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Sustainable Heritage Buildings: The Impact on Heritage Values, Energy Performance, and CO_2 Emissions

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Abstract

The Dutch national CO_2 emission targets for heritage buildings are a 60% reduction by 2040. However, holistic insights on the impact of this reduction on heritage values, energy performance, and CO_2 emissions are understudied. In this article, the impact in four heritage buildings by comparing the situation before and after the renovation process was studied. These energy reduction measures were part of a larger restoration or adaptive reuse process. We used archival documentation about the original design, assessed project documentation regarding the previous technical conditions of materials, and conducted fieldwork. The data was used in a heritage assessment, focussing on cultural, historical, architectural, ensemble, authenticity, and rarity values. Energy performance and CO_2 emissions were calculated based on desk research, fieldwork, and additional information provided by the owners. The CO_2 emission calculations included all materials that were removed or added during the construction process. We concluded that in some cases, heritage values have been degraded by the energy reduction measures, whereas in other cases, they were improved. In all cases, we found that heritage values were lost to a certain extent. The impact on energy performance and CO_2 emissions varied. CO_2 emissions for operational energy were reduced by approximately 52% on average, and CO_2 emissions for carbon energy were reduced by approximately 6% on average. Therefore, we conclude that energy-efficient restoration of heritage buildings considerably reduces environmental impact but comes at a cost to heritage values.

Keywords

CO_2 emission; energy performance; heritage values

1. Introduction

Following the ratification of the Paris Agreement (United Nations, 2015), the Dutch government (Eerste Kamer der Staten Generaal, 2017) adopted a participatory approach to enhance public support for climate targets. Specific policies were developed through sectoral climate tables (*Klimaattafels*), involving governmental agencies, companies, and non-governmental organisations. The Dutch Climate agreement (*Klimaatakkoord*) aims to reduce CO_2 emissions by at least 49% by 2030 and 95% by 2050, compared to 1990 levels (Klimaatakkoord, 2018a). These targets were further specified per sector, with the built environment sector focussing on insulation and heat transition strategies (Klimaatakkoord, 2018b).

In the Netherlands, approximately 120,000 heritage buildings are protected by national, provincial, and municipal authorities by the Heritage Act (OCW, 2024) and by local heritage policies (I&W, 2024). This allows governmental authorities to exempt listed buildings from climate policy targets when heritage values are threatened. Recognising the urgency for climate action, the heritage sector organised a specific climate table for heritage buildings and resulted in the Sustainable Built Heritage Roadmap (*Routekaart Duurzame Monumenten*). The Roadmap aims to reduce CO_2 emissions from energy consumption by 40% by 2030 and 60% by 2040 (Routekaart Duurzaam Erfgoed, 2019). Furthermore, the Roadmap called for a Sustainable Heritage Monitor to measure progress, which was implemented through a yearly survey of approximately 20,000 listed buildings.

1.1. Knowledge About Energy Reduction in Heritage Buildings

The European Green Deal (European Commission, 2019) and the Energy Performance of Buildings Directive ("Directive (EU) 2024/1275," 2024) emphasise the urgent need to reduce energy consumption and greenhouse gas emissions within the built environment, including heritage buildings. For historic buildings, NEN-EN 16883:2017 (Stichting NEN, 2017) provides guidelines to enhance energy performance while safeguarding cultural heritage values.

Several literature reviews on energy reduction in heritage buildings have been conducted in the past decade (Lidelöw et al., 2019; Webb, 2017). Webb argues that the literature indicates a shift in perception: from seeing energy reduction in heritage buildings as a threat to heritage to considering it as an opportunity to protect it. Furthermore, she showed that software can enhance the process of decision-making regarding energy reduction measures, for instance, by predicting risks and energy consumption via building energy models (BES; Webb, 2017). Both Webb (2017) and Lidelöw et al. (2019) concluded that energy reduction in heritage buildings necessitates a holistic approach, where energy reduction measures result from balancing multiple criteria. According to Webb (2017), the main criteria are heritage conservation and energy consumption. Wise et al. (2021) suggested to add occupant behaviour, because users of historical buildings often apply energy-saving living and heating strategies.

Baker et al. (2021) adopted a wider environmental perspective on energy reduction in heritage buildings through life cycle analysis (LCA). Based on interviews with stakeholders, they suggest including both operational carbon (energy consumption) and embodied carbon (materials). Dişli and Ankaralıgil (2023) investigated how the life cycle of existing buildings could be prolonged by applying the concept of circular economy. See also Yang et al. (2014) and Potting et al. (2017). The concepts of heritage conservation and circular economy share a common ground, namely reducing material loss, acting carefully, and ensuring the reversibility of changes to buildings (Costantino et al., 2024; Huuhka & Vestergaard, 2020). However, Huuhka and Vestergaard (2020) conclude that these concepts are based on different discourses and therefore can be complementary as well as contradictory. For example, repurposing ornaments combines well with a conservation approach, whereas urban mining does not. Serrano et al. (2022) investigated the concepts of restoration and circular economy through a case study of historic Danish farmhouses. By applying life-cycle assessment methodology, they quantified both operational carbon and embodied carbon impacts (Serrano et al., 2022). The study compared two design scenarios: an energy-efficient restoration design scenario, which incorporated energy reduction measures, and an energy renovation design scenario, which aimed for high energy performance targets and did not include heritage valuation. Their findings indicated a minor advantage for the energy-efficient restoration design scenario, as the associated CO_2 emissions were marginally lower than those of the renovation design scenario.

1.2. Dutch Practice of Sustainable Heritage

To support decision-making on energy reduction measures in heritage buildings, several instruments have been developed specifically for the Dutch heritage sector. Examples include the Sustainable Heritage Method (*DuMo-methode*; Nusselder et al., 2008; Van der Schoor, 2020; Van der Schoor et al., 2024), the Sustainably Improved Method (*methode Duurzaam Verbeterd*; De Jonge, 2011), and The Green Menu (*De Groene Menukaart* by *De Groene Grachten*; De Erfgoedstem, 2014). Additionally, the Foundation for High Quality of Restoration of Heritage Buildings (*Stichting Erkende Restauratiekwaliteit Monumenten*, *ERM*) developed guidelines for sustainable heritage advice (Stichting ERM, 2020). The Dutch methods and guidelines primarily focus on heritage conservation and energy consumption.

In the Netherlands, few studies have assessed the practical impact of energy reduction measures on heritage buildings. Generally, progress is monitored through the Dutch Sustainable Heritage Monitor, which supports the Sustainable Heritage Roadmap. This monitoring is based on annual surveys conducted from 2020 onwards (Right Marktonderzoek en Advies, 2022a, 2022b, 2024, 2025; Routekaart Duurzaam Erfgoed, 2022). In 2020, 264 owners of listed buildings participated; in 2021, this rose to 500 owners, and in 2022 and 2023, 555 owners took part. The Monitor provides insight into the users' appreciation of their heritage building, thermal comfort, and applied energy reduction measures. Furthermore, the available data included general figures about energy consumption. Throughout the years, the owners indicated the effect of energy reduction measures on heritage values and indicated the reduction in natural gas and electricity demands. However, for the primary aim of the Monitor—i.e., assessing progress on the climate targets—the results are limited. Only one PowerPoint presentation was published, which contained some figures that illustrate that, compared with 2018, both natural gas and electricity demand were reduced by approximately 19% by 2024 (De Vries & De Jong, 2024). The impact of energy reduction measures on heritage values was not assessed, nor was the material impact regarding CO_2 emissions.

1.3. Research Aim

The published data of the Roadmap are limited to energy reduction figures and lack insight into the decision-making process, especially regarding the impact on heritage values. A comprehensive understanding is essential to explain why certain outcomes were achieved (Lidelöw et al., 2019; Webb, 2017; Wise et al., 2021). Additionally, Serrano et al. (2022) successfully integrated heritage values into their study, which assessed energy performance and life-cycle carbon impacts using an LCA-based approach. Although their findings suggest that an energy-efficient restoration design scenario may yield more favourable environmental outcomes than an energy renovation design scenario that leaves out heritage valuation, this was not assessed in practice.

In this article, we present the findings of an evaluation study on recently restored Dutch heritage buildings where energy reduction measures were incorporated. Our aim was to assess the impact of these measures on heritage values, energy performance, and CO_2 emissions. Section 2 outlines our research approach, including the selection of case study projects and the assessment methods. Sections 3 to 6 detail the results of four case studies. Finally, Section 7 presents our conclusions.

2. Research Approach

We employed the case study method (Yin, 2009) to evaluate the impact of energy reduction measures in heritage buildings in the province of Groningen, the Netherlands. We applied a holistic approach, relying on Wise et al. (2021), who emphasised that technical performance studies on heritage buildings should consider both the social and technical contexts of these buildings. Furthermore, we adopted elements of the methodology of Serrano et al. (2022) to assess both energy performance (operational carbon) and life-cycle carbon impacts of materials (embodied carbon) using an LCA-based approach. This article specifically focuses on three aspects of the case studies: heritage values, energy performance, and CO_2 emissions.

Our case study buildings were part of a subsidy program in the province of Groningen: Major Maintenance, including Restoration of National Listed Buildings Groningen (*Groot onderhoud waaronder Restauratie Rijksmonumenten Groningen*; Provincie Groningen, 2024). An advantage of selecting case studies from this subsidy program was the availability of comprehensive project documentation. The province contacted subsidy recipients, and six building owners responded positively. Preference was given to buildings where the owner was actively involved in daily operation. As a result, one case was excluded because the owner leased the property to a commercial tenant. The remaining five buildings are privately owned and used as residences. In this article, only four case studies (Figure 1) are presented due to insufficient data for one project.

Figure 1. The case study buildings: Leens, Musselkanaal, Appingedam, and Spijk (Mark Sekuur, 2024).

The subsidy program of the province primarily subsidised restoration activities for up to 300,000 euros, of which 5,000 euros could be used for insulation measures. We estimated this was a welcome bonus for owners, though it provided only a limited boost for owners who have greater energy reduction ambitions. The data, research methodology, and findings were published in a practice-oriented report in Dutch (Vieveen et al., 2024).

2.1. Interviews

To explore the motivations and experiences of the building's owners, we conducted semi-structured interviews focussing on their reasons for buying the property, their initial ambitions and challenges, the energy consumption prior to the interventions, the energy reduction and restoration measures applied, and the role of various stakeholders throughout the design and construction process. The interviews were prepared by using project documentation that was provided by the province of Groningen, by carrying out brief archival research and internet searches, and by conducting preparatory phone calls with the owners. Interviews were conducted at locations preferred by the interviewees—typically in their homes, which also served as the buildings in the case studies. Three researchers carried out the interviews, each focussing on different aspects of the sustainable heritage process. All interviews were recorded, transcribed, and subsequently shared with the interviewees for review and correction of any inaccuracies.

2.2. Heritage Assessment

The heritage impact assessment included a study of the architecture and typology of the buildings. This involved desk research, using documentation provided by the province of Groningen and the owners, as well as additional archival research at local heritage agencies. Relevant literature on architectural styles and typologies was also consulted. Field research was conducted through on-site inspections of the buildings. Furthermore, oral histories—such as information about how previous owners used and modified the buildings—were shared by the owners during the interviews (see Section 2.1).

The heritage assessment involved a comparative analysis of heritage values across two timeframes. The original historic construction periods are described in the general introduction of the case study sections and include the significant alterations and defining characteristics of the building, up to the point when it was listed for its national importance. Timeframe 1 includes the *pre-intervention state*, representing the condition of the building immediately before the implementation of energy reduction measures. This included legal modifications (with permits) and unauthorised alterations (without permits) made since the building's heritage designation. Timeframe 2 includes the *current state*, reflecting the building after the energy reduction measures were applied.

We relied on the Dutch heritage valuation standard (RCE, 2024) to determine the heritage values. This standard includes five main categories:

- *Cultural historical value*: Reflects the narrative a building conveys about the past, including its age, its role in shaping local identity, and the emotional connection people may have to it.
- *Architectural historical value*: Pertains to the visual shape of buildings, such as their building typology, architectural style, and, in some cases, the influence of a notable architect on design and construction.
- *Ensemble value*: Connects the building to its location and immediate context, including its relationship to surrounding structures. This value considers whether the building is part of a coherent group or cluster, either functionally or visually.
- *Authenticity value*: The extent to which a building has remained unchanged since its original construction and whether its original function is still discernible. This criterion focuses on historical integrity.

- *Rarity value*: Concerns the uniqueness of a building, which may be expressed through its building typology. For example, a distinctive architectural style or distinctive ornaments that are uncommon for this type.

For scoring the impact of interventions on heritage values, we followed the Dutch Practical Guidelines for Building History Research (*Handboek Bouwhistorisch Onderzoek*; Stichting ERM, 2024), which uses a four-point scale:

- *Negative values*: The intervention has a detrimental effect on one or more heritage values. This may include the removal of original historic material in good condition or alterations that compromise significant visual characteristics.
- *Indifferent values*: The intervention has little to no impact on the values of the building.
- *Positive values*: Although not original, the intervention supports or enhances the building's heritage values—for example, by restoring original visual elements or using more appropriate materials.
- *High values*: The intervention makes a substantial contribution to the building's heritage values, such as restoring severely damaged original features or applying appropriate materials on a large scale.

The heritage assessment was conducted at multiple levels: individual building elements, broader architectural components, and the building as a whole. It considered both material integrity and visual heritage values. When the technical condition of building materials was found to be in poor condition and required replacement, they were classified as "lost" in terms of heritage value.

This study is restricted to the impact of energy reduction measures on heritage values. Other interventions—such as foundation improvements or adaptations for new uses—were excluded from the scope of this assessment. As a result, the overall heritage value assessment of all interventions on the building may differ from the findings presented in this article.

Although our heritage assessment approach is widely supported in the Netherlands, it inherently involves a degree of subjectivity. In this study, the assessment was conducted by a researcher with extensive experience in evaluating the impact of interventions on listed buildings in the Netherlands.

2.3. Energy Performance

We calculated the energy performance of each building for timeframe 1 and 2. For this part, we also used documents provided by the province of Groningen and the owners. Furthermore, we carried out on-site surveys of materials, energy systems, and envelope characteristics. Additional insights were drawn from the interviews with the owners (see Section 2.1), for example on wall constructions, thermal user behaviour, and indoor temperature patterns throughout the year.

We calculated the heated surface areas and volumes of each building based on architectural drawings. Building materials were inventoried through on-site inspections and supported by information provided by the owners regarding both the original construction and newly applied materials and energy systems.

For the energy performance calculations, we followed the recommendations of Wise et al. (2021) to develop a tailor-made baseline using a BES-model. This involved calibrating the modelled scenarios with actual energy consumption data.

Energy performance was assessed using the MESH tool (MESH Energy, 2024), an Excel-based steady-state BES-model for heritage applications. MESH calculates energy demand for heating, electricity use, and renewable generation. Where available, calibration was performed using metered data, and results were weather-normalised using degree-day correction to ensure comparability across different years.

All energy carriers were converted to kWh for comparability, using standard European conversion factors (European Environment Agency, 2019). Energy performance results are reported as absolute annual totals in kg CO_2e/m^2. Household electricity consumption was included where relevant. For photovoltaic (PV) systems, electricity was categorised into self-consumed and exported fractions, with transparent crediting rules applied. For biomass fuels (e.g., wood, pellets), biogenic CO_2 emissions were reported separately from fossil upstream emissions.

2.4. CO_2 Emissions

For the assessment of embodied carbon (changed materials), we used the LCA across five stages (Stichting NEN, 2012). We limited our calculations to:

- The construction stage (A1–A5), restricted to removing and adding materials, categorised as:
  - Restoration and maintenance (e.g., replacing the roof or reconstructing en-suite doors);
  - Modernisation (e.g., adding a kitchen or new internal walls);
  - Energy reduction measures (e.g., insulation or solar panels). When energy reduction measures were part of maintenance (e.g., replacing a broken window) or modernisation (e.g., a new insulated wall), the CO_2 emissions were not allocated to energy reduction measures.
- The energy consumption related to the use stage (B1–B7).

We argue that it is sufficient to calculate only these categories, since unchanged parts of the building will not affect environmental impacts differently after the interventions. Both embodied energy of existing materials, their maintenance, and end-of-life impacts remain constant.

The CO_2 emissions of the LCA stages were assessed using the MESH tool (MESH Energy, 2024). MESH calculates the environmental product declarations for material life-cycle impacts. To capture the time dimension, impacts were annualised using reference service lives (RSLs): 15–20 years for HVAC, 35–50 years for windows, and 50 years for insulation, instead of a uniform 30-year depreciation. RSLs and emission factors were derived from the Dutch National Environmental Database (Stichting Nederlandse Milieudatabase, n.d.).

3. Case Study 1: Rentenierswoning Leens

A *rentenierswoning* is a typical Dutch building type that was prominent around 1900. Wealthy farmers (*herenboeren*) would pass their farm on to their successor and retire in style. They often hired a well-known architect to design their private house in the latest architectural fashion in the village near the farm.

The *rentenierswoning* in Leens was built in 1910 and is valued as an example of its type. Its architectural historical values are found in a historizing style with specific building features from a prominent design, such as valuable Art Nouveau ornaments. It is designed by notable architects Klaas and Gerhardus Hoekzema. Ensemble values are found in its prominent location at a crossroad. Furthermore, the building is part of an ensemble of multiple *rentenierswoningen*, that are characterised by a diversity of architectural styles. A notable feature is its relationship with a similarly designed rentenierswoning across the road, designed by architect W. Reitsema.

3.1. Heritage Assessment

3.1.1. Timeframe 1

The technical condition of the building in Leens was mixed. Several parts were in poor technical condition, such as the cavity wall anchors and roof tiles. Other parts were in remarkably good condition, such as the 100-year-old original wooden window frames and the wooden beams construction of the ground floor. As a result of the overall poor technical condition of the building, some materials needed to be replaced and could be considered lost.

The building was in a relatively authentic condition before the interventions were applied. The occurring loss of authenticity in this building was caused by the necessary replacement of historically significant materials that were in poor condition. This provided an opportunity for energy reduction measures that had virtually no effect on heritage values. Overall, the heritage values were high before the energy reduction measures were applied:

- *Cultural historical values*: Unchanged, thus highly valued;
- *Architectural historical values*: Unchanged, thus highly valued;
- *Ensemble values*: Unchanged, thus highly valued;
- *Authenticity*: The building is highly authentic, with regard to its floor plan, exterior elements, and interior features;
- *Rarity*: The *rentenierswoning* is relatively rare.

3.1.2. Timeframe 2

The current owners expressed great responsibility in their ambition: “We wanted to restore the house in such a way that it would last for at least another hundred years.” They believed that incorporating energy reduction measures was essential to achieve this goal. To protect heritage values, the owners aimed to minimise or prevent the loss of historical materials and visual changes.

The following measures were applied:

- Exterior walls: Maintenance and applying cavity wall PIR granulate insulation;
- Windows: Replaced the single glazing with vacuum glass;
- Roof: Fully replacing the broken roof tiles and applying glass wool insulation;
- Modernisation: New bathroom and kitchen;

- Heating system: Applying a new highly efficient central heating boiler (natural gas), suitable for hydrogen energy in the future;
- Other systems: PV panels.

As part of the sustainable heritage strategy, the Restoration Ladder (*Restauratieladder*; Stichting ERM, 2019) concept was used in decision-making to prevent the loss of heritage values. For example, vacuum glass was used. The owners expressed their satisfaction with it:

> We are very happy with the glass; due to its limited thickness, the original wooden frame and its detailing were preserved. Guests do not even see the tiny dots between the glass layers. The room is more comfortable, not only because of better insulation characteristics but also because traffic noise is almost absent.

Additionally, the building contained cavity walls, an early example of this building feature. These allowed reversible insulation granules to be applied. Overall, heritage values have remained high after the energy reduction measures were applied:

- *Cultural historical values*: The impact is negligible;
- *Architectural historical value*: The impact is negligible;
- *Ensemble value*: The impact is negligible;
- *Authenticity*: Some impact on the authenticity of the building due to the replacement of historic materials;
- *Rarity*: The impact is negligible.

A photo impression of the building after renovation is presented in Figure 2.

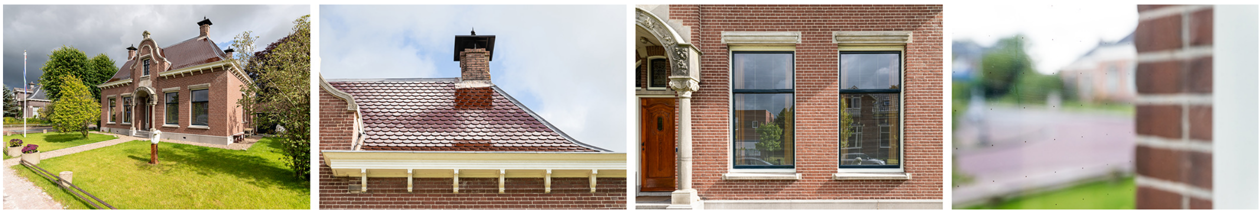

Figure 2. Case in Leens after the construction process (Mark Sekuur, 2024).

3.2. Energy Performance

The building's heated surface area (201 m^2) and volume (656 m^3) remained unchanged with the implementation of energy reduction measures. Heating behaviours were consistent across both timeframes: rooms are heated to 16°C when vacant and to 19°C when occupied.

Energy consumption figures for timeframes 1 and 2 are presented in Table 1. The applied energy reduction measures resulted in a 53% decrease in energy consumption and a 62% reduction of CO_2 emissions.

Table 1. Energy performance.

	Timeframe 1		Timeframe 2	
	kWh	*kg CO_2e/m^2*	*kWh*	*kg CO_2e/m^2*
Heating system	40,090	36	22,666	20
Other energy consumption	4,371	8	2,855	5
Energy generation	Not applicable	Not applicable	−4,761	−9
Total	44,461	44	20,760	17

3.3. CO_2 Emissions

Timeframe 1 includes the CO_2 emissions for energy consumption during the use stage (B1–7), which were calculated at 44 kg CO_2e/m^2. In timeframe 2 this changed to 17 kg CO_2e/m^2. The impact of the construction stages (A1–5) totalled at (2,220 kg CO_2e/yr or) 11 kg CO_2e/m^2 and is specified as follows:

- Restoration and maintenance: (1,485 kg CO_2e/yr or) 7 kg CO_2e/m^2;
- General modernisation: (105 kg CO_2e/yr or) 1 kg CO_2e/m^2;
- Primary energy reduction measures: (630 kg CO_2e/yr or) 3 kg CO_2e/m^2.

To determine the overall CO_2 emissions reduction, we combined the emissions from material changes with those from energy consumption. This resulted in a total reduction of 16 kg CO_2e/m^2, representing an approximately 37% reduction compared to timeframe 1.

4. Case Study 2: Church Musselkanaal

Since the eighteenth century, many protestant communities have separated themselves from the Dutch Protestant church. These separated churches would initially be housed in accommodation provided by church members, such as barns. By the early twentieth century, new churches started to be built. The choice of architect and architectural style tended to be used as a means of distinguishing themselves from other churches/communities.

The church community in Musselkanaal was a small church congregation that belonged to the *Nederlandse Protestanten Bond*, a liberal denomination. The liberal movement expressed itself with contemporary progressive expressionist architecture. Their new church, designed by A.H. Kleinenberg, was completed in 1926. Architectural historical values are found in the unchanged, originally designed hall-church in expressionistic brick *Amsterdam school* architecture, in a variation that is specific to Groningen. Both the architecture and detailing are meticulously crafted. The interior is almost fully original and an integral part of the design. Most of the buildings on Kerkstraat were constructed between 1925 and 1935, giving the street high ensemble values. Many buildings share architectural similarities, such as the school and the associated headmaster's house at the top of the street. Both the school and church are slightly set back from the street compared to the other buildings, emphasising their different functions.

4.1. Heritage Assessment

4.1.1. Timeframe 1

Since 2002, the church has not been used on a daily basis. Consequently, no changes were made to the church, and both the interior and exterior have remained largely authentic. Only the interior colours of the church have been altered in the past. Due to the building's lack of use, maintenance was neglected, resulting in material deterioration.

The church was in a moderate technical condition. The owner elaborated: "Some parts were in a poor condition, for example, the roof. Occasionally, tiles were falling off, which was a risk for the neighbours and their dog." Furthermore, due to the absence of heating, the interior walls had been affected by moisture, which resulted in damaged interior wooden panelling and window frames. Overall, the heritage values were high before the energy reduction measures were applied:

- *Cultural historical values*: Unchanged, thus highly valued;
- *Architectural historical values*: Unchanged, thus highly valued;
- *Ensemble values*: The buildings in the street have positive ensemble values;
- *Authenticity*: Highly valued due to a high degree of originality in both its interior and exterior;
- *Rarity*: The building is relatively rare.

4.1.2. Timeframe 2

The main plan was to both restore the building and initiate an adaptive reuse process to make the church suitable for living and a small enterprise. This involved transforming the church council chamber behind the church into an apartment and converting the main church area into a multifunctional space, to be used as a storage room for an antiques and curiosities business. The building was not insulated and only the council chamber was heated.

The following measures were applied:

- Exterior walls: Thin PIR insulation in partition walls;
- Windows and doors: Plexiglass front windows on the interior side of the stained-glass windows;
- Roof: Thin multi-layered insulation foil;
- Modernisation: Addition of bathroom, toilet, and kitchen;
- Heating system: A wood heating stove and a highly efficient central heating boiler.

The owner is satisfied with the result: "It was challenging to find tailor-made solutions for insulating the curved roof. The architectural detailing of the connection of the roof and front facade is very fragile. The knowledge and advice of the restoration architect were very important." The energy reduction measures improved the thermal comfort required for the new building's function, thereby enabling its conservation. However, these measures did impact the heritage values by altering the architectural design and replacing original materials. Note: all interventions are relatively reversible. It is evident that the decision-making process involved balancing the conservation of authentic elements with the need to adapt the building for contemporary use. Without any changes, the building would likely have suffered further loss of heritage values. Overall, heritage values have remained high after the energy reduction measures were applied:

- *Cultural historical values*: The impact is negligible;
- *Architectural historical values*: A negative impact on visual values because of the visual effect of the insulation of interior walls and roof, and wood pellet stove. Note: These interventions are all relatively reversible;
- *Ensemble values*: The impact is negligible;
- *Authenticity*: A minor negative impact on authenticity values because of the loss of some original materials;
- *Rarity*: A minor negative effect due to the impact on the architectural, historical, and authenticity values. Note: These interventions are all relatively reversible.

A photo impression of the building after renovation is presented in Figure 3.

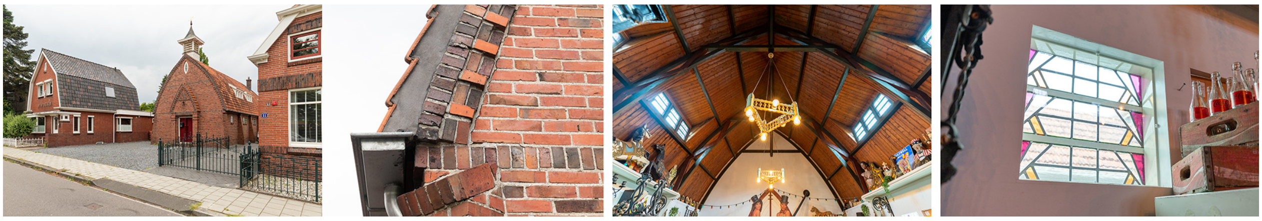

Figure 3. Case in Musselkanaal after the construction process (Mark Sekuur, 2024).

4.2. Energy Performance

The building's heated surface area and volume changed between both timeframes. In timeframe 1, the heated surface area was 74 m^2 and the volume 334 m^3. In timeframe 2, these increased to 201 m^2 and 656 m^3, representing a 1.9-fold increase in surface area and a 1.4-fold increase in volume. Heating behaviour was consistent across both timeframes: rooms are heated to 16°C when vacant, and to 19°C when occupied. The building is used only every other weekend, resulting in a usage intensity of approximately 29% (4 out of 14 days).

Energy consumption figures for timeframe 1 and 2 are presented in Table 2. The applied energy reduction measures resulted in a 14% decrease in energy consumption and a 63% reduction of CO$_2$ emissions.

Table 2. Energy performance.

	Timeframe 1		Timeframe 2	
	kWh	*kg CO_2e/m^2*	*kWh*	*kg CO_2e/m^2*
Heating system	1,899	5	1,612	1
Other energy consumption	272	1	255	0
Energy generation	Not applicable	Not applicable	Not applicable	Not applicable
Total	2,171	5	1,867	2

4.3. CO_2 Emissions

Timeframe 1 includes of the CO_2 emissions for energy consumption during the use stage (B1–7), which were calculated at 35 kg CO_2e/m^2. In timeframe 2, this changed to 20 kg CO_2e/m^2. The impact of the construction stages (A1–5) totalled at (2,921 kg CO_2e/yr or) 15 kg CO_2e/m^2 and is specified as follows:

- Restoration and maintenance: (2,250 kg CO_2e/yr or) 11 kg CO_2e/m^2;
- General modernisation: (544 kg CO_2e/yr or) 3 kg CO_2e/m^2;
- Primary energy reduction measures: (127 kg CO_2e/yr or) 1 kg CO_2e/m^2.

To determine the overall CO_2 emissions reduction, we combined the emissions from material removal and addition with those from energy consumption. This resulted in a total major increase of 11 kg CO_2e/m^2, representing an approximately 224% increase compared to timeframe 1. This is explained by the low CO_2 emissions for energy consumption compared to the changed building materials.

5. Case Study 3: Villa Appingedam

The villa holds high cultural historical value as an example of dwellings of the wealthy bourgeoisie around 1900 in Appingedam. The affluence of some citizens of Appingedam is reflected in the large villa, the carriage house, and the landscaped garden. This prosperity is also reflected in the architectural historical values. The villa and attached carriage house are extraordinary examples of the villa architecture from about 1900 in the province of Groningen. The architect is presumed to have been Geert Kruizinga (1863–1949). The design includes Neo-Renaissance elements, with the interior featuring various highly valuable Neo-Renaissance elements and some later-added Jugendstil decorations. Regarding ensemble values, the location of the villa is special and highly iconic, situated at the crossroads of multiple main roads. Additionally, there is a valuable spatial-visual relation with the monumental landscape garden.

The villa underwent multiple changes throughout the twentieth century. The first major alteration occurred when the building was used for hospitality purposes in the 1960s and a dance hall was added to the western part of the cellar. To this end, the cellars' ceiling had to be elevated by one meter, affecting the styled room, the old kitchen, and the intermediate room on the ground floor. The old staircase was removed and a new one was installed in the intermediate room and the old kitchen. In the 1980s, the carriage house was used as a dental clinic.

5.1. Heritage Assessment

5.1.1. Timeframe 1

The exterior and interior of the monumental villa and carriage house have been changed several times since 1900. Nevertheless, the buildings remain virtually authentic, with the exception of the western part of the cellar and ground level rooms of the villa.

The current owners purchased the villa in 2010 with the ambition of restoring it to its original design and modernise it without compromising its heritage values. The technical condition of the buildings varied between moderate to reasonable; the sunroom was in poor condition, as were the roof and the paintwork on the window frames, mouldings, and especially the lionhead ornaments around the villa. The owners stated:

> For us, it was impossible to apply all interventions at once; that was far too costly. Therefore, we phased our ambitions. As soon as we had amassed a sufficient budget, we would apply the next set of interventions. Furthermore, an expert supported us in developing the design, obtaining the building permit, and guiding the construction process of large restoration interventions.

To summarise, the following measures were applied:

- Floors: Lifting part of the floor of the ground level of the villa to its original level, including alterations on adjacent walls. PIR granulate in the space underneath the first floor of the villa;
- Exterior walls: In the kitchen, glass wool insulation in partial walls. Repairing stone ornaments in the masonry brick walls of the villa. Restoring the timber walls of the sunroom;
- Windows: Glass was replaced with HR++ glass of the villa, including replacing the yellow glass windows in the sunroom. Window and door frames were repaired and painted;
- Roofs: Damaged roofing was replaced and the roofs were insulated with glass wool. The villa's hatch panel to the roof was repaired;
- Internal walls: Glass wool was applied in the timber framed walls on the first floor;
- Maintenance and restoration: Restoring (rebuilding) an old staircase in the villa;
- Modernisation: Replacing the villa's kitchen and adding a professional kitchen in the carriage house;
- Heating system: Two highly efficient central heating boilers (in the villa and in the carriage house). Restoring the wood stove in the living room. An electric heating system on the first floor;
- Other systems: PV panels on the villa.

Because the majority of heritage values was still intact, overall, the heritage values were highly valued before energy reduction measures were applied:

- *Cultural historical values*: Unchanged, thus highly valued;
- *Architectural historical values*: Although several elements have been altered, the overall design remains, including Neo-Renaissance elements and some later-added Jugendstil decorations;
- *Ensemble values*: Unchanged, thus highly valued;
- *Authenticity*: The villa has positive values as most of the original design and materials of both the interior and exterior are largely intact with minor changes and reconstructions due to the different functions the building has had over the years;
- *Rarity*: The villa is relatively rare.

5.1.2. Timeframe 2

The restoration included modernisation but did not involve large-scale energy reduction measures. The applied measures had a minor impact on heritage values, as the primary goal was to reinforce these heritage values. The owners revealed:

> You know you did not buy a modern energy-efficient building, therefore we accepted that thermal comfort in the villa is somewhat limited and energy costs are relatively high. We have chosen to apply a zoning concept, which means that we only heat the rooms that we use.

These types of energy reduction measures resulted in remaining high heritage values:

- *Cultural historical values*: The impact is negligible;
- *Architectural historical values*: The villa is restored to its original function as residential house. The impact is negligible;
- *Ensemble values*: The impact is negligible;
- *Authenticity*: The impact is negligible, with the exception of replaced materials and the detailing of the stairs due to wall insulation;
- *Rarity*: The impact is negligible.

A photo impression of the building after renovation is presented in Figure 4.

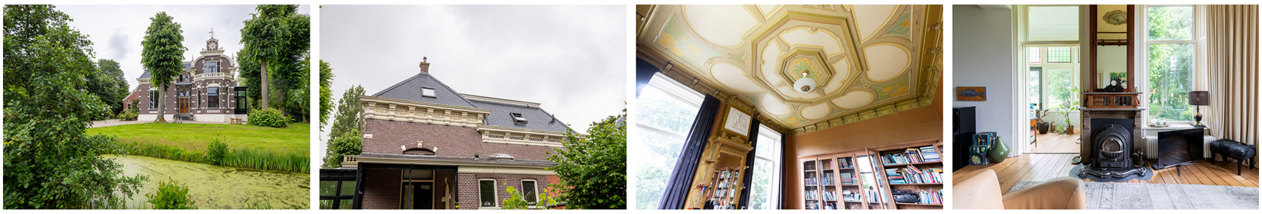

Figure 4. Case in Appingedam after the construction process (Mark Sekuur, 2024).

5.2. Energy Performance

The building's heated surface area (389 m^2) and volume (1,227 m^3) remained unchanged after the implementation of energy reduction measures. Heating behaviour was consistent across both timeframes: rooms are heated to 15°C when vacant and to 18°C when occupied.

Energy consumption figures for timeframe 1 and 2 are presented in Table 3. The applied energy reduction measures resulted in a 37% decrease in energy consumption and a 41% reduction of CO_2 emissions.

Table 3. Energy performance.

	Timeframe 1		Timeframe 2	
	kWh	*kg CO_2e/m^2*	*kWh*	*kg CO_2e/m^2*
Heating system	68,575	31	46,563	22
Other energy consumption	3,750	4	3,750	4
Energy generation	Not applicable	Not applicable	−5,000	−5
Total	72,325	35	45,313	20

5.3. CO_2 Emissions

Timeframe 1 includes the CO_2 emissions for energy consumption during the use stage (B1–7), which were calculated at 35 kg CO_2e/m^2. In timeframe 2, this changed to 20 kg CO_2e/m^2. The impact of the construction stages (A1–5) totalled at (4,684 kg CO_2e/yr or) 15 kg CO_2e/m^2 and is specified as follows:

- Restoration and maintenance: (3,906 kg CO_2e/yr or) 10 kg CO_2e/m^2;
- General modernisation: (542 kg CO_2e/yr or) 1 kg CO_2e/m^2;
- Primary energy reduction measures: (1,237 kg CO_2e/yr or) 3 kg CO_2e/m^2.

To determine the overall CO_2 emissions reduction, we combined the emissions from material removal and addition with those from energy consumption. This resulted in a total reduction of 0 kg CO_2e/yr, i.e., 0% reduction compared to timeframe 1.

6. Case Study 4: Farm Spijk

The farm building from 1900 holds significant cultural historical value as a representative example of agricultural buildings in the province of Groningen around the turn of the century. Its substantial size and the richly detailed interior of the front house reflect the lifestyle and status of the small group of wealthy farmers in this region during that period. Furthermore, the farm building holds significant architectural historical values as an example of the regional farm type of *dwarshuisboerderij*, a farm where the house is transversely oriented in front of the barn. The story of the wealthy farmers is reflected in the Eclectic architecture of the *dwarshuis*' exterior and interior that exhibit exceptionally rich detailing. Furthermore, it is reflected in the ensemble values: the tree-filled and in part moated farm property retains its original character in its iconic location just outside the village of Spijk, situated on one of the oldest exit roads. Its significance is further enhanced by the local ensemble of a wide canopy of trees, drive-up avenue, moat enclosure with pedestrian bridge, and decorative garden.

In 1962, the farm lost its function, and it was bought by an artist couple who respected its heritage values. Before the building was listed, a watchtower was placed on the barn, and an atelier was built inside it.

6.1. Heritage Assessment

6.1.1. Timeframe 1

The previous owners made several modifications to the interior of the farm, such as converting the attic of the old house (located between the front house and barn) into a bedroom and also modernising the atelier room in the barn. The exterior of the farm remained in an almost original condition prior to the implementation of energy reduction measures. The cessation of the agricultural activities did not lead to significant alterations or loss of heritage values. Many of the historic materials, the building's layout, and the architectural details were still intact.

Due to prolonged neglect of maintenance needs, some historical materials were severely damaged and irreparable, such as window frames, the roof, and areas affected by leaks and insects. Additionally, structural issues arose from both previous poor interventions and soil subsidence.

Overall, the heritage values were high before energy reduction measures were applied:

- *Cultural historical values*: Unchanged, thus highly valued;
- *Architectural historical values*: The valued elements are largely intact, thus highly valued;
- *Ensemble values*: Although the building lost its agricultural function, the property retains its original character, thus highly valued;
- *Authenticity*: The building holds positive authenticity values due to the largely originality of the exterior, floor plan, and decorative interior elements;
- *Rarity*: The *dwarshuisboerderij* is relatively rare.

6.1.2. Timeframe 2

The current owners initiated a large-scale restoration and maintenance process. The sustainability ambitions were significant, but they did not want to compromise heritage values. Therefore, energy reduction measures were applied with caution, ensuring that heritage values were not adversely affected. The owners stated:

> We were impressed by the beauty of the front house and compromising its values was out of the question. But we also needed to be able to live here comfortably. Therefore, we used a living area in the former atelier in the barn as a winter residence. It avoided applying major interventions in the front house.

The following measures were applied:

- Foundation: A new foundation was applied in the conservatory;
- Exterior walls: Damaged walls were repaired;
- Windows: Glass was replaced with HR++ glass. Window and door frames were repaired and painted;
- Roof: The roof of the front house was repaired and glass wool was applied. The barn's roof plates (partly asbestos) were replaced by a thatched roof. Furthermore, the roof construction near the sunroom and part of the front house was strengthened;
- Maintenance and restoration: Various minor maintenance work;
- Modernisation: Upgrading the former atelier space in the barn into a well-insulated living room for the cold season;
- Heating system: A high-efficiency heating boiler for the front house and a heat stove in the former atelier space in the barn.

The owners are satisfied with the results:

> The historic atmosphere of the front house was preserved; it is a pleasure to live here. Although, we would like to find a way to further improve the use of sustainable energy. Currently, we cannot and do not want to apply solar panels on the thatched roof or in the garden that is full of trees.

The impact of energy reduction measures on heritage values was negligible; heritage values remained high:

- *Cultural historical values*: The impact is negligible;
- *Architectural historical values*: A little to no negative effect on the architectural values and in part contributed to their enhancement with the restoration of the thatched roof of the barn;
- *Ensemble values*: The impact is negligible on the ensemble values;
- *Authenticity*: Some loss of certain authenticity values, while others contributed to their enhancement;
- *Rarity*: The impact is negligible.

A photo impression of the building after renovation is presented in Figure 5.

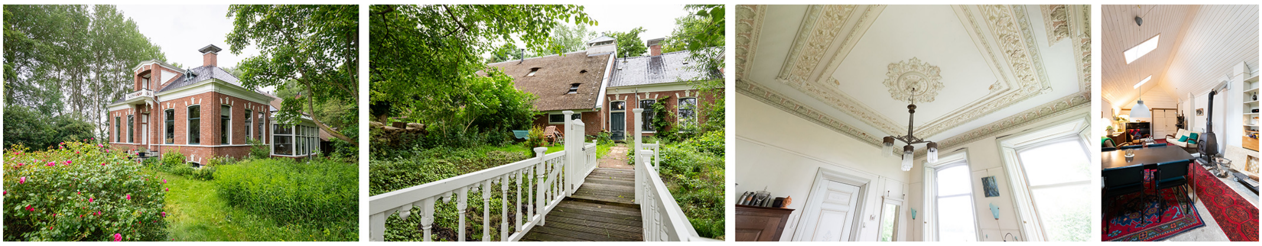

Figure 5. Case in Spijk after the construction process (Mark Sekuur, 2024).

6.2. Energy Performance

The buildings' heated surface area and volume changed slightly between both timeframes. In timeframe 1, the heated surface area was 333 m^2 and the volume 974 m^3. In timeframe 2, these increased to 360 m^2 and 1,031m^3, respectively—representing a 1.1-fold increase in both metrics. Heating behaviour was consistent across both timeframes: rooms are heated between 10–15°C when vacant and to 19°C when occupied. Moisture levels are actively monitored, allowing the temperature to be increased when critical values are reached, particularly during the cold season.

Energy consumption figures for timeframe 1 and 2 are presented in Table 4. The applied energy reduction measures resulted in a 12% decrease in energy consumption and a 47% reduction of CO_2 emissions.

Table 4. Energy performance.

	Timeframe 1		Timeframe 2	
	kWh	*kg CO_2e/m^2*	*kWh*	*kg CO_2e/m^2*
Heating system	30,818	16	28,066	9
Other energy consumption	2,656	3	1,519	2
Energy generation	Not applicable	Not applicable	Not applicable	Not applicable
Total	33,474	19	29,585	10

6.3. Assessment of CO_2 Emissions

Timeframe 1 includes the CO_2 emissions for energy consumption during the use stage (B1–7), which were calculated at 19 kg CO_2e/m^2. In timeframe 2 this changed to 10 kg CO_2e/m^2. The impact of the construction stages (A1–5) totalled at (2,440 kg CO_2e/yr or) 7 kg CO_2e/m^2 and is specified as follows:

- Restoration and maintenance: (1,455 kg CO_2e/yr or) 4 kg CO_2e/m^2;
- General modernisation: (536 kg CO_2e/yr or) 1 kg CO_2e/m^2;
- Primary energy reduction measures: (449 kg CO_2e/yr or) 1 kg CO_2e/m^2.

To determine the overall CO_2 emissions reduction, we combined the emissions from material removal and addition with those from energy consumption. This resulted in a total reduction of 2 kg CO_2e/m^2, representing an approximate 11% reduction compared to timeframe 1.

7. Conclusion

The aim of this study was to deepen the understanding of sustainable heritage practice in the Netherlands by evaluating the impact of energy reduction measures on heritage values, energy performance, and CO_2 emissions.

We found that heritage values—both visual and material—were lost to varying extents across the case studies. For example, the removal of single glazing and the addition of insulation impacted architectural details. In all cases, stakeholders tried to minimise the loss of heritage values by applying reversible energy reduction measures. Consequently, several “lost” heritage values are concealed. In one case, a new living room was created in the barn to avoid damaging high heritage values in the original rooms. In other cases, heritage values had already been compromised due to a poor technical condition, which created opportunities for energy reduction measures. Additionally, some owners noted that restoration activities were inherently sustainable, as they prevented heat loss through cracks, for example.

Energy performance varied significantly across the four case studies. This can partly be attributed to the different energy reduction measures implemented, particularly to the transition from fossil fuels to renewable energy, and, in one case study, to the increased heated volume. On average, energy performance improved with a CO_2 reduction of approximately 52%. This exceeds the 19% of the Dutch Sustainable Heritage Monitor (De Vries & De Jong, 2024), but matches the ambitions set in Dutch Sustainable Heritage Roadmap (Routekaart Duurzaam Erfgoed, 2019)—which are a 40% CO_2 reduction by 2030 and a 60% reduction by 2040. Two of the investigated case studies already achieve the 2040 ambitions, by approximately 62% and 63%. We want to emphasise that the primary focus of the four projects was restoration, with energy reduction ambitions only as secondary objectives.

The CO_2 emissions assessment accounted for both the use stage (operational carbon or energy consumption) and the construction stage (or embodied carbon or removed and added building materials). These measures on average lowered the CO_2 emissions by circa 6%. While examining the four individual case studies, we observed widely different outcomes; three cases showed a reduction in emissions ranging between approximately 0–37%, while one case saw CO_2 emissions increase by approximately 224%. This particular increase can be attributed to the building's prior low use intensity, minimum reduction in energy consumption, and extensive restoration and modernisation interventions. Overall, the findings indicate that CO_2 emissions are strongly influenced by the following factors:

- *Energy consumption figures*: For three cases (Leens, Appingedam, Spijk), energy consumption constituted a dominant contributor to baseline CO_2 emissions (timeframe 1). Traditionally, the environmental impact of the energy source, such as natural gas or solar energy, played a strong role;
- *Daily use*: All cases exhibited relatively low indoor temperatures, ranging between 16–19°C. Moreover, when the heated surface area and volume of the building increase, the effectiveness of energy reduction measures tended to diminish. This was found in two cases (Musselkanaal, Spijk);
- *Interaction between operational and embodied carbon*: In cases where buildings were only occasionally used during timeframe 1 (and in some instances timeframe 2), the baseline CO_2 emissions were relatively low. As a result, material interventions such as restoration and modernisation could lead to a net increase in CO_2 emissions. This was observed in one case (Musselkanaal). Furthermore, extensive interventions required for maintenance or modernisation also contributed to increased emissions in two cases (Musselkanaal, Appingedam).

Our findings offer added value to the Monitor for Sustainable Heritage (De Vries & De Jong, 2024) by demonstrating how a more holistic approach is crucial for comprehending why specific results for sustainable heritage are achieved (Lidelöw et al., 2019; Webb, 2017; Wise et al., 2021). We recommend expanding the Monitor's survey to include questions on daily use, simultaneous execution of maintenance, modernisation, and energy interventions, and impact of energy reduction measures on heritage values. The latter should be addressed using a consistent and accessible approach, particularly for owners of built heritage who are not trained in heritage value assessment. Therefore, we recommend further developing the approach of Serrano et al. (2022) who distinguish sustainable heritage scenarios, such as the energy-efficient restoration design scenario and the energy renovations design scenario that does not include a heritage valuation.

To close, our study concludes that even when energy reduction ambitions are secondary targets of restoration, good results can be achieved, although it may come at a cost.

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Conflict of Interests

The authors declare no conflict of interests.

Data Availability

Due to the nature of the research, data sharing is not applicable to this article.

LLMs Disclosure

During the writing process, we used the AI language model Copilot from Microsoft to check our concept article for spelling and grammar mistakes. The software operates in a closed environment, ensuring that the input texts are not uploaded to a public database.

References

Baker, H., Moncaster, A., Remøy, H., & Wilkinson, S. (2021). Retention not demolition: How heritage thinking can inform carbon reduction. *Journal of Architectural Conservation*, *27*(3), 176–194. https://doi.org/10.1080/13556207.2021.1948239

Costantino, C., Benedetti, A. C., & Gulli, R. (2024). The role of circular design principles in the language of residential architecture. A reflection on the implications that technical aspects bring to the contemporary way of building. In C. Bartolomei, A. Ippolito, & S. H. T. Vizioli (Eds.), *Contemporary heritage lexicon* (pp. 1–23). Springer. https://doi.org/10.1007/978-3-031-61245-9_1

De Erfgoedstem. (2014). *Stichting stelt 'menukaart' op voor duurzame monumenten*. https://erfgoedstem.nl/stichting-de-groene-grachten-zorgt-voor-doorbraak-duurzame-monumenten

De Jonge, W. (2011). *Duurzaam verbeterd! Bepaling duurzaamheid herbestemming karakteristieke gebouwen*. Wessel de Jonge Architecten bna BV & Climate Design Consult; Bouwadviesgroep voor bouwfysica.

De Vries, P., & De Jong, J. H. (2024). *Monitor Routekaart Verduurzaming 2024, week van het duurzame erfgoed 2024* [PowerPoint presentation].

Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings. (2024). *Official Journal of the European Union*. https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng

Dişli, G., & Ankaralıgil, B. (2023). Circular economy in the heritage conservation sector: An analysis of circularity degree in existing buildings. *Sustainable Energy Technologies and Assessments*, *56*, 103126. https://doi.org/10.1016/j.seta.2023.103126

Eerste Kamer der Staten Generaal. (2017). *Goedkeuring Overeenkomst van Parijs betreffende klimaatverandering*. https://www.eerstekamer.nl/wetsvoorstel/34589_goedkeuring_overeenkomst_van

European Commission. (2019). *Communication from the Commission: The European Green Deal*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52019DC0640

European Environment Agency. (2019). *EMEP/EEA air pollutant emission inventory guidebook 2019*.

Huuhka, S., & Vestergaard, I. (2020). Building conservation and the circular economy: A theoretical consideration. *Journal of Cultural Heritage Management and Sustainable Development*, *10*(1), 29–40. https://doi.org/10.1108/JCHMSD-06-2019-0081

I&W. (2024). *Omgevingswet*. Overheid.nl. https://wetten.overheid.nl/BWBR0037885/2024-01-01#Hoofdstuk23

Klimaatakkoord. (2018a). *Hoe het Klimaatakkoord tot stand kwam*. https://www.klimaatakkoord.nl/organisatie/hoe-het-klimaatakkoord-tot-stand-kwam/sectortafels

Klimaatakkoord. (2018b). *Ontwerp van het Klimaatakkoord—hoofdstuk Gebouwde omgeving*. https://www.klimaatakkoord.nl/organisatie/documenten/publicaties/2018/12/21/gebouwde-omgeving

Lidelöw, S., Örn, T., Luciani, A., & Rizzo, A. (2019). Energy-efficiency measures for heritage buildings: A literature review. *Sustainable Cities and Society*, *45*, 231–242. https://doi.org/10.1016/j.scs.2018.09.029

MESH Energy. (2024). *Mesh_Stage_1_Embodied_Carbon_Calculator_v8_Released_7-6-24*. https://www.mesh-energy.com/resources/embodied-carbon-calculator-v2

Nusselder, E. J., Van de Ven, H., Haas, M., & Dulski, B. (2008). *Handboek Duurzame Monumentenzorg. Theorie en praktijk van duurzaam monumentenbeheer*. Stichting ISSO.

OCW. (2024). *Erfgoedwet*. Overheid.nl. https://wetten.overheid.nl/BWBR0037521/2024-01-01#Hoofdstuk11

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: Measuring innovation in the product chain*. PBL Netherlands Environmental Assessment Agency. https://library.wur.nl/WebQuery/groenekennis/2200191

Provincie Groningen. (2024). *Subsidieregeling groot onderhoud en restauratie rijksmonumenten provincie Groningen 2024*. Overheid.nl. https://lokaleregelgeving.overheid.nl/CVDR724996/1

RCE. (2024). *Eenheid en verscheidenheid (achtergronddocument), een zoektocht naar een integrale cultuurhistorische waardestelling van het materiële erfgoed*. https://www.cultureelerfgoed.nl/onderwerpen/waarderen-van-cultureel-erfgoed/documenten/publicaties/2014/01/01/eenheid-en-verscheidenheid-achtergronddocument

Right Marktonderzoek en Advies. (2022a). *Rapportage monitor verduurzaming monumenten 2021*. Routekaart Verduurzaming Monumenten. https://www.duurzaamerfgoed.nl/sites/default/files/2022-02/2021_Rapportage%20monitor%20verduurzaming%20monumenten_0.pdf

Right Marktonderzoek en Advies. (2022b). *Rapportage monitor verduurzaming monumenten 2022*. Routekaart Verduurzaming Monumenten. https://www.duurzaamerfgoed.nl/sites/default/files/2022-11/2022_Rapportage%20monitor%20verduurzaming%20monumenten.pdf

Right Marktonderzoek en Advies. (2024). *Rapportage monitor verduurzaming monumenten 2023*. Routekaart Verduurzaming Monumenten. https://www.duurzaamerfgoed.nl/sites/default/files/2024-09/2023_Rapportage%20monitor%20verduurzaming%20monumenten.pdf

Right Marktonderzoek en Advies. (2025). *Rapportage monitor verduurzaming monumenten 2024*. Routekaart Verduurzaming Monumenten.

Routekaart Duurzaam Erfgoed. (2019). *Routekaart verduurzaming monumenten*. https://www.duurzaamerfgoed.nl/sites/default/files/2020-06/2019%20Routekaart%20Verduurzaming%20Monumenten.pdf

Routekaart Duurzaam Erfgoed. (2022). *Monitoringrapportage monumenten 2022*. https://www.duurzaamerfgoed.nl/sites/default/files/2022-11/29092022%20monitoringsrapportage%20monumenten%20def.pdf

Sekuur, M. (2024). *Foto's behorend bij de Evaluatie verduurzaming Rijksmonumenten Groningen (Libau 2024)*. Rijksdienst voor het Cultureel Erfgoed.

Serrano, T., Kampmann, T., & Ryberg, M. W. (2022). Comparative life-cycle assessment of restoration and renovation of a traditional Danish farmer house. *Building and Environment*, *219*, 109174. https://doi.org/10.1016/j.buildenv.2022.109174

Stichting ERM. (2019). *Restauratieladder als leidraad*. https://www.stichtingerm.nl/restauratieladder

Stichting ERM. (2020). *Uitvoeringsrichtlijn 2001, Bouwkundig advies monumenten*.

Stichting ERM. (2024). *Uitvoeringsrichtlijn 2007 Bouwhistorisch Onderzoek met waardenstelling*.

Stichting Nederlandse Milieudatabase. (n.d.). *De Nationale Milieudatabase*. https://milieudatabase.nl/en/database

Stichting NEN. (2012). *NEN-EN 15978:2011—Duurzaamheid van constructies—Beoordeling van milieuprestaties van gebouwen—Rekenmethode*.

Stichting NEN. (2017). *NEN-EN 16883:2017* [Behoud van cultureel erfgoed—Richtlijnen voor verbetering van de energieprestatie van historische gebouwen].

United Nations. (2015). *Adoption of the Paris Agreement*. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

Van der Schoor, T. (2020). *Strategies for energy reconfigurations: Obduracy, values and scripts* [Unpublished doctoral dissertation]. Maastricht University. https://doi.org/10.26481/dis.20200528ts

Van der Schoor, T., Peine, A., & Van Lente, H. (2024). Contested commensuration: The case of a valuation instrument for historical buildings. *Valuation Studies*, *11*(1), 138–161. https://doi.org/10.3384/VS.2001-5992.2024.11.1.138-161

Vieveen, M., Banninga, A., & Munuswamy, T. (2024). *Evaluatie verduurzaming rijksmonumenten Groningen*. Libau. https://hbo-kennisbank.nl/record/oai:research.hanze.nl:publications/8ce10c1b-ecf9-4dcc-9da3-1074306f7500

Webb, A. L. (2017). Energy retrofits in historic and traditional buildings: A review of problems and methods. *Renewable & Sustainable Energy Reviews*, *77*, 748–759. https://doi.org/10.1016/j.rser.2017.01.145

Wise, F., Moncaster, A., & Jones, D. (2021). Rethinking retrofit of residential heritage buildings. *Buildings & Cities*, *2*(1), 495. https://doi.org/10.5334/bc.94

Yang, Q. Z., Zhou, J., & Xu, K. (2014). A 3R implementation framework to enable circular consumption in community. *International Journal of Environmental Science and Development*, *5*(2), 217–222. https://doi.org/10.7763/IJESD.2014.V5.481

Yin, R. K. (2009). *Case study research: Design and methods* (4th ed.). Sage.

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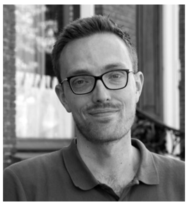

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