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Is Heritage Protection a Limiting Factor for Passive Deep Energy Retrofitting? A Cold-Climate Case Study of University Buildings

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Abstract: Reducing the energy consumption of the existing building stock is of paramount importance in the race to reach national and international climate goals. While multiple initiatives are in place and provide guidance, heritage-protected buildings are often not part of the equation. Protected buildings make up a large share of the existing building stock and therefore offer large savings potential. In Trondheim, Norway, alone, that share is close to 10%, which demands the establishment of representative retrofitting cases. A case study of the central buildings on the NTNU campus was established to specifically test passive retrofitting measures, which are greatly affected by heritage protection. The application of measures selected in collaboration with heritage authorities led to overall energy savings of 16% to 18%, while the energy for heating alone was reduced by 34% to 40%. The reductions were especially prominent during cold winter months, where overall consumption peaks were reduced by up to 37%, greatly decreasing the dependence on cold outdoor temperatures. The results make a case for the application of passive retrofitting measures to heritage-protected buildings despite them not reaching deep energy retrofitting goals, especially in cold climates and alongside other energy-saving or -producing measures.

Keywords: passive retrofitting measures; cold climate; case study; non-residential; educational buildings; energy retrofitting; deep energy retrofitting; heritage protection; building energy modeling (BEM); building performance simulation (BPS)



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1. Introduction

1.1. Climate Goals and International Initiatives

The main motivators for retrofitting buildings today include climate goals and the associated energy reduction ambitions set nationally and internationally. The European Union (EU), as an international actor, has the long-term goal of achieving climate neutrality by 2050 [1], with milestones in 2030 and 2040 [2]. While these are overall goals, there are more specific goals for the respective sectors, such as the building sector. Again, the overall goal is a fully decarbonized building stock by 2050, as it is stressed that buildings are among the largest consumers of energy [3]. The Energy Performance in Buildings Directive (EPBD) [4] and Energy Efficiency Directive (EED) [5] were established as part of a legislative framework, and the Renovation Wave for Europe was established as a strategy to renovate 35 million buildings in the EU by 2030 [6]. The relevance of both directives extends beyond the 27 EU countries to all countries within the European Economic Area (EEA), including countries such as Norway. While the Renovation Wave for Europe does not specifically mention the EEA, the strategy can be seen as an important guide all across Europe, as

the aim is “to improve overall living standards for Europeans” [7]. The strategy has three focus areas that should be prioritized due to their potential, two of them being “tackling energy poverty and worst-performing buildings” and “renovating public buildings, such as administrative, educational and healthcare facilities” [6].

1.2. Heritage Protection Within the European Building Stock

While frameworks and strategies for the retrofitting and renovation of buildings are in place, there is a lack of focus on how to target and include heritage-protected buildings. These protected buildings make up a large proportion of the building stock, have high energy consumption, and offer great potential for energy reductions. It is estimated that about 85–95% of all existing buildings will still be in use in 2050, with about 85% of these buildings built before 2001 [6]. Protected buildings were previously studied in projects such as the EFFESUS project on “Energy Efficiency for EU Historic Districts’ Sustainability”, which ran on from 2012 to 2016, funded by the European Commission (EC). Here, it was mentioned that about 23% of all the buildings of the total building stock were built before 1945, many of them officially listed [8]. Other sources report a share larger than 25% of European buildings that are historic [9]. While not all historic buildings are considered heritage-protected, this large share serves as an indicator of current and future heritage protection. The Renovation Wave for Europe recognizes that renovation must respect heritage and that the cultural heritage of historical buildings must be safeguarded, but does not offer further guidance [6]. The recently updated EPBD specifies that heritage buildings may be exempt from minimum performance standards [4]. The EED also states that less stringent requirements and energy levels should be applied to historical buildings [5]. The strategy and directives may be interpreted in such a way that exemptions are only to be made for heritage buildings, if meeting the standards is not possible or feasible. Because energy reduction efforts in the building sector have already been going on for many years, the importance of protected buildings is increasing because non-protected buildings, as “low-hanging fruit”, have mostly already been looked at and more buildings will be protected in the future.

1.3. Energy Upgrading Definitions and Reduction Goals

The Renovation Wave for Europe aims not only to increase the renovation rate, in general, but also to increase deep renovation. Deep renovation is defined in a recommendation on building renovation from 2019, again with EEA relevance [10]. It is the most ambitious renovation recommendation, with energy savings of more than 60% compared to light (less than 30%) and medium (between 30% and 60%) renovation [10]. The International Energy Agency (IEA) Annex 61 on the Definition of Deep Energy Retrofit (DER) defines a deep energy retrofit as a major renovation project through which the site energy use intensity, including plug loads, is reduced by at least 50% compared to a pre-renovation baseline [11]. While there are definitions for both deep renovation and deep retrofitting, there is no clear distinction, and the terms are often used analogously. Retrofitting can, however, be seen as a continuation of a renovation. Che Husin et al. summarize commonly used terms as follows [12]:

- Refurbishment: A process of returning the building or its systems to their original condition, addressing the forces of physical obsolescence.
- Renovation: A process of taking refurbishment as one step onward by integrating changes to physical parameters of the building.
- Retrofit: A process of replacing and upgrading systems and technology in an existing building to address its technological or environmental obsolescence.

An extended list of commonly used terms is available in a recent literature review on building retrofitting [13]. While referring to the Renovation Wave for Europe as an overarching strategy, the term “retrofitting” will be used for the case study and ambition

covered in this study to highlight the aim to not only restore previous qualities, but also to further increase energy performance.

1.4. Passive Retrofitting in Cold Climates

Retrofitting projects mostly consist of combinations of active and passive retrofitting measures. Passive measures, often synonymous with building envelope measures, are weather-induced without occupancy control, while active measures, often associated with building control and systems operation, are operator-induced [14]. The installation of renewable energy sources such as PV systems is partly categorized as passive measures [14], as active measures [15], or separately as renewable energy integration [16]. The combination of multiple types of measures undoubtedly leads to the best results. Smaller active measures, such as the switch to LED lighting, can be seen as low-hanging fruit in retrofitting projects, requiring little money and overall effort. They are often simpler to implement, especially in heritage-protected cases where passive measures are subject to restrictions, as they greatly impact the building's esthetic character. The implementation of passive measures must therefore be considered carefully, in collaboration with heritage protection authorities, and in consideration of the feasibility of expected outcomes. This feasibility was shown to greatly depend on the project's location and climate conditions. As passive retrofitting measures mainly impact the heating demand, they are more feasible if implemented in cold climates, compared to warmer climates [17]. A study on Positive Energy Districts (PEDs) confirms the higher economical value of passive retrofitting in cold climates [15]. Passive retrofitting measures have also been shown to be effective in future climate scenarios [16].

1.5. The Need for Retrofitting Heritage-Protected Buildings on a Local Scale

Upon studying the effect of passive retrofitting measures on heritage-protected buildings, the need for local case studies becomes clear. The local approach targets both buildings defined as focus areas of the Renovation Wave for Europe [6] and local heritage protection classifications. Taking Norway as an example, non-uniform heritage protection definitions pose difficulty for national retrofitting strategies and guidelines. There are both national heritage authorities, the "Riksantikvaren" [18], and local ones, such as the "Byantikvaren" in the city of Trondheim [19]. Up to 10% of the existing building stock in Trondheim is heritage-protected to a degree [19]. The heritage protection data contain detailed descriptions of the heritage value of each building.

The heritage protection classes in Trondheim range from class A (3% of all cases) to class B (18% of all cases) and class C (76% of all cases), from highest protection status to lowest [19,20]. In addition to local heritage protection classes, some buildings are protected according to the national Norwegian Act concerning the cultural heritage [21] and marked as "Freda" (3% of all cases), which is the highest possible protection, demanding heritage approval for all measures for the protected object that extend beyond usual maintenance [19]. In recent research, all heritage-protected buildings in Trondheim were analyzed to establish the most representative cases for energy retrofitting. The results showed that certain combinations of features clearly outnumber others. Taking educational buildings, protected according to class C, as an example, the focus should be on buildings built between 1950 and 1975 from concrete as the main construction material. That specific combination represents about 44% of the educational class C cases, with the next most representative combinations only accounting for about 10% [22].

The implications of retrofitting class C-protected buildings depend on the protected aspect, most typically the building envelope. Protecting envelopes aims to safeguard both the building's individual esthetic and its surroundings. Consequently, all measures changing the envelope must be avoided or complement the existing characteristics with the

approval of the heritage protection authorities. An unchanged visual impression is the aim; the original color schemes should be maintained, windows and shading systems should be visually unintrusive, the insulation thickness should be limited, etc. All these principles must be followed even more strictly in higher heritage protection classes.

1.6. Past Research Efforts and Reference Case Studies

Retrofitting heritage-protected buildings comes with an inherent challenge of two competing objectives [23,24]. While energy reduction goals demand changes to be applied to a building, conservation goals aim to preserve a building and safeguard architectural and cultural value. Compromises can still be found when considering both parties during the retrofitting processes.

Focusing on non-residential buildings, a less covered protected building typology, multiple past cases showed great reductions in energy consumption. In a historical educational case in Benevento, Italy, it was demonstrated that adapted management regimes alone could reduce annual electricity usage by about 24% and the application of passive retrofitting measures could reduce the annual primary energy demand by about 38% [25]. An energy refurbishment study of the historic Aviation Museum in Belgrade, Serbia, concluded that a combination of envelope renovation and the installation of Renewable Energy Solutions (RES) may even result in a power surplus and a zero-emission status [26]. In a case study on the Southeast University campus in Nanjing, China, the energy savings ranged from 10% to 44% for scenarios including measures increasing operational efficiency, and additional passive building envelope measures. Added energy production resulted in up to 505% savings (as the energy production greatly exceeded the demand) [27]. A comprehensive literature review by Herrera-Avellanosa et al., covering 69 case studies of energy retrofits of historic buildings, confirms a great distribution of possible energy reductions that may be achieved. For non-residential buildings, the heating energy savings were 20% to 40% (in 2 of 10 cases), 40% to 60% (in 1 of 10 cases), 60% to 80% (in 5 of 10 cases), and more than 80% (in 2 of 10 cases). Notably, the authors report high reductions in energy use independent of the level of protection [28].

1.7. Objective and Scope

The aim of this study was to explore heritage protection as a possibly limiting factor for passive deep energy retrofitting. With this aim, we build on the international need to energy retrofit heritage-protected buildings to facilitate reaching climate goals, despite possibly conflicting objectives. Passive retrofitting measures, which are more effective in cold-climate settings, might be especially subject to protection regulations due to their effects on the buildings' esthetics. Past efforts have demonstrated the demand for local, but representative, case studies due to the large variety of heritage protection definitions. While previous case studies exist, there is a lack of cases representing the focus areas of the Renovation Wave of Europe in cold climates and for passive retrofitting and heritage protection specifically.

The novelty of this study is the particular focus on a newly emerging group of heritage-protected non-residential concrete buildings that were built from 1950 to 1974 in the Norwegian cold climate. Due to relatively young age and protection definitions, there is an apparent demand to cover these buildings' role in energy reduction efforts. We explore the potential of reaching deep energy retrofitting goals by implementing passive retrofitting measures in a university case study in Trondheim, Norway. We utilize both digital representations and energy simulations, as well as local heritage protection definitions. Three research questions were defined based on the observed research gaps and the objective of the study:

1. Which passive retrofitting measures can be applied to heritage-protected buildings?
2. Is passive deep energy retrofitting achievable in cold-climate heritage-protected cases?

3. What are the implications of passive retrofitting in cold-climate heritage-protected cases?

1.8. Limitations

When simulating building energy scenarios, the quality and fit of the building energy model are of great importance. The two models used in this study were previously calibrated to satisfactory statistical fits, based on measured data provided by the university, as summarized in Table 1. Most of the building documentation that was used for reference during the modeling process contained building construction details, but there was greater uncertainty surrounding the technical systems and constantly evolving control schemes. Consequently, and due to the scope of the study, no active retrofitting measures were analyzed. The settings of the calibrated baseline models resulted in a few retrofitting measures that were non-applicable and therefore had to be excluded from the analysis to only consider measures realistic to the case study, as marked in Tables 2 and 3.

The selection of passive retrofitting measures, displayed in Table 2, is based on both commonly applied measures and recommendations, and made in agreement with local heritage protection authorities. As there are many different heritage protection authorities at the local and national levels, the specific selection and configuration of measures may be different in other cases. Nevertheless, the case chosen does have a representative character at a local level, allowing a certain transfer of solutions and results to future cases. The combinations of retrofitting measures chosen to represent both more conservative and more ambitious retrofitting packages, displayed in Table 4, must additionally be tested for their building physics behavior before actual implementation, especially in terms of their hygro-thermal behavior.

2. Materials and Methods

2.1. Project Workflow

The project followed an established workflow that ensured it was based on past research efforts on the establishment of representative case studies [22]. The workflow then followed a clear retrofitting evaluation path that was quality controlled and approved by the local heritage protection bureau, Byantikvaren (Kjøpmannsgata 36, 7011 Trondheim, Norway) [19]. Finally, the results prepare the way for future studies on the project's implications for the wider protected building stock. The full workflow is displayed in Figure 1.

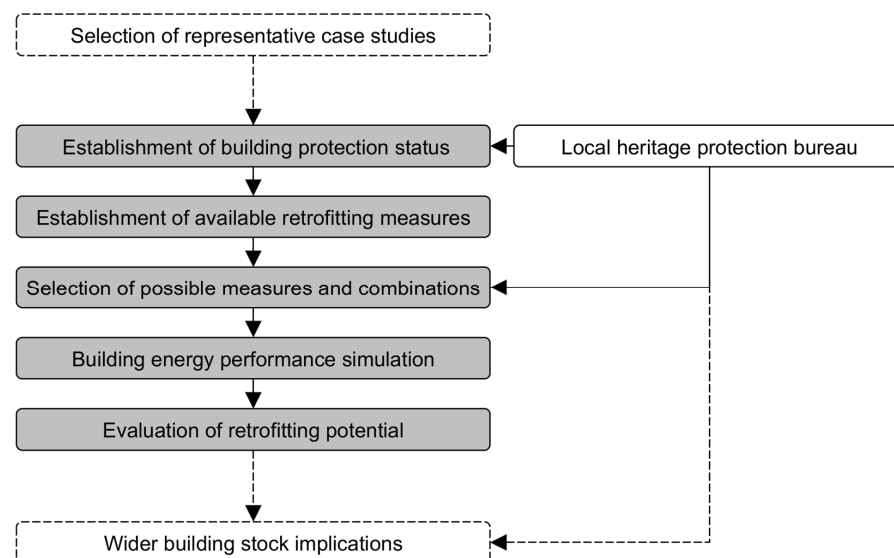


Figure 1. Project workflow flowchart including past research efforts as a starting point and future building stock implications.

2.2. Case Description

The case study selected lies in the center of the Gløshaugen campus of the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. It consists of a total of five buildings, connected by a passage, that are grouped into two complexes: Central Building 1 (two low-rise buildings and one high-rise building in the south) and Central Building 2 (one low-rise building and one high-rise building in the north), displayed in Figure 2. The exterior of the case is heritage-protected according to class C in Trondheim. The case was chosen for its prominent and representative characteristics on the university campus and for other heritage-protected buildings in the surroundings.



Figure 2. Image of the case study: the central buildings on the NTNU campus Gløshaugen in Trondheim, Norway.

Dividing the case into its two parts offers the greatest level of detail and represents the actual energy meters, divided into district/local heating and electricity. Energy consumption data were obtained from the property maintenance section at the university (S. P. Andersens veg 3, 7031 Trondheim, Norway) [29] at an hourly resolution for the year 2022. The reference data were used to calibrate the digital representations in the simulation software IDA ICE (version 5.1) [30], using a novel calibration schematic for manual calibration [31]. These representations are considered a precursor to true digital twins, where the real-time bidirectional flow of information is available. Both building complexes were modeled and calibrated according to the three statistical indicators normalized mean bias error (NMBE), coefficient of variation root mean square error (CV RMSE), and the coefficient of determination (R^2) for monthly values. Table 1 summarizes the characteristics of both parts of the case.

2.3. Numerical Simulation Approach

In IDA ICE (version 5.1), whole-year simulations were used to evaluate the performances of the retrofitting measures applied. Figure 3 depicts the two energy models. The two chosen objectives were (1) delivered energy for heating and (2) delivered energy for electricity, corresponding to the measured energy data received from the university [29].

Table 1. NTNU case study summary.

Characteristic	Central Building 1	Central Building 2
Climate zone (Köppen–Geiger) [32]	Dfb	Dfb
Year of construction	1961	1968
Typology/usage	University incl. offices, cantina, and library	University incl. offices
Main construction material	Concrete	Concrete
Heritage protection status	Class C *	Class C *
Heated floor area	16,403 m ²	11,439 m ²
Total heating (calibrated for 2022)	1,793,404 kWh	909,937 kWh
Total electricity (calibrated for 2022)	2,050,862 kWh	1,457,235 kWh
Total delivered energy for 2022	234 kWh/m ²	207 kWh/m ²
NMBE (lim. $\leq \pm 5\%$) [31]	0.7%	−3.7%
CV RMSE (lim. $\leq 15\%$) [31]	5.8%	13.1%
R ² (lim. $\geq 75\%$) [31]	95.7%	74.8%

* Class C is the lowest of the three local heritage protection classes in Trondheim, followed by Class B and Class A, with increasing protection. See also Section 1.5.

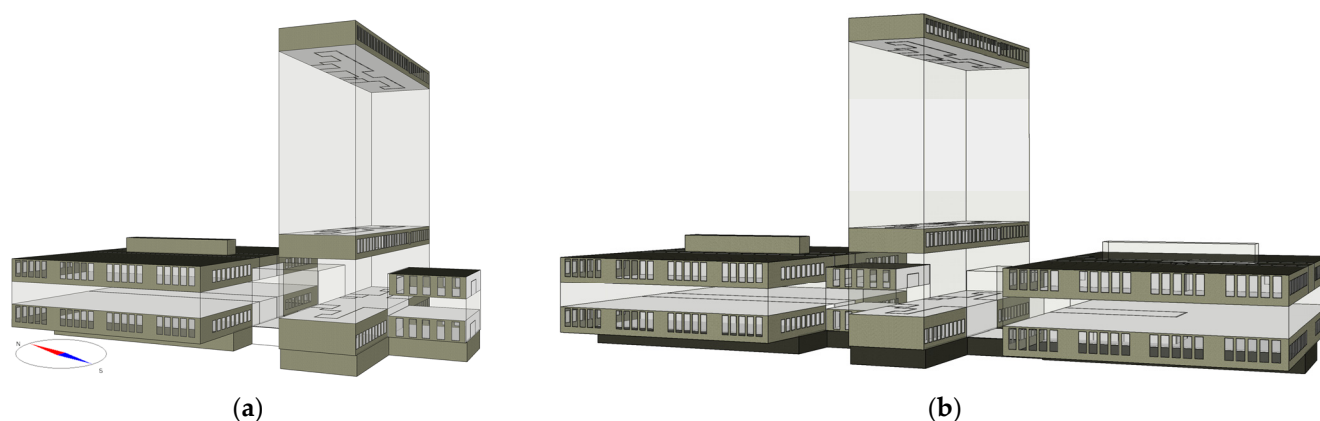


Figure 3. Digital representation of the two building complexes in IDA ICE: (a) Central Building 2 as the northern part of the overall case study; (b) Central Building 1 as the southern part of the overall case study.

Equivalent to the obtained data, the simulation data have an hourly resolution. Weather data were downloaded for the case location specifically, utilizing the Shiny Weather Data application (updated 2021-04-04) [33]. For the simulation workflow itself, the parametric runs tool was used in IDA ICE (version 5.1), with the sensitivity analysis option that allows the user to define and simulate all the desired values of a parameter. The effect of the selected measures was analyzed per measure individually and for combined measures.

2.4. Selection of Passive Retrofitting Measures

A list of passive retrofitting measures to be tested in this case was selected in collaboration with the local heritage protection bureau, responsible for the heritage protection classification of the case study. Additionally, the selection was based on past research efforts, official public recommendations for retrofitting educational buildings in Norway [34], and the practical and technical limitations of the buildings' construction (such as the geometric features of the façade and room heights). Table 2 summarizes the retrofitting measures found in reference cases, their availability in the protected case study, and finally the implemented parameters. The heritage protection status is unique to every protected object. While the classification of heritage protection can allow for a general understanding of possible measures and create comparability to a certain degree, all objects must be evaluated separately. The local heritage bureau in Trondheim, Byantikvaren (Kjøpmannsgata 36, 7011

Trondheim, Norway) [19], was contacted for their evaluation of the specific case study of the central buildings on the NTNU campus and likely possible retrofitting measures. In Table 2, the selected retrofitting measures are listed along with their values as applied to the two case-study building complexes. The selection of values was dependent on the starting values of the calibrated models, which varied slightly for the two building complexes.

Table 2. Selection of passive retrofitting measures and value selection for the implementation in the case study.

Measure	Reference Project(s)	Protection Class C Applicability [19]	Value Selection for Application in the Case Study			Unit
Building composition						
Changed thermal inertia	[16]	N.A. ¹	-	-	-	-
Changed window-to-wall ratio	[16]	☑ ²	-	-	-	-
Changed building shape	-	N.A.	-	-	-	-
Building envelope measures						
Improved airtightness	[16,35,36]	☑☑☑☑ ⁴	2	1.5	1	ACH [h ⁻¹]
Improved thermal bridges	[16]	☑☑ ³	0.15	0.10	0.05	[W/m ² ·K]
Improved external solar absorption	[16]	☑	-	-	-	-
Improved natural ventilation	[16]	N.A.	-	-	-	-
Improved passive solar heating	[16]	N.A.	-	-	-	-
Implemented shading	[16,35,36]	☑☑	0.65	0.33	0.14	gmultip. [-]
External wall measures						
Added external insulation	[16,28,34–37]	☑☑	30 ⁵	50 ⁵	70 ⁵	[mm]
Added internal insulation	[28,34–36]	☑☑☑	20 ⁶	30 ⁶	-	[mm]
Added insulating render	[28,35]	☑☑☑	30 ⁷	50 ⁷	70 ⁷	[mm]
New facade system	-	☑	-	-	-	-
Roof measures						
Added roof slab insulation	[35,36]	☑☑☑	100 ₆	200 ₆	-	[mm]
Added rafter insulation	[28,37]	☑☑☑	-	-	-	-
Renewal of truss	[28]	N.A.	-	-	-	-
Floor slab measures						
Added insulation above slab	[28]	☑☑☑	70 ⁸	100 ₈	-	[mm]
Added insulation below slab	[28]	☑☑☑	-	-	-	-
Other insulation						
Improved HVAC insulation	[34]	☑☑☑	-	-	-	-
Window measures						
Restored old windows	[28,34]	N.A.	-	-	-	-
Installed new windows	[16,28,34,36,37]	☑☑☑	0.35	0.25	-	gvalue [-]

¹ Not applicable, as not part of the energy retrofitting scope; ² implementation limited by many heritage requirements; ³ implementation limited by key heritage requirements; ⁴ implementation limited by few/no heritage requirements; ⁵ application of PIR insulation with thermal conductivity of 0.022 W/(m²·K); ⁶ application of mineral wool insulation with thermal conductivity of 0.034 W/(m²·K); ⁷ application of aerogel render with thermal conductivity of 0.028 W/(m²·K); ⁸ application of XPS insulation with thermal conductivity of 0.034 W/(m²·K).

All the retrofitting configurations displayed in Table 2 were selected in collaboration with the local heritage protection authorities, who limited the implementation if needed, providing a framework. Concerning the overall building envelope, air tightness and

thermal bridge values were derived from discussions and achievable values for buildings of that age. External wall measures were limited by esthetic requirements, preventing any application thicker than 70 mm on the exterior and 50 mm on the interior (limited by existing technical installations). Lower thicknesses were chosen in widely available steps of 20 mm. Roof and floor slab insulation were not limited by heritage definitions but instead by technical applicability and room height. The selection of windows and shading devices was directed by available products and specifications while being made as visually unintrusive as possible. The best available materials and material properties were chosen for added insulation, shading, and windows.

3. Results

To test the energy-saving effect of all the chosen passive retrofitting measures in the case of the central buildings on the NTNU campus (with the parameters set in Table 2), a total of 25 scenarios were simulated for both Central Building 1 and Central Building 2 individually, which was possible due to the previously established and calibrated digital representations of the buildings. In total, 23 of those simulations were used to test the effectiveness of individual energy saving measures, while the remaining 2 were used to simulate the effectiveness of multiple energy-saving measures combined. The simulation outcomes were compared to the calibrated baseline performance for the two objectives of total annual heating energy and total annual electricity consumption, as summarized in Table 3. The effect of the passive retrofitting measures was negligible for electricity consumption, with maximum energy savings of about 2%, while the heating energy savings for individual measures were close to 30%. Not all the parameter configurations were equally applicable to both building complexes, due to the differing calibrated baseline configurations; some configurations would result in worse scenarios than the baseline. These specific configurations were marked as not applicable (N.A.). All the applications of shading systems resulted in higher heating energy consumption as they were sun-controlled at every window individually, presumably from reduced thermal gains.

After considering the measures individually, the most effective ones, marked in bold in Table 3, were established and then combined to form packages of measures. This result-based approach resulted in different configurations of measures for the two building complexes. For Central Building 1, the combination consisted of additional external insulation, additional internal insulation, and new windows. For Central Building 2, on the other hand, the combination consisted of reduced infiltration and thermal bridges, added internal insulation, added insulating render, and new windows. Based on this selection, conservative and more ambitious packages were defined, as presented in Table 4. Resulting energy consumption scenarios are also provided as Supplementary Materials and can be downloaded: Text S1: CB1_Baseline.txt; Text S2: CB1_Conservative.txt; Text S3: CB1_Ambitious.txt; Text S4: CB2_Baseline.txt; Text S5: CB2_Conservative.txt; Text S6: CB2_Ambitious.txt. While resulting in lower energy savings, the conservative packages were included as slightly more cost- and emissions-effective alternatives. The conservative packages resulted in heating energy savings of 38% for Central Building 1 and 25% for Central Building 2. The more ambitious packages resulted in heating energy savings of 42% for Central Building 1 and 36% for Central Building 2. As for the individual measures, the electricity savings were negligible for all the passive retrofitting package measures, with reductions of around 2%.

Table 3. Energy-saving effects of applying selected energy retrofitting measures to the case study for the parameters of the total energy for heating and total energy for electricity for 2022. Non-applicable parameters, based on the baseline model, are marked with N.A. Bolded measure alternatives show the greatest savings and are thus kept for the next step of establishing packages of combined measures.

Baseline Energy Consumption and Retrofitting Measures	Central Building 1		Central Building 2	
	Energy for Heating [kWh/a]	Energy for Electricity [kWh/a]	Energy for Heating [kWh/a]	Energy for Electricity [kWh/a]
Calibrated baseline	1,793,404	2,050,862	909,937	1,457,235
Envelope property measures				
Improved airtightness (2/h)	N.A.	N.A.	868,790 (95%)	1,452,252 (100%)
Improved airtightness (1.5/h)	N.A.	N.A.	843,979 (93%)	1,449,564 (99%)
Improved airtightness (1/h)	N.A.	N.A.	810,510 (89%)	1,445,765 (99%)
Imp. thermal bridges (0.15 W/(m ² ·K))	N.A.	N.A.	N.A.	N.A.
Imp. thermal bridges (0.10 W/(m ² ·K))	N.A.	N.A.	897,520 (99%)	1,455,691 (100%)
Imp. thermal bridges (0.05 W/(m ² ·K))	N.A.	N.A.	858,252 (94%)	1,452,074 (100%)
Implemented shading (external)	2,003,982 (112%)	2,027,673 (99%)	1,013,103 (111%)	1,465,096 (101%)
Implemented shading (cavity)	1,926,416 (107%)	2,026,360 (99%)	982,823 (108%)	1,461,067 (100%)
Implemented shading (internal)	1,809,739 (101%)	2,025,281 (99%)	943,159 (104%)	1,458,496 (100%)
External wall measures				
Added external insulation (30 mm)	1,653,228 (92%)	2,022,318 (99%)	883,952 (97%)	1,454,380 (100%)
Added external insulation (50 mm)	1,628,687 (91%)	2,021,844 (99%)	872,341 (96%)	1,453,251 (100%)
Added external insulation (70 mm)	1,613,776 (90%)	2,021,559 (99%)	864,039 (95%)	1,452,371 (100%)
Added internal insulation (20 mm)	1,697,036 (95%)	2,023,180 (99%)	900,192 (99%)	1,456,063 (100%)
Added internal insulation (30 mm)	1,676,799 (93%)	2,022,782 (99%)	893,850 (98%)	1,455,438 (100%)
Added insulating render (30 mm)	1,666,523 (93%)	2,022,582 (99%)	880,259 (97%)	1,453,822 (100%)
Added insulating render (50 mm)	1,640,703 (91%)	2,022,081 (99%)	869,218 (96%)	1,452,776 (100%)
Added insulating render (70 mm)	1,624,752 (91%)	2,021,767 (99%)	861,014 (95%)	1,451,928 (100%)
Roof measures				
Added roof slab insulation (100 mm)	1,788,240 (100%)	2,025,035 (99%)	919,237 (101%)	1,457,862 (100%)
Added roof slab insulation (200 mm)	1,788,192 (100%)	2,025,032 (99%)	919,298 (101%)	1,457,868 (100%)
Floor slab measures				
Added insulation above slab (70 mm)	1,783,000 (99%)	2,025,011 (99%)	910,112 (100%)	1,456,771 (100%)
Added insulation above slab (100 mm)	1,782,603 (99%)	2,025,005 (99%)	910,112 (100%)	1,456,771 (100%)
Window measures				
Installed new windows (gvalue 0.35)	1,308,896 (73%)	2,016,668 (98%)	830,341 (91%)	1,443,923 (99%)
Installed new windows (gvalue 0.25)	1,267,338 (71%)	2,016,188 (98%)	797,309 (88%)	1,439,665 (99%)

For the overall analysis in terms of the goals set by regulations or efforts such as deep energy retrofitting and deep renovations standards, the overall energy savings were analyzed. Figures 4 and 5 summarize these overall savings for energy for heating and electricity both individually and combined for Central Building 1 and Central Building 2, respectively. For increased comparability, the calibrated baseline and the simulated scenarios were normalized based on their heated floor area (HFA) [kWh/m²·a]. The baseline consumptions of 234 kWh/m²·a and 207 kWh/m²·a for Central Building 1 and Central Building 2, respectively, were reduced to 191 kWh/m²·a (−19%) and 185 kWh/m²·a (−11%), respectively, by conservative measure combinations, and to 187 kWh/m²·a (−20%) and 175 kWh/m²·a (−15%) by ambitious measure combinations. The TEK17 reference for educational buildings in Norway is 125 kWh/m²_{HFA} for both new buildings and renovations

(while exemptions for protected buildings apply) [38]. For Central Building 1, displayed in Figure 4, the largest energy reduction effects were achieved by changing windows, adding external insulation, adding insulating render, and adding internal insulation. Similarly, for Central Building 2, displayed in Figure 5, the same measures resulted in significant energy reductions, while a reduction in the infiltration ratio and thermal bridges reduced the energy consumption further.

Table 4. Energy-saving effects of applying a combination of energy retrofitting measures to the case study. The differing combinations applied were based on the largest individual savings for the two building complexes individually. Non-applicable parameters are marked with N.A.

Baseline Energy Consumption and Retrofitting Measure Combinations	Central Building 1		Central Building 2	
	Energy for Heating [kWh/a]	Energy for Electricity [kWh/a]	Energy for Heating [kWh/a]	Energy for Electricity [kWh/a]
Calibrated baseline	1,793,404	2,050,862	909,937	1,457,235
Conservative combined retrofitting measures				
50 mm external insulation; 20 mm internal insulation; new window gvalue = 0.35	1,112,463 (−38%)	2,013,654 (−2%)	N.A.	N.A.
Infiltration = 1.5/h; thermal bridges = 0.10 W/(m ² ·K); 20 mm internal insulation; 50 mm insulating render; new window gvalue = 0.35	N.A.	N.A.	680,059 (−25%)	1,430,944 (−2%)
Ambitious combined retrofitting measures				
70 mm external insulation; 30 mm internal insulation; new window gvalue = 0.25	1,048,642 (−42%)	2,012,668 (−2%)	N.A.	N.A.
Infiltration = 1.0/h; thermal bridges = 0.05 W/(m ² ·K); 30 mm internal insulation; 70 mm insulation render; new window gvalue = 0.25	N.A.	N.A.	578,977 (−36%)	1,424,082 (−2%)

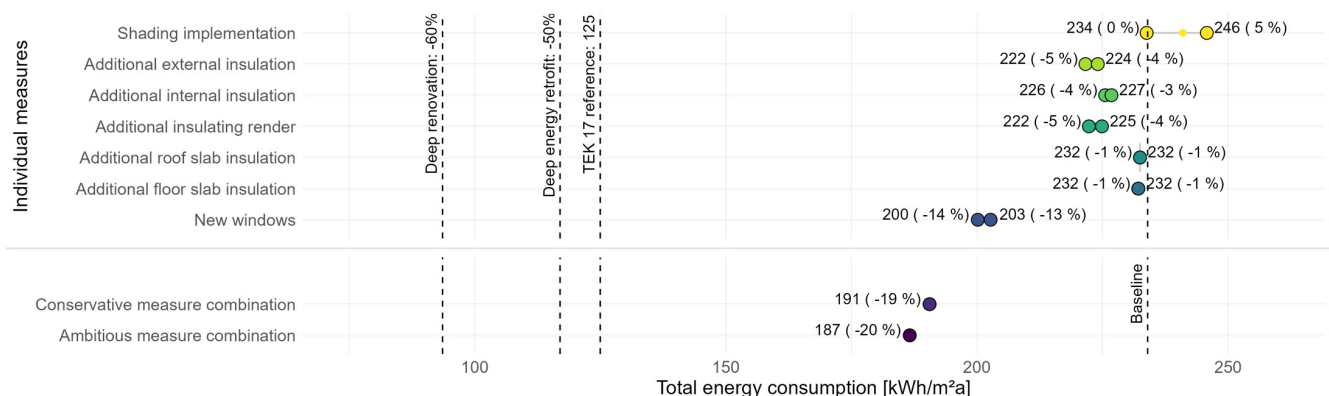


Figure 4. Total energy consumption (heating and electricity) for Central Building 1 before and after the application of individual and combined retrofitting measures including the baseline reference, the TEK17 reference, and both deep energy retrofitting and deep renovation references. Combinations include additional external and internal insulation, as well as new windows.

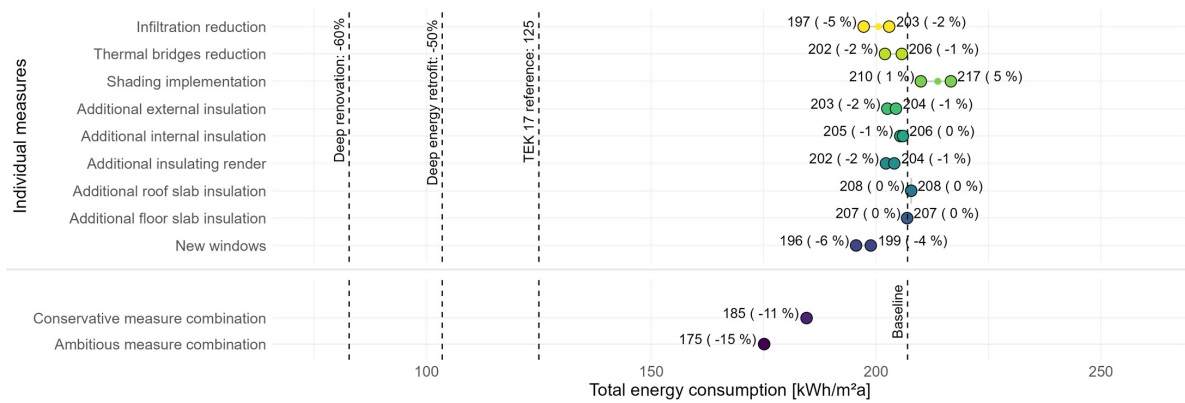


Figure 5. Total energy consumption (heating and electricity) for Central Building 2 before and after the application of individual and combined retrofitting measures including the baseline reference, the TEK17 reference, and both deep energy retrofitting and deep renovation references. Combinations include lower infiltration and thermal bridges, internal insulation, external insulating render, and new windows.

Increasing insulation levels in the roof and on top of the floor slab did not result in significant savings, with the energy reductions achieved with all the alternatives staying below 1% for both building complexes. Looking at the entire case study consisting of Central Building 1 and Central Building 2, 16% of the total energy could be saved when implementing conservative passive measures and 18% when implementing more ambitious passive measures, all while staying within the boundaries of heritage protection. In the case study, the heating energy consumption depended more strongly on outdoor temperature and therefore showed greater seasonal variability than electricity consumption.

As heating is mostly affected by the application of passive retrofitting measures, the simulated results also show considerable seasonal differences in energy reduction compared to the baseline performance. Figure 6 displays monthly values for both Central Building 1 and Central Building 2 including conservative and ambitious retrofitting packages. All the retrofitting combinations have greater effects during the winter months compared to summer months. For Central Building 1, the winter savings reached 33% with conservative retrofitting and up to 37% with ambitious retrofitting for total energy consumption, with heating and electricity combined. For Central Building 2, the winter savings reached 20% with conservative retrofitting and 28% with ambitious retrofitting, respectively. The summer savings stayed below 10% for both cases, except in July for Central Building 1, with savings of 18%. These seasonal characteristics led to considerably flatter consumption curves and thereby less dependence on outdoor temperature for the entire case study.

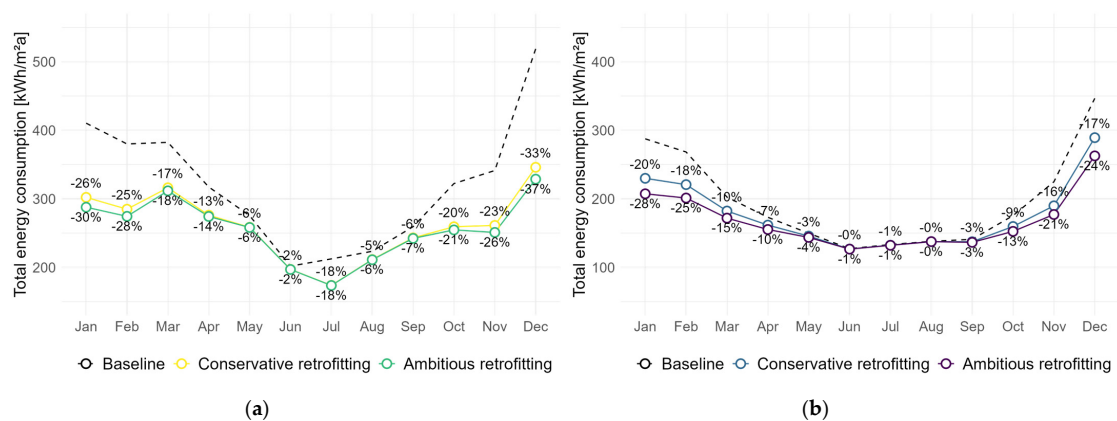


Figure 6. Monthly energy savings of conservative and ambitious retrofitting for Central Building 1 (a) and Central Building 2 (b) compared to baseline performance.

4. Discussion

4.1. Passive Retrofitting Measures Applicable to Heritage Protected Buildings

The selection of retrofitting measures applicable to heritage-protected buildings is influenced by aspects such as the protected feature, the protection class, and agreements with local heritage protection authorities.

In the case of the chosen campus case study, the exteriors of the central buildings are protected according to local protection class C in Trondheim. The main protection aim is to maintain the existing esthetic of the buildings, which have prominent visual and cultural roles due to their height, elevated position, and functions for the university. All measures affecting the exterior must therefore be discussed, despite class C being the lowest class. That may lead to measures that are acceptable in this case but would not have been so for buildings of higher protection status. Table 2 displays which of the commonly applied measures were applicable to the case and which were not. Those determined not applicable were all measures altering the building composition and shape, measures that require great visual changes to the color or type of façade system, and measures such as insulation between rafters, which were technically not applicable.

The case features very prominent vertical columns on the façade, visible in Figure 2. All the insulation measures were restricted in their thickness to preserve that visual impression, leading to a maximum thickness of 70 mm in accordance with heritage authorities. For interior insulation, however, existing technical installations close to the façade were the technical limiting factor, limiting the thickness to 30 mm of insulation. The same rules of unchanged visual appearance were also true for all the shading systems, which were required to be as visually unobtrusive as possible, like window-integrated systems that are partly in place already. While larger savings could be achieved with additional reducing measures, the solutions selected and implemented in this study represent those that are realistically achievable through minimal alteration of the façade and thereby respect the heritage protection status.

4.2. Passive Retrofitting of Cold-Climate Heritage Buildings Towards Deep Energy Retrofitting

The effect of passive retrofitting depends on multiple factors, such as the baseline performance of the case study, the energy reduction effect of individual and combined retrofitting measures, and the energy-saving objective.

Previously established and calibrated building energy models were required as digital representations to model the impact of both individual and combined retrofitting measures. Once established, these models not only provide accurate results, but also offer great time savings due to the relatively short simulation times and even the parallel simulation of multiple measures or measure implementations. The calibrated baseline energy consumption of Central Building 1 is higher than the baseline energy consumption of Central Building 2, at 234 kWh/m²·a compared to 207 kWh/m²·a. The difference in starting point leads to differences in the impact that is achievable through the implementation of the selected retrofitting measures. Taking the addition of external insulation of 70 mm as an example, the energy consumption was reduced by 5% (or 12 kWh/m²·a) in the worse-performing building complex, compared to 2% (or 4 kWh/m²·a) in Central Building 2. The same trend applied for all other measures that were equally applied to both parts of the case study; worse baseline performance resulted in greater savings.

Individual measures had varying effects on the heating energy performance of the case. The results range from −14% (the exchange of windows) to +5% (the implementation of shading) in the case of Central Building 1, and from −6% (the exchange of windows) to +5% (the implementation of shading). The implementation of sun-controlled shading devices was the only applicable measure that resulted in increased energy consumption in

both parts of the case, presumably due to a larger decrease in solar gains compared to the reduction in losses. Depending on the simulation outcomes, the best-performing measures were combined into two retrofitting packages, for both building complexes. The results showcase the importance of the simulation of combined measures, as they differ from the sum of the effect of individual retrofitting measures. For Central Building 1, the heating energy savings of the individual measures sum up to 41% (9% + 5% + 27%), while the combined savings are 38% (−3%) for conservative measures, and to 46% (10% + 7% + 29%) and 42% (−4%), respectively, for ambitious measures. For Central Building 2, the savings were 22% (7% + 1% + 1% + 4% + 9%) and 36% (11% + 6% + 2% + 5% + 12%) for individual conservative and ambitious measures, respectively, while the combined effects were 25% (+3%) and 36% (±0%).

While larger savings were achieved for the heating energy, the overall energy consumption for the entire case study was reduced by 16% with conservative retrofitting measures and by 18% with more ambitious retrofitting measures only. That corresponds to 191 kWh/m²·a and 187 kWh/m²·a for Central Building 1 and to 185 kWh/m²·a and 175 kWh/m²·a for Central Building 2, respectively. The reference value of 125 kWh/m²·a in Norwegian regulations is not met, and the same goes for deep energy retrofitting and deep renovation goals. These shortcomings can be attributed to a combination of both heritage protection restrictions and the sole application of passive measures, which are greatly impacted by given, building-specific restrictions.

4.3. The Implications of Passive Retrofitting in Cold-Climate Heritage Cases

Passive retrofitting does have positive implications, such as a greatly reduced demand for heating during some months and greater resilience against low outdoor temperatures, but also comes with specific challenges. In the demonstrated case, all the implemented retrofitting measures conformed with heritage-protection definitions, as visualized by the heritage bureau interventions in Figure 1. This ensured visually unintrusive solutions, even for more ambitious combinations of measures. A maximum of 70 mm of insulation was added to the exterior, safeguarding the building envelope. Windows and shading systems were chosen according to existing systems, and measures improving air tightness were limited to solutions not affecting the esthetic. The more conservative packages had even lower visual impact on the buildings, with further reduced visual interventions, such as even lower thickness of the added insulation.

While the overall energy savings are relatively low, greater effects were achieved for the heating demand of the case. The share of the heating demand of the overall energy consumption is higher in cold-climate settings. In the studied university case, the annual heating demand accounted for 47% to 34% of the total energy in Central Building 1 and 38% to 29% in Central Building 2 for the baseline and the applied retrofitting packages. That large share resulted in savings mostly during winter months, where the overall savings reached close to a third of the overall energy consumption in both parts of the case. In summer; however, the savings proved to be negligible and mostly below 10% for Central Building 1 and below 5% for Central Building 2.

The energy savings, predominantly during the winter months, lead to an annual peak-shaving effect. Up to 37% and 24% were shaved for Central Building 1 and Central Building 2, respectively, for more ambitious measures in December, the coldest month, and 30% to 28% in January, the second coldest month of the year. The same effect is valid for a daily resolution, as plotted in Figure 7, where the dependence of the daily energy consumption on the average outdoor temperature is explored. Daily consumption in the retrofitting scenarios is generally lower and more concentrated, visually highlighting lower consumption on cold days and thereby less dependency during winter months, despite the

relatively small retrofitting interventions applied. Depending on the energy contracts in place, peak shaving can contribute to significantly lower costs.

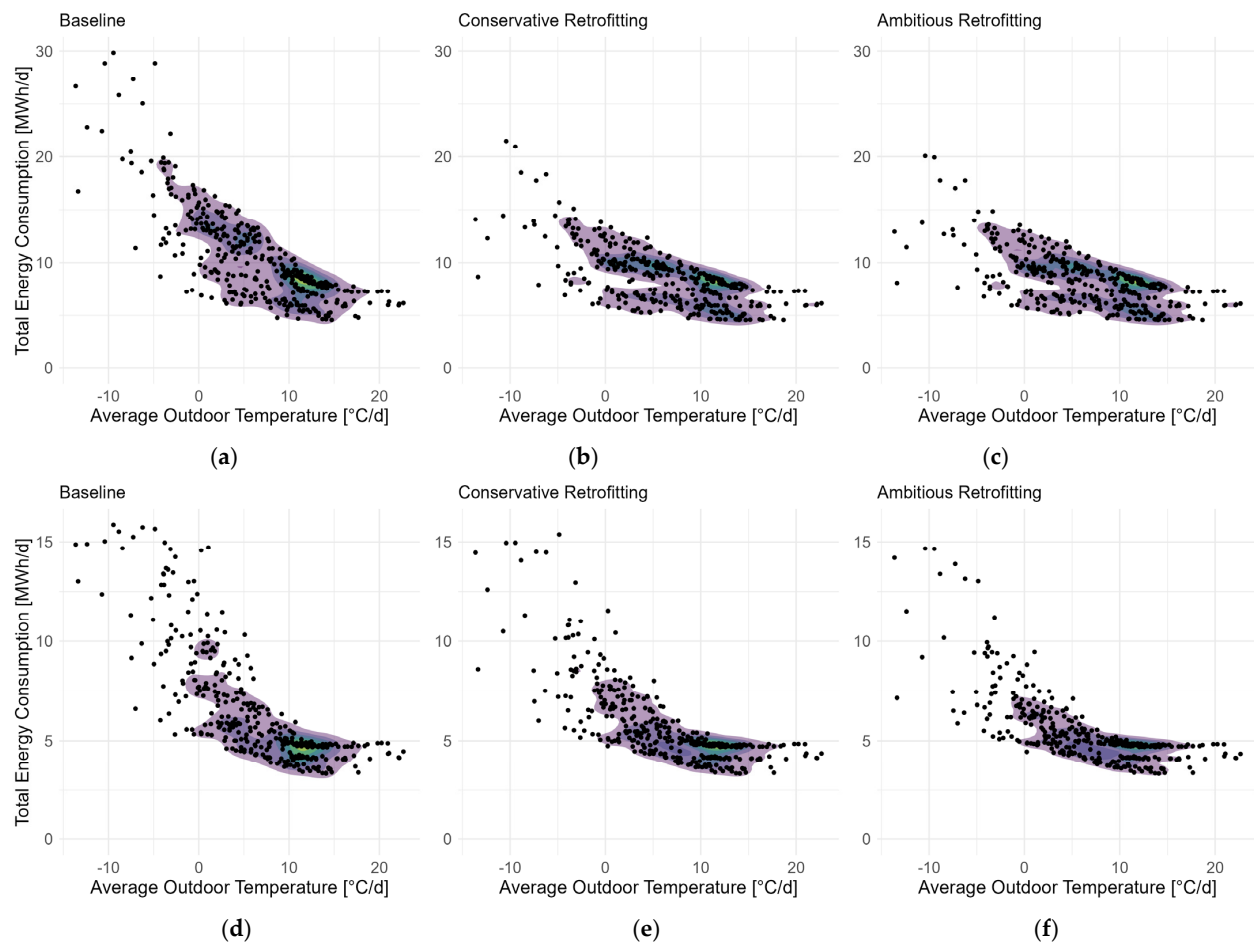


Figure 7. Plot of total daily energy consumption against average daily outdoor temperature for Central Building 1, (a–c), and Central Building 2, (d–f), respectively, with density plots, visually highlighting the change in distribution.

Another characteristic specific to colder climates is the reduced risk for overheating and associated consequences such as added cooling systems. In this university case, there is no dedicated cooling system, while ventilation systems account for a base cooling load if needed. The application of sun-controlled shading systems did not yield the expected outcomes, as no energy was saved overall, and energy demand was increased. That effect may be attributed to the shading system not preventing the buildings from overheating but instead reducing solar gains through the windows to a point where additional energy for heating was required.

5. Conclusions

This study of the central buildings on the NTNU campus shows that, while restricted, passive retrofitting measures can also be applied to heritage-protected buildings, and the selection can even exceed general recommendations. The type and configuration of measures must be selected in close collaboration with heritage protection authorities, as each protected object is evaluated separately, despite being divided into general classes. More intrusive measures may be possible but require far greater temporal and economic resources throughout the project. The exterior of the central buildings is protected according to protection class C, so the aim is to keep the esthetics as unchanged as possible, limiting,

among other factors, the thickness of added layers or excluding measures that alter the shape or color of the façade. While the specific shape of the façade may only apply to the case, the same principles and values can be applied elsewhere as a well-informed and protection-conform retrofitting baseline. Most local class C-protected educational buildings (44% of all instances) have the same characteristics as the central buildings in terms of the construction period and construction material, highlighting the importance of the case study as a reference project. The overall local heritage-protected building stock, however, has quite different characteristics for other building typologies, making a direct transfer difficult. Class C-protected residential buildings, for example, are more likely to have been constructed from either brick or wood, between 1875 and 1925. While this demands the establishment of typology-specific case studies, it also highlights the relatively young age of heritage-protected educational buildings made from concrete, as an emerging group of protected buildings.

Passive retrofitting of the heritage-protected case study in a cold-climate setting did not satisfy the requirement of deep energy retrofitting or deep renovation. The overall savings for the entire case of more than 27,000 m²_{HFA} were 16% for a selection of more conservative passive retrofitting measures, and 18% for a selection of more ambitious passive retrofitting measures. While these numbers are considerably lower than the savings in other heritage-protected cases, they represent realistic and case-specific scenarios for the NTNU central buildings that were formed in accordance with heritage boundaries and technical limitations. Energy consumption is divided into local/district heating and electricity in the case, whereas heating in most of the Norwegian building stock is now electrified. The application of passive measures had a negligible effect on the power consumption of the case, which remained at levels close to the baseline. Additional active measures, less prone to heritage protection limitation, concerning building operation and technical systems are required to effectively target electrical consumption. Heating consumption alone, on the other hand, could be reduced by 34% by applying the conservative package, and by 40% by applying the ambitious package.

The significant reduction in heating energy becomes even more clear when analyzing seasonal variations, showing strong results especially during cold winter months and for worse-performing buildings. The heating energy savings were reduced by 37% and 30% in Central Building 1 for the two coldest months, December and January. In Central Building 2, the heating energy savings amounted to 24% and 28% during the same months. The application of only limited passive measures therefore led to large shifts in the energy consumption characteristics, considerably flattening the annual consumption curve and reducing the dependence on cold outdoor temperatures, especially during winter months. The differences in the initial energy performance of the two building complexes of the case ($\Delta 27 \text{ kWh/m}^2_{\text{HFA}}$) led to differing effects of the applied measures, with increased savings in the worse-performing complex, Central Building 1 (+6% to +13%). These results make the case not only for the cold-climate application of passive measures in protected cases but also for targeting the worst-performing buildings.

Future work, as visualized in the project workflow flowchart, must focus on the effect and implications for the wider building stock, based on lessons from individual retrofitting projects. This includes going back to the underlying characteristics of the represented heritage-protected building stock and the projection of individual achievements to a larger scale.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/heritage8030088/s1>, Text S1: CB1_Baseline.txt; Text S2: CB1_Conservative.txt; Text S3: CB1_Ambitious.txt; Text S4: CB2_Baseline.txt; Text S5: CB2_Conservative.txt; Text S6: CB2_Ambitious.txt.

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