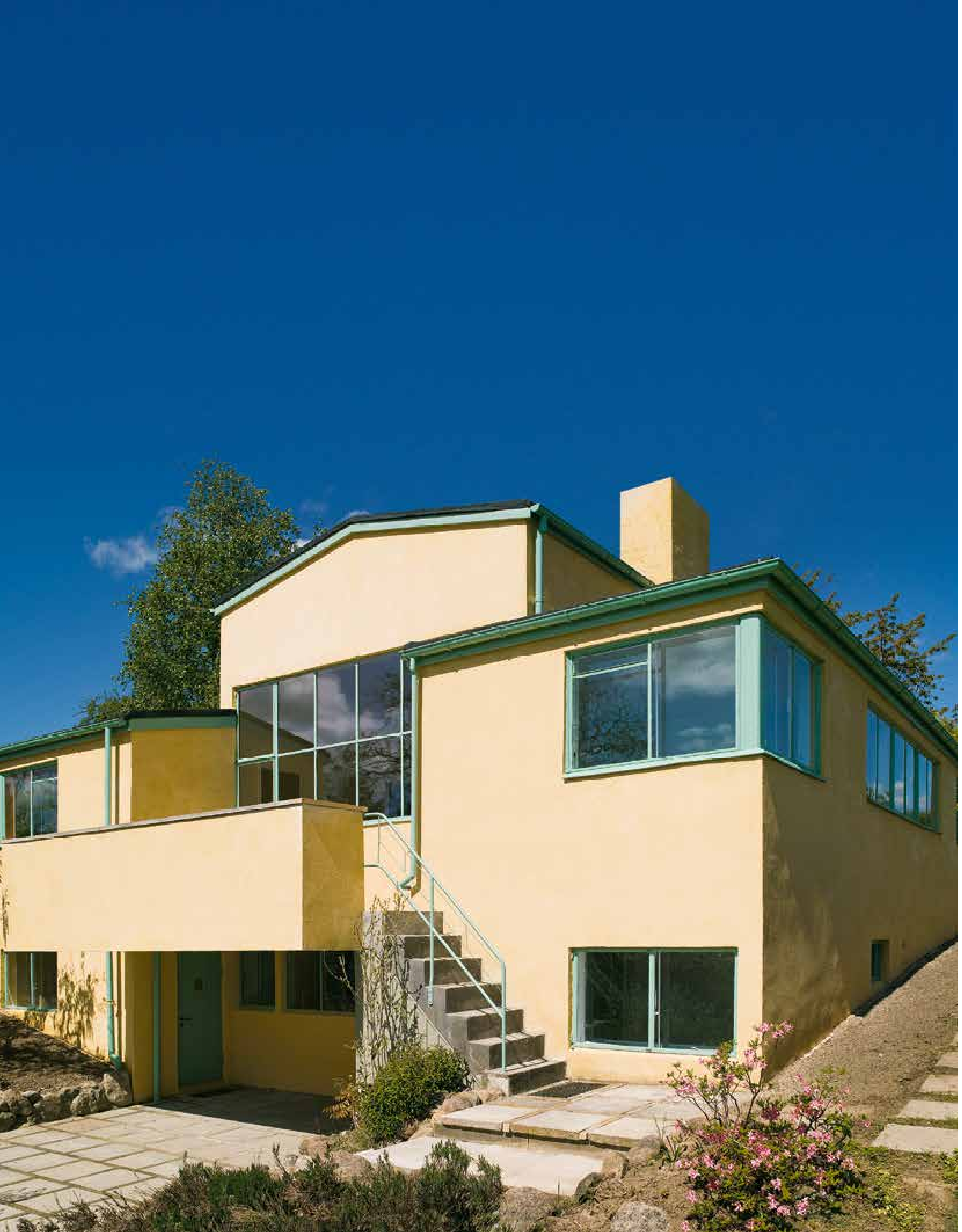
However, a factor in favour of thatching is that, in itself, thatching insulates better than tiles, for example, and this means that less $CO_2$-emitting insulation material is required.

However, overall, the most climate-friendly type of roof depends on the circumstances, and a tiled roof built with Danish tiles could be better for the climate than a thatched roof with reeds imported from far away.

**Uncertainties in using EPDs**
However, this case also exemplifies that LCAs can include factors that are hard to fully account for, and they can be based on average calculations of very different transport situations that mean that the carbon impact stated cannot necessarily simply be transferred to a specific project.

The EPDs on which Realdania By & Byg takes outset show that a thatched roof emits 28.5 kg $CO_2$ per m² roof from cradle to grave, and that a tiled roof emits a lot of less: around 16 kg $CO_2$ per m² roof. The difference in insulation requirements may, however, significantly reduce the difference between the types of roof and the $CO^2$ figure for the thatched roof is also uncertain, because it is very much based on a supplier-specific EPD, as it has not been possible to get a clear basis for calculation for all details, particularly with regard to "manufacturing process".

There may also be other environmental reasons than carbon emissions for choosing a thatched roof, as a natural material such as reeds does not contain chemicals.



CASE 5

Edvard Heiberg's Family Home:

# Scandinavia's first functionalist house taken back to its original condition

**Edvard Heiberg's family home was controversial in terms of its architecture and colouring. In the restoration by Realdania By & Byg, the house has been carefully returned to its original expression and the architect's original intentions. Even the windows in the functionalist building were a challenge, which bears witness to the fact that having to change something costs both money and $CO^2$.**

The architect, critic and pundit Edvard Heiberg's family home from 1924 is considered the first functionalist house in Scandinavia. The building consistently pursues the ideas of international modernism that were scoffed at by many at the time. Heiberg was politically active and driven by the desire for greater equality between social classes and between genders, and he had a mission to design good, healthy and rational housing for everyone.

The house is situated in Virum, north of Copenhagen, on a site with a view across Lyngby and Bagsværd lakes, and it served as both a drawing office and a residence for Heiberg and his family. The functionalistic house distinguishes itself with its simple and sharp expression, without decoration and historical details. It has a kitchen focusing on function, with a hatch to the dining room and, unusually for the period, corner windows. Like Poul Henningsen, Heiberg was inspired by the international trends in which function came before form, and he further emphasised this with very untraditional colouring.

Realdania By & Byg acquired the house in 2006 and started the restoration aiming to restore and preserve Heiberg's house as closely as possible to its original expression. In order to do this, prior to the restoration itself, detailed construction and colour-archaeological studies were completed.

Even though the building had been spared from major rebuilding in the past, comprehensive restoration work was required. Realdania By & Byg restored and repainted all facades. Interior surfaces were also restored and repainted from one end to the other in the original colours and paint types. The kitchen was restored in part, but possibilities for modern conveniences were also incorporated. The iron balcony, which was once reinforced with load-bearing columns, was shored up so that the columns could be removed and the balcony could regain its original "floating" expression.

### Difficulties with the windows

The windows and doors of the house also received attention. A previous owner had fitted new aluminium secondary glazing, but Realdania By & Byg decided to replace this with a new system specially developed for the project, in an attempt to establish prototype secondary glazing for iron windows in functionalist buildings. Unfortunately, the windows were not made accurately enough because priority was on craftsmanship rather than industrial production. This could have given more accurate and more refined solutions to achieve the required tightness and a reliable opening/closing mecha-

← The corner windows were one of the most controversial elements in the modernistic architecture of the house.

→ The windows in Heiberg's home presented challenges in the restoration.

nism. As the new secondary glazing did not function as intended, it was discarded, and it was decided not to use secondary glazing to improve the energy performance of the house at all.

Learning from this experience, Realdania By & Byg instead fit new thermal windows in the existing iron window frames in the house. The new windows work and fit well in the frames, as the glazed surfaces are only eight mm thick, but there is still the disadvantage that, over time, their weight may distort the frames.

Work on the windows is an example of the more tricky aspects in restoring old houses that also have to function in modern times, and there are also examples of some of the most important learning from trying to grope forward on the tightrope between preservation and practicability.

Besides the financial costs of this experience, there are also additional costs in the $CO_2$ accounts. The LCA shows that by far the highest carbon costs are in production of the subsequently discarded new secondary glazing, while the disposal of both the old and the new secondary glazing has had very limited impact.

Restoration of the windows in Edvard Heiberg's house cost a total of around 27.6 kg $CO_2$ per m² floorspace, of which approx. 19.5 kg was the result of the unsuccessful attempt to develop prototype secondary glazing.

The total $CO_2$ emissions for the restoration of Heiberg's house were, according to the LCA approx. 64.8 kg per m².


The carbon impact of restoring the windows in Edvard Heiberg's family house. The middle bar is the carbon cost of Realdania By & Byg's attempt to develop special secondary glazing for this and other functionalist buildings.

# Transformations

Some of Realdania By & Byg's renovation projects go a step further than just restoring by returning a building to its original expression and improving comfort for the present users, for example. These more extensive projects are called transformations and they fundamentally change a building's function while also retaining its preservation values. Transformations generally impact the climate more than restorations, but the alternative to transforming a building is often even more $CO^2$ intensive, i.e. to demolish and build anew.

The following pages present some of the projects in which Realdania By & Byg has completely changed the function of historic buildings to allow for modern and sustainable use. There is also a description of some of the experience and considerations arising from the LCAs.

CASE 6

Hindsgavl Castle:

# Recycled bricks benefit both the climate and aesthetics

**The farm buildings at Hindsgavl Castle have been completely transformed into modern hotel and conference facilities with bedrooms and a large combined events room and restaurant. The project has emitted a lot of $CO_2$, but using recycled bricks has benefitted both the aesthetics and the carbon footprint.**

Hindsgavl Castle is a full-fledged piece of architectural heritage; a building which bears witness to the role of the Danish country estate and its development over the centuries. The story began more than 800 years ago, with a royal castle built facing the Little Belt strait on the Hindsgavl peninsula near Middelfart on Funen, and the present castle was built in 1784-85 as a luxurious home for an aristocratic family.

The main building is particularly attractive from the garden side, with its fantastic position in the landscape overlooking the sea. On the opposite side of the castle stands the three-winged farm building, which reflects in the main building and its two wings: *Kavalerfløjen* and *Fruerfløjen*. The architecture is classicism, although Hindsgavl also has Baroque features.

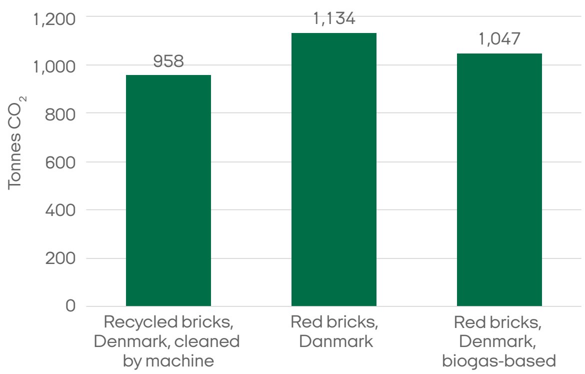
**Solid conversion**

Today, Hindsgavl is a modern hotel and conference business with 121 rooms and two restaurants. The Castle therefore continues to bring life to the area. The site was boosted by the comprehensive restoration of the castle by Realdania By & Byg in 2003 to 2005, and not least by the subsequent transformation of the farm buildings into hotel rooms and conference facilities with the high-ceilinged combined events room and restaurant.

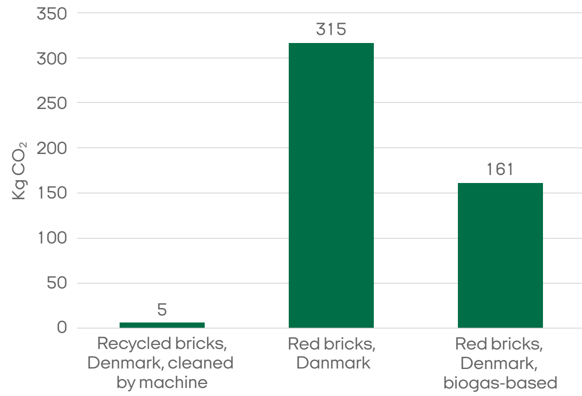
In 2006, the two side wings of the farm building, the cowshed and pigsty, were completely revitalised as part of a modern hotel. Transformation required a high-quality conversion of the interior of the buildings, which meant that the project overall was one of Realdania By & Byg's more carbon-intensive renovations.

**Large $CO_2$ savings from second-hand bricks**

A positive factor in the climate accounts, however, was the decision to use recycled bricks instead of new for the internal walls in the old cowshed and pigsty. When bricks are manufactured, firing the bricks is responsible for by far the majority of carbon emissions and therefore there are huge climate-accounts savings from reusing them.




Total $CO_2$ emissions for the transformation of the farm buildings, as calculated (with recycled bricks), and what they would have been had new bricks been used.




The difference between $CO_2$ emissions for one tonne of bricks: recycled bricks as used at Hindsgavl and various possible new bricks (including manufacture, disposal and waste treatment).

In fact, LCAs by Realdania By & Byg show that carbon emissions from different types of emissions using new bricks vary from between 30-times and 60-times higher than recycled bricks.

As anyone who stays in one of the two hotel wings will quickly realise, the recycled bricks have also added aesthetic benefits because, even though everything is newly refurbished, the historical atmosphere seems intact, with a rough touch that contrasts with the castle rooms.

Besides the transformation of the farm building, Hindsgavl Castle has regularly been restored, and it has functioned as a conference centre. Realdania By & Byg has upgraded the catering and staff facilities, making sure not to damage the patina. The elegant living rooms and vestibule in the main building have been renovated, and a new roof has been laid on the two wings to the main building: *Kavalerfløjen* and *Fruerfløjen*.

**Recycling bricks**
In principle, bricks can never be too old, but nevertheless only a few are reused. The bricks have to be cleaned one by one, and only bricks previously held together with lime mortar can be cleaned. Since cement is used in the walls of many modern houses, the bricks cannot be reused. This is because cement mortar is stronger than the brick itself, and therefore the brick will break during cleaning.

CASE 7

Højergård:
# Historic marshland farm transformed into food camp

**In the centre of the town of Højer in southern Jutland stands a cultural environment comprising an historic marshland farm, a German-inspired house with Jugendstil characteristics, and an old barn. The whole site has undergone restoration and transformation with focus on incorporating entirely new content in the buildings, while making sure they retain their soul.**

The town of Højer has one of the highest concentrations of listed and preservation-worthy buildings in Denmark, and it is one of the few places where you can still see farms and town houses side by side. In the centre of the town, facing the central square, stands Højergård: a classical salt-marsh farm built as a traditional western Schleswig longhouse.

The building was previously part of a larger farm, which had a quadrangular layout for many years. Today, Højergård comprises the farmhouse from 1823, an 18th century barn, a German-inspired house from 1906 and a recently added black carport from 2019, and these recreate the sense of a quadrangular construction around a central, green courtyard. The old farm garden has been preserved between the farmhouse and the square.

**Preservation and revitalisation in one**
In 2017, Realdania By & Byg took over the salt-marsh farm in order to preserve the valuable, site-specific building culture and convert the buildings for a new and modern use. Vitality and activity have now been secured in the buildings throughout the year, and jobs have been created in the town after the farm was taken over for the ARLA Fonden's food camp and as a venue for local food and nature events in Tønder Municipality. The project is part of the Tøndermarsk Initiative supported by Realdania, Tønder Municipality, the A. P. Møller Foundation and Nordea-fonden.

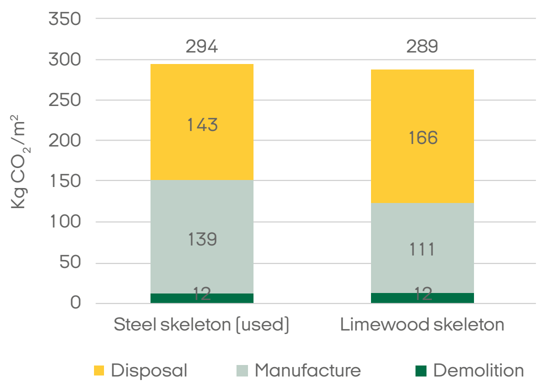
Restoration and transformation of Højergård entailed getting all the new elements to fit in with the farmhouse, the house and the barn, while also maintaining the very different souls and atmospheres of the three buildings.

All the original furnishings in the farmhouse were renovated and the walls were painted in colours identified in colour-archaeological studies. False ceilings, partitions and thermal windows fitted later were removed, but some of the changes that have been made over the years were retained to help depict the history of the house.

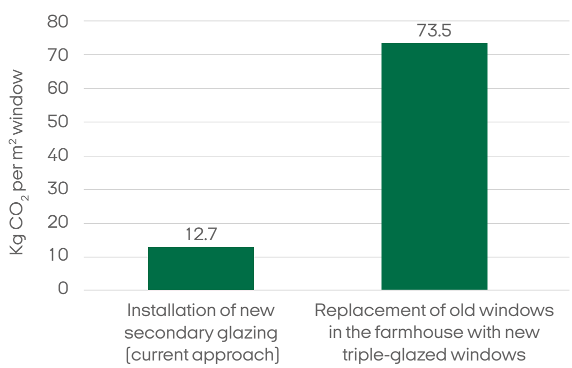
The German-inspired house has many typical Jugendstil details, and the colouring, wall ornamentation and ceiling decoration have been recreated as far as possible on the basis of findings by colour archaeologists.

**New steel skeleton makes it possible to preserve old walls**
Finally, the farm's oldest building, the barn, was transformed into a modern cookery-school kitchen, which today has 60 pupils. The barn was built in a traditional western Schleswig style with red-fired brickwork, and it tells a narrative about the area, the farm and agriculture in Tøndermarsken.


$CO_2$ impact from fitting the steel skeleton in the barn at Højergård to preserve the old walls, compared with a 50% larger timber skeleton.




Total $CO_2$ emissions for restoration of the barn at Højergård using the current girdle and an alternative to stiffen the building.




The graph shows the difference in $CO_2$ emissions from fitting new secondary glazing with wood frames in the farmhouse and the intended replacement of the old windows with new triple-glazed windows, including replacement of the wood frames. The figures shown are per m² window area.

A gentle transformation of the old barn has worked by giving the building ridge support.

On the inner side of the walls the barn has simply been stiffened with modern, concealed steel stiffeners - a kind of girdle. This has made it possible to preserve the old outer walls with all their traces of history and wear, without the walls having to bear the weight of the roof structure and other building components.

Today the building contains two high-ceilinged teaching kitchens. The room stretches right up to the ridge, where the massive roof structure with visible cross beams from the 18th century reflect the building's past as a large, spacious barn.

The concealed steel skeleton is an addition that, on the basis of an LCA, costs around 13.1 kg $CO_2$ per m², when calculated for the barn alone. An alternative could have been a timber skeleton that would have cost approx. 7.9 kg $CO_2$ per m². However, the savings have to be weighed against the higher bearing capacity requirement resulting in a 50% larger girdle.

**Renovation verses modern energy efficient windows**
Another restoration consideration was the windows in the farmhouse. They were 70 years old and no longer functional. Today it would be usual to use triple-glazed thermal windows when building new or renovating, but there are other rules for listed properties.

The solution was to repair the old windows and fit new secondary glazing behind them. In this respect, the LCA shows that restoration in itself, only emits one-seventh of the $CO_2$ that the new triple-glazed windows would have cost. Experience shows that the heating system works very well, but the long-term sustainability of the solution will become clearer when data on heat consumption is included in the LCA.

The German-inspired house holds many historical decorations that have been recreated as far as possible following colour-archaeological studies.

The interior of the barn has been transformed to enable the old outer walls, with their patina and traces of history, to be preserved for many years to come.

CASE 8

## Dyrehave Mill:

# Well-preserved cultural environment with new functions

**Dyrehave Mill has been restored, and the nearby buildings have been transformed into business premises and modern housing. The total renovation has been relatively carbon-intensive, but could be considered as an alternative to building new homes.**

For more than 160 years, Dyrehave Mill in Nyborg has been a landmark for residents and visitors to the town. The mill is one of the few remaining in Denmark, and it is in unusually good condition and well-preserved. For more than 100 years, the same family has looked after the mill and its out buildings.

The mill property also includes a miller's house, a garage building and a storehouse. Together with a large garden, they constitute a fully intact pre-industrial cultural environment.

After Realdania By & Byg acquired the site in 2018, the listed windmill was revitalised and the other buildings have been renovated and converted for new functions.

The mill itself has been fully restored inside and out, and the mechanics have been repaired so that the sails can again turn to mill flour - at least for the museum.

### Transformed into homes and offices

The garage building previously contained stables, a baking oven and a carport, but it has now been transformed into two semi-detached rented houses. The old outer walls have been preserved, while the large garage doors have been converted into windows and smaller doors. The old timber doors have been preserved on the outside as large "shutters". The interior of the building is supported by a type of girdle so that the old walls do not have to bear the weight of the roof and other components.

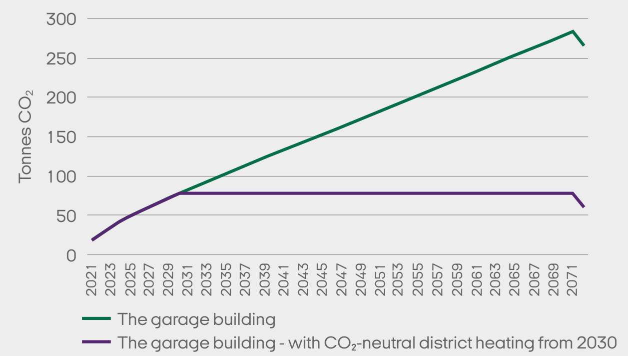
The previous miller's house has also been converted into two modern rented semi-detached houses.

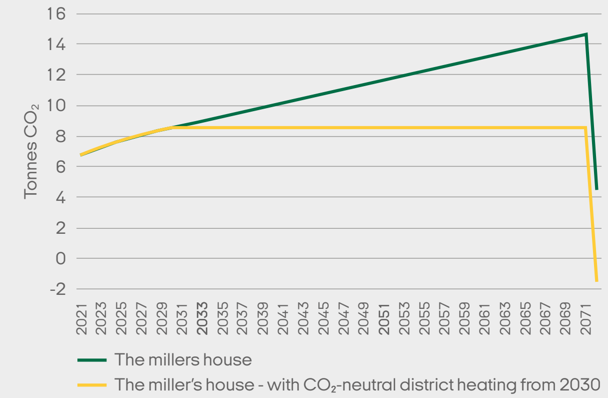
Finally, the two-floor storehouse has been converted for commercial purposes. Together with the mill, it has been leased to Kongens Fadebur, who communicate history through food experiences, guided tours and other events. A reception for visitors has been established, and Kongens Fadebur also use new rooms on the first floor, with toilets, kitchenette and facilities for events. A new mill association will communicate about the mill and organise tours. The mill is open for visitors in the daytime.

### Large but deferred $CO_2$ emissions

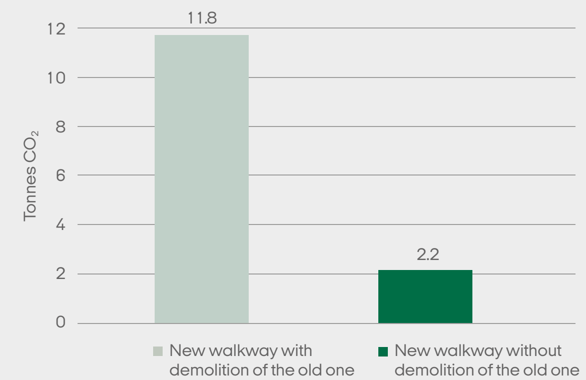
The restoration of Dyrehave Mill and associated buildings is one of the most $CO_2$-intensive projects in the Realdania By & Byg portfolio, with estimated emissions of about 179 kg $CO_2$ per square metre. On the other hand, approx. 80% of emissions will not take place until future disposal, and such a "delay" will counteract the acceleration in climate change, in contrast to having most emissions occur today in materials manufacture.

The garage building before and after the transformation.

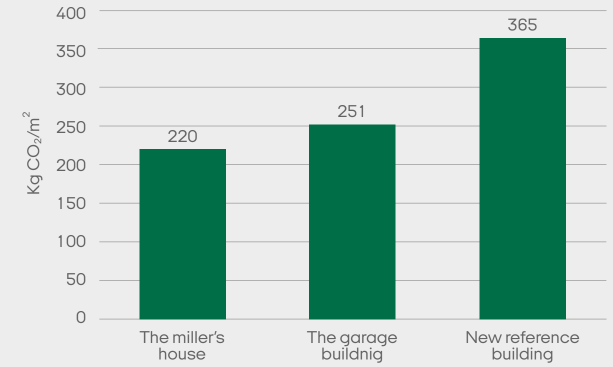



These two graphs show $CO_2$ savings from insulating the farmhouse and the garage building using wood fibre. Insulation of the garage building will continue to be a $CO_2$ benefits, while the miller's house will end as a cost, if $CO_2$-neutral district heating is fitted in 2030, as there was a certain amount of loft insulation previously.




Graph illustrating the issue of "double demolition": Carbon impact of replacing the walkway around Dyrehave Mill, including both demolition of the old balcony and the new walkway, and an alternative LCA including only the new walkway.




Carbon emissions per m² for transformation of the miller's house and the garage building for housing compared with new building (average of 12 terraced houses investigated in the report by Harpa Birgisdóttir et al (Klimapåvirkning fra 60 bygninger)). The comparison only takes account of the materials and does not include heating consumption, in which an energy efficient new building would reduce the difference in $CO_2$ emissions in the long term. However, calculations by Realdania By & Byg show that the situation can only reverse in the long term if it neither turns out to be possible to produce carbon-neutral district heating, nor a more climate-friendly way to dispose of materials be found.

The bulging wooden walkway construction around the mill has been replaced with new timber. Disposal of the old timber emitted about 118 kg $CO_2$ per m² of the mill's floor area, while production of a new walkway has saved about 91 kg $CO_2$ per m² because this was absorbed as the tree grew. When the new wood has to be disposed of, it will again emit 118 kg $CO_2$ per m², giving total emissions of 145 kg $CO_2$ per m². However, note that this calculation includes a "double demolition", and it is debatable whether disposal of the old walkway should instead be included in a previous owner's LCA. At all events, it would have to be disposed of sooner or later.

**Wood-fibre insulation**

Transformation of the other buildings has also had a cost in the $CO_2$ accounts. The garage building and the farmhouse, both of which have been converted into modern semi-detached houses, have wood-fibre roof insulation to help retain heat.

Manufacture of the wood-fibre insulation in the two buildings constitutes -36 kg $CO_2$ per m² (calculated on the basis of the area of the two buildings together) and future disposal 55 kg $CO_2$ - i.e. net emissions from the material of 19 kg $CO_2$ per m². However, obviously the overall picture includes the $CO_2$-saving effect during routine operation when the home is heated.

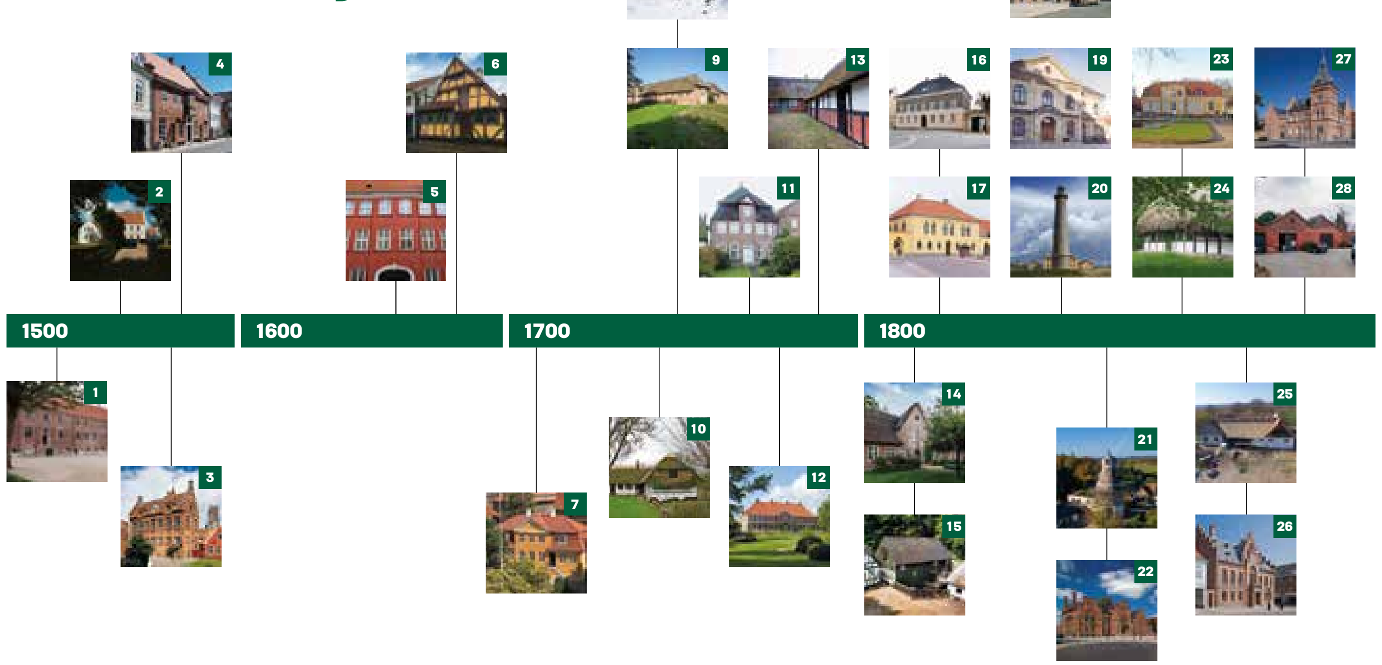
Taking into account that the two buildings have to serve as homes and be heated in any case over the coming years, there will be larger and larger $CO_2$ benefits, although these will fall away when the wood-fibre insulation is disposed of.

The garage building, which has never been insulated, would end with $CO_2$ benefits in any case. The farmhouse, which had previously been insulated with a thin layer of granulate, ends with a $CO_2$ benefit of 4 tonnes with the current district heating. If district heating becomes $CO_2$-neutral from 2030, the initiative will result in additional emissions of 1.5 tonnes $CO_2$ in the LCA of the garage building, but with a positive background, in that the reduced heating consumption will have contributed to the green transition to district heating. And if at that time in the distant future a $CO_2$-neutral way to dispose of wood has been invented, the wood-fibre insulation will end up as a pure climate benefit.

**Alternative to new building**

The garage building would naturally never have been a home without Realdania By & Byg's transformation, and therefore the $CO_2$ savings for this in itself are theoretical. Such an extensive transformation can rightly better be compared with new building, and as the overall objective of the project was to preserve a cohesive cultural environment around Dyrehave Mill, the extensive transformation has been the right choice in this context, even though the carbon footprint is higher than for other projects.

# Realdania By & Byg's historic buildings





Year: 1504 and later
**1** **Odense Secular Convent for Noblewomen**

Year: 1542-2007
**2** **Nørre Vosborg, Vemb**

Year: 1580
**3** **Taarnborg, Ribe**

Year: 1586 and later
**4** **The Maternal House of Oluf Bager, Odense**

Year: 1663-1669
**5** **The Harboe Widow's Convent, Copenhagen**

Year: 1690
**6** **Priors House, Ærøskøbing**

Year: 1742 and later
**7** **The Fortification Depot, Copenhagen**

Year: 1757-1770
**8** **Poul Egede's Home, Ilimanaq, Greenland**

Year: 1767
**9** **Nørre Sødam Farm near Møgeltønder**

Year: 1775
**10** **Stine's House, Lolland**

Year: 1777-1779
**11** **Digegreven's House, Tønder**

Year: 1784-1785
**12** **Hindsgavl Castle, Middelfart**

Year: 1795
**13** **Bent Madsen's Farmhouse, Dreslette**

Year: 1823
**14** **Højergård, Højer**

Year: 1827
**15** **Gammelby Mill, Fredericia**

Year: 1838
**16** **Koch's Courthouse, Store Heddinge**

Year: 1843-1845
**17** **Kornerup's Town Hall, Vordingborg**

Year: 1853
**18** **Bindesbøll's Town Hall, Thisted**

Year: 1858
**19** **Naval School for Girls, Copenhagen**

Year: 1858
**20** **Skagen's Grey Lighthouse, Skagen**

Year: 1858
**21** **Dyrehave Mill, Nyborg**

Year: 1860
**22** **Meldahl's Town Hall, Fredericia**

Year: 1860
**23** **Riise's Country House, Frederiksberg**

Year: 1865
**24** **Kaline's House, Læsø**

Year: 1871
**25** **Højgården, Sejerø**

Year: 1880
**26** **Tvede's Town Hall, Sorø**

Year: 1892
**27** **Amberg's Town Hall, Esbjerg**

Year: 1898
**28** **The Foundries, Præstø**

Year: 1901
**29** **The Jensen Family Farm, Korup**

Year: 1905
**30** **The Harbour Master's House, Skagen**

Year: 1906
**31** **The German-inspired House, Højer**

Year: 1907-1908
**32** **J.F. Willumsen's Family Home, Hellerup**

Year: 1908
**33** **Gelsted Station, Gelsted**

Year: 1910
**34** **The County Governor's Residence, Hjørring**

Year: 1913
**35** **The Rose House, Hellerup**

Year: 1917
**36** **Bakkekammen 40, Holbæk**

Year: 1917
**37** **The Balloon Hangar, Copenhagen**

Year: 1918
**38** **Ejnar Ørnsholt's Private House, Nakskov**

Year: 1918
**39** **Country House designed by Kay Fisker, Snekkersten**

Year: 1924
**40** **Edvard Heiberg's Family Home, Virum**

Year: 1929/1931
**41** **Arne Jacobsen's Private Home, Charlottenlund**

Year: 1934
**42** **State-guaranteed Smallholding, Skovbølling**

Year: 1936
**43** **Kay Fisker's Private Flat, Copenhagen**

Year: 1936
**44** **Arne Jacobsen's Private Holiday Cottage, Gudmindrup**

År: 1937
**45** **Poul Henningen's Family Home, Gentofte**

Year: 1939
**46** **Viggo Møller-Jensen's Family Home, Kgs. Lyngby**

Year: 1951
**47** **Arne Jacobsen's Private Home, Klampenborg**

Year: 1952
**48** **Varming's Family Home, Gentofte**

Year: 1953
**49** **Clemmensen's Family Home, Gentofte**

Year: 1954
**50** **Esken, Fårevejle**

Year: 1955
**51** **Erik Chr. Sørensen's Private Residence, Charlottenlund**

Year: 1956
**52** **Bertel Udsen's Private Residence, Lyngby**

Year: 1956-1959
**53** **Jarmers Plads, Copenhagen**

Year: 1958
**54** **Gunnløgsson's Residence, Rungsted Kyst**

Year: 1958
**55** **Knud Friis' Family Home, Brabrand**

Year: 1960
**56** **The Roman House, Elsinore**

Year: 1963
**57** **Exner's Family Home, Skodsborg**

Year: 1967
**58** **Glasalstrup, Hasselager**

Year: 1969
**59** **Poul Erik Thyrring's House, Herning**

# Photos

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**Life cycle assessment for historic buildings**
**– Realdania By & Byg's experience with LCA in restorations and transformations**

Realdania By & Byg A/S, 2022

ISBN: 978-87-93746-66-4

Author/journalist - interview articles pages 6-23: Mikkel Meister

Other text: Realdania By & Byg

Translation: GlobalDenmark A/S

Layout and illustrations: OAB-Tryk ApS, Odense

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Restoring a historic building is a balancing act under which preservation values, aesthetics, present use, finances, the climate and the environment have to be weighed against each other.

In this context, LCAs can sharpen focus on the climate dimension by clarifying the total carbon emissions linked with restoration with the individual choices and with alternative to these.

Over the past almost 20 years, Realdania By & Byg has acquired and restored or transformed around 60 historic buildings, and most recently completed life cycle assessments (LCA) of the majority of these projects on the basis of data from the company's own files and from the materials manufacturers.

In sections based on three interviews and eight specific cases, this publication focusses on how LCA is used to analyse the climate footprint of restoration and transformation projects run by Realdania By & Byg, and how learning from this work can be included in new projects.

Realdania | Realdania By & Byg