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Energy retrofitting of non-residential buildings with effects on the indoor environment: a study of university buildings at NTNU in Trondheim, Norway

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Abstract. The year 2050 is considered the deadline for achieving the European climate goal of net zero emissions, an essential sustainability milestone. Current strategies ask for higher retrofitting rates in the building sector, as most of today's buildings will still be standing and be used in 2050, and longer. However, retrofitting strategies must consider energy and emissions reductions alongside social sustainability, targeting not only the building but also its users. Historically, the focus has been on indoor environmental quality, while other aspects of human well-being such as the quality of views were not addressed as frequently. Educational buildings can function as lighthouse projects, profiting from its many users as communicators. This article presents the retrofitting potential of the central building complex of the Gløshaugen campus of the NTNU in Trondheim in terms of energy, as basis to study the impact of retrofitting strategies on the indoor environment. The study consists of a selection of details, their building physical assessment, and a proposal of retrofitting measures. The results highlight the importance of human-centric definitions in the early (re-)design stages. Human-centric planning aspects can have diverse positive influences on the building's users, especially in educational and other highly cognitive settings. Their impact however is strongly dependent on the selection of measures and their implementation. Interactions of the many aspects of well-being that can be addressed during retrofitting must be studied further as their interdependencies are often unclear and case specific. Human-centric retrofitting can function as a guide for upcoming mass retrofits throughout Europe for the sustainable achievement of climate goals.

Keywords: Energy retrofitting; Indoor environment; Indoor comfort; Occupant well-being; Non-residential buildings

1. Introduction

This section explains the motivation of the case study. It contains a description of the climate goals of 2050 concerning the built environment and links these efforts to the two fields of indoor comfort and well-being.

1.1. Climate goals of 2050 and the role of non-residential building retrofit

The European Commission aims to reach climate neutrality by the year 2050 [1]. To achieve this goal, the "European Green Deal", aligned with the Paris Agreement, was initiated [2]. The Green Deal is dedicated to improving the "well-being and health of citizens and future generations", supporting among others renovated and energy efficient buildings in "A Renovation Wave for Europe" [3].

The main argument for retrofitting instead of building new and highly efficient buildings is the prediction that 85 – 95 % of today's buildings will still be standing and used in 2050, when climate-neutrality is wanted to be achieved. Existing buildings consume currently about 40 % globally, emitting 36 % of global climate gas emissions. [4] As all economic sectors aim to reduce energy consumption and related emissions, the relative share of the building and construction industry might get less insightful, which is why absolute values must be looked at. The International Energy Agency (IEA) states for 2021 that energy use in buildings increased to about 135 EJ (+ 17% compared to 2010) and associated emissions to about 9.9 Gt CO2 (+10 % compared to 2010) and concludes that the building industry currently is not on track when it comes to set goals. Intermediate reductions due to Covid19 restrictions did not sustain, and lead to a rebound effect. [5]

Within the Renovation Wave, the three priorities are (1) energy poverty and worst-performing buildings, (2) public buildings, and (3) decarbonization of heating and cooling [3]. By targeting public buildings, the European Commission aims to establish role models for private buildings. Incentives are highly needed, as currently only 0.2 % of the building stock undergoes deep energy retrofit annually. The year 2030 represents an intermediate milestone for retrofits, where the European Commission aims for a 55 % reduction of emissions that cannot be achieved without the help of the building industry [4].

To align with the Renovation Wave, this case study focuses on a public, non-residential, university building complex which has a poor energy performance as typical for buildings that were built more than 50 years ago. The goal is to inspire other building retrofits and focus on buildings of educational usage with high energy demands.

1.2. Indoor environment

Indoor environmental quality ideally refers to the overall question whether a building or a room affects the comfort and well-being of the occupants. Its components traditionally include factors such as air quality, lighting, temperature, humidity, acoustics, and ergonomics. Widely accepted models exist for all those factors, making an integration relatively straight forward. However, it can be argued that aspects of well-being such as the quality of views and the effect on productivity that can and should be addressed are missing in most projects. To gather information on overall well-being that can be addressed in buildings, Hanc et al. performed a scoping review, where they established the eight themes of (1) subjective well-being, (2) eudaimonic well-being, (3) social well-being, (4) productivity, (5) environmental quality, satisfaction, and comfort, (6) mental health, (7) physical health, and (8) other [6]. All these themes have sub-themes that can be addressed in design such as the feeling of control (e.g., deployment of a sunshade) within eudaimonic well-being, the sick building syndrome (e.g., contamination, noise etc.) within physical health, and many more. The assumed biggest challenge of including parameters of human well-being, outside of established comfort parameters, is that that often introduces conflicts and contradictions especially among subjective aspects. Such an instance is easily demonstrated through the case of planning window areas (mostly) in new buildings. Here, it is desired to increase the areas as much as possible (under privacy constraints) to introduce natural daylight and stimulating views of the outdoors for enhanced productivity and learning, less stress etc. At the same time, depending on location, the risk for overheating versus the heat transmission's loss demands a more optimized and balanced design of components, which often ends with window openings as small as possible. This simplified example shows the importance of the ability to compromise between contradicting requirements. Standards, such as the Norwegian building code TEK17 often don't provide guidance for issues like that for non-residential buildings [7]. In retrofits, the conflicts are limited by whatever is kept of the original structure and materials etc. Another difficulty is the interdisciplinary and already mentioned subjective nature of well-being that might include fields such as philosophy, social sciences, medicine, and psychology [8].

This case study aims to include aspects that exceed traditional factors of indoor environmental quality. As the buildings are mostly occupied by students and academic staff, the focus lies on the well-being theme of productivity. According to Hanc et al., the theme of productivity includes the sub-themes of (1) productivity and performance, (2) learning, and (3) cognitive performance. Large window areas for example can lead to higher test scores and increased learning speed for students by provision of daylight [9,10], while views of the outside can increase mental function and memory [11].

Despite not being able to focus on more aspects of well-being the authors believe that every (retrofit) project should assess what aspects of indoor comfort and well-being can be addressed additionally. With this study, the authors aim to contribute to combining previous and current research on an educational building case study in Norway, including social aspects with energy ambitions.

2. Method

Different methods and materials were used for the case study analysis of this paper. The introduction section is based on literature on climate goals and the role of energy-related building retrofit in that context, as well as scientific literature such as the mentioned review by Hanc et al. on the topics of indoor comfort and occupant well-being. The case study description within the ongoing FEM ZEN (Research Centre on Zero Emission Neighbourhoods in Smart Cities) research project is based on building information that was obtained in archives and through monitoring of the buildings' actual energy use. Hygro-thermal building physical simulations in the results section where then performed using the tools THERM [13] and WUFI [14] to build a basis for the retrofit measures proposed in the results section. The hygro-thermal analyses were performed on detailed level (mm scale), for representative building components, while the energy analyses represent the entire building complex using monthly and annual data.

2.1. Case study

This section contains a description of the research project, as well as the construction of the buildings looked at, their heritage value, energy, and the resulting retrofitting potential.

2.1.1. Project description

The building complex looked at in this paper is part of a pilot project by the "Research Centre on Zero Emission Neighbourhoods in Smart Cities" (FME ZEN) [15] that looks at the "Knowledge Axis" including the NTNU university campus in Trondheim, Norway. The research centre follows the zero-emission goal on neighbourhood level and contributes with its own definitions, KPIs, and active research on pilot projects [16]. Its predecessor, "The Research Centre on Zero Emission Buildings", builds the basis for the bigger neighbourhood scale. That is comprised of the categories (1) GHG Emissions, (2) Energy, (3) Power, (4) Mobility, (5) Spatial Qualities, and (6) Economy [17]. Even though the research centre focuses on Norwegian projects, it contributes very much to European goals and developments through its definitions and research cooperations. The "Knowledge Axis" project of NTNU, however, focuses mostly on the three categories of (1) GHG Emissions, (2) Energy, and (5) Spatial qualities. The central building complex on campus, as displayed in Figures 1 and 2 is the subject of this paper.

Apart from being part of the FME ZEN pilot, studying the building complex additionally aims to contribute to the "Campus development" project, in which the university strives for a unified campus including both new and retrofitted buildings [18]. The development project is currently in the design phase in which a mapping of the retrofit potential of existing buildings plays a crucial role.

The chosen complex of buildings is comprised of two high-rise buildings with three adjacent/ connecting buildings. The complex is, for the sake of the following analysis, divided into two parts: central buildings 1 (southern low-rise, southern high-rise, and central low-rise) and central buildings 2 (northern high-rise and the northern low-rise), see Figures 1 and 2.

Figure 1. Campus Gløshaugen of NTNU in Trondheim, Norway with the central building complex as case study (circle). [Google Maps]

Figure 2. Campus Gløshaugen Central building complex Foreground: southern low-rise building, background: two high-rise buildings and the central low-rise building. [photo by the authors]

2.1.2. Construction

To analyse the existing structure, old documentation was retrieved from multiple archives throughout Norway. It revealed probable construction types, but the results were non-conclusive. The current state represented in this paper is therefore comprised of a combination of multiple sources and assumptions: archived information, previous renovation documentation, and recent maintenance efforts. Details on the main construction type and materials used can be found in Table 3 in the results section 3. All buildings of this case study are built with prefabricated concrete elements above ground level and a poured concrete under ground level, with interior insulation along the external walls. The construction type is considered typical and representative for many similar university buildings of the 1960`s.

A WUFI analysis (simulation software for heat and moisture transiency) was performed to assess the assumed current state of the construction. The results indicate a risk for condensation and thereby a risk for mold in the existing, external wall construction, as shown in Figure 3. That is indicated by the points above the limit's lines, with the dashed line as limit for biodegradable substrates and the grey line as limit for non-biodegradable substrates. The analysis was performed for multiple wall variations due to uncertainties related to materials used. The risk for mold must be addressed in present and future considerations as the building documentation indicates the use of organic materials between two vapor-tight layers. These findings have a significant impact on the following retrofit propositions described in the results section 3.

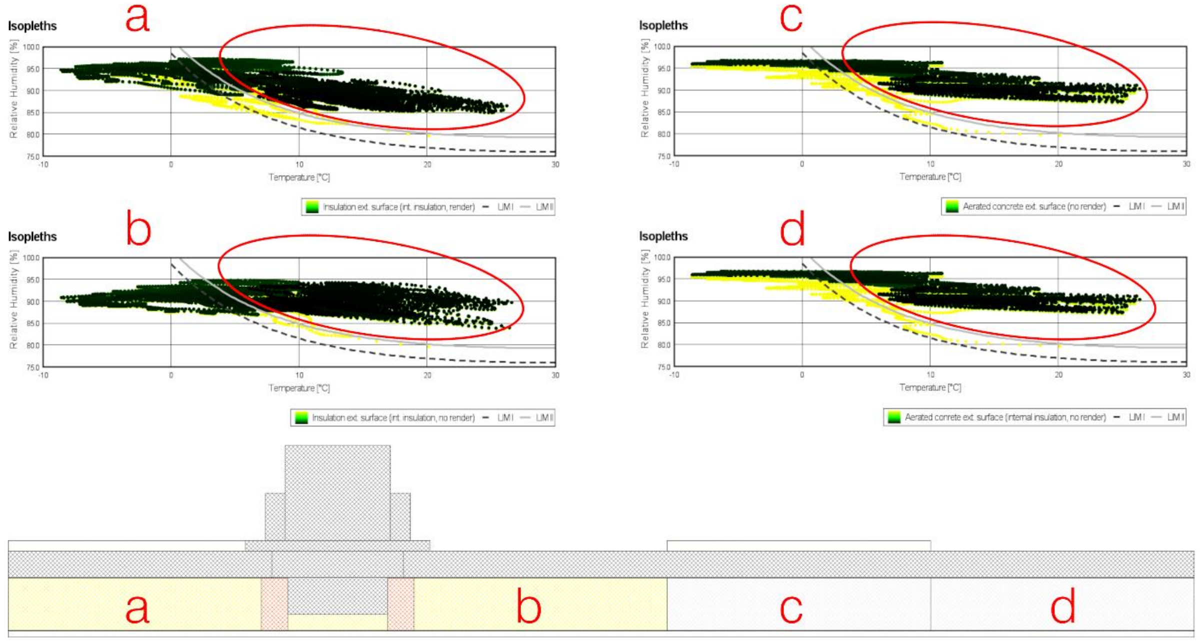


Figure 3. Hygro-thermal WUFI analysis of case study construction alternatives including mineral wool insulation (a,b) vs. porous concrete (c,d) and exterior render (a,c). Points above the limit lines (marked with red) indicate mold risk (with the dashed line as limit for biodegradable substrates and the grey line as limit for non-biodegradable substrates). [analysis by the authors]

2.1.3. Heritage value

The entire complex of central buildings built in the 1960's has heritage value and is classified as protection class C, which means that there might be restrictions to what can be done to the exterior aesthetic of the buildings. The entire campus "Gløshaugen", shown in Figures 1 and 2, is part of the ongoing and extensive process of the campus development described in section 2.1.1. This is relevant for this study, as even rebuilding measures on buildings of the highest heritage value class A (such as the main building, the northern most building colored dark red in Figure 4) have recently been approved by the Directorate of Cultural Heritage [19]. As the building complex looked at here is part of the same axis and therefore the established architectural landscape, proposed retrofitting measures have a significant potential to be approved. Especially as the entire campus, as neighbourhood, could be pushed one step closer toward a ZEN (Zero Emission Neighbourhood), improving occupant's overall well-being and sharing energy gains saved and generated between buildings.

Considering possible restrictions, proposed measures include solutions with exterior insulation (alternative 1) and a combination of both exterior and interior insulation (alternative 2), both of which must be considered under heritage value constraints. The alternatives will be further investigated and presented as separate studies after consulting the Norwegian Directorate of Cultural Heritage.

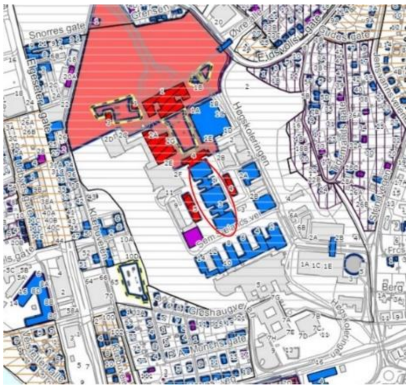


Figure 4. Campus Gløshaugen of NTNU in Trondheim, Norway with buildings of heritage value, the case study has value category C (red circle) [Byantikvaren].

Protection class A (red): Very high heritage value.
Protection class B (purple): High heritage value.
Protection class C (blue): Heritage value.
Buildings having overall values
and potential as a cultural environment.
Unclassified: Value of protection.

2.1.4. Energy use

Monitored energy usage data from the year 2021 was retrieved as basis for energy-related retrofit analyses. The data has a time-step resolution of one hour and is divided into energy carrier. Table 1 shows that the main carrier was electricity, followed by the local heating system on campus which, to some degree, allows for energy sharing between buildings already now.

Table 1. Energy use of the case study buildings in 2021.

	Electricity [kWh/a]	Local heating [kWh/a]	District heating [kWh/a]	Total energy [kWh/a]	Area [m²]	Energy per area [kWh/(m²·a)]
Central buildings 1	1864024	1390830	508724	3763578	17387	216
Central buildings 2	1460759	1164880	8706	2634345	12149	217

The choice of looking at the year 2021 was made for reasons of availability. Implications that the choice might have, are discussed in the discussion section 4.

3. Results

3.1. Retrofitting potential

As the retrofitting potential is hard to quantify, it was important to start with comparing the current measured energy consumption incl. heating and electricity to the Norwegian building standard TEK 17 [7]. In its current form, the regulation requires university buildings/high schools to have a maximum net energy consumption of 125 kWh/(m²·a). For the chosen case study this means that the energy consumption must be reduced by about 92 kWh/(m²·a) to reach the minimum energy requirements. That equals to a minimum needed energy reduction of about 42 %. When compared to both international and national retrofitting projects, a cut of about 42 % is realistic and can even be exceeded with extended retrofitting measures. A typical Austrian retrofit is reported to cut about 43 % of energy, while a reduction of up to 87 % was shown to be possible after the retrofit of a university building in Vienna [20]. A renovation study of Norwegian office buildings, on the other hand, showed that both a reduction of 50 % and 75 % is achievable [21]. Following Figure 5 shows the amount of energy that can be saved totally in different scenarios ranging from a minimum to an ambitious reduction of 80 %, equalling to a save of 2.69 to 5.12 GWh/a.

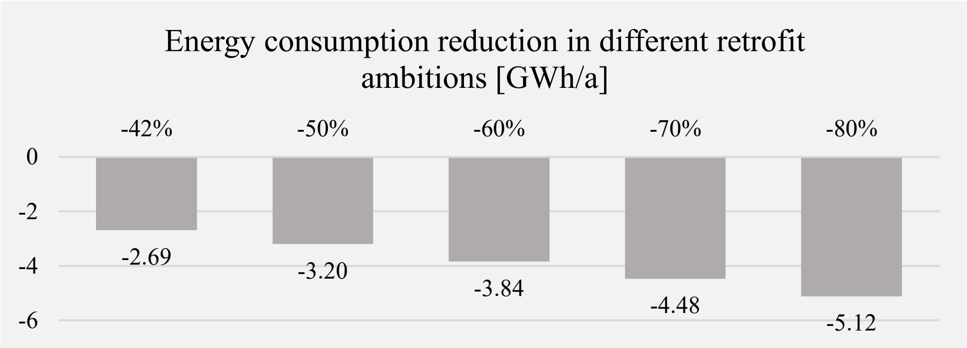


Figure 5. Saving potential of different levels of retrofitting ambitions for the entire complex comparing measured consumption to minimum requirements (-42 %), and more ambitious scenarios. [figure by the authors]

In Norway, both new buildings and total renovations must meet the minimum energy requirements, according to the Norwegian building code, TEK17 [7], which therefore also applies to the chosen case. If necessary, an exception must be requested and approved by authorities. The currently valid minimum energy requirements are based on maximum allowed U-vales for components of a building envelope and shortly presented in Table 2. Additionally, applying to university buildings, the total net energy demand must be ≤ 125 kWh/(m²·a), heated area (BRA).

Table 2. Minimum energy requirements, Norwegian building code, TEK17.

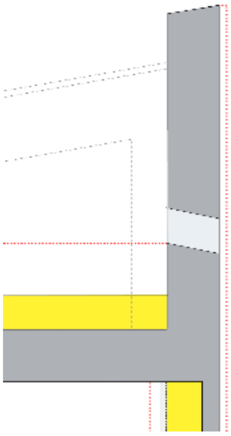
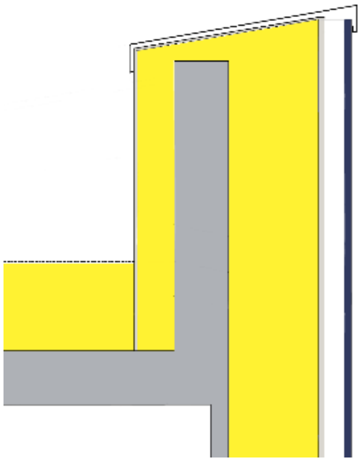
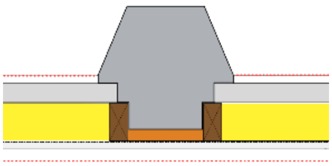
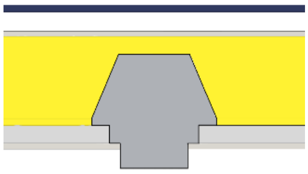
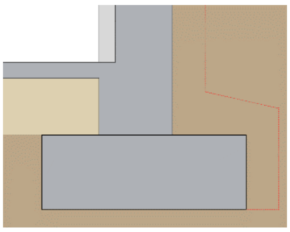
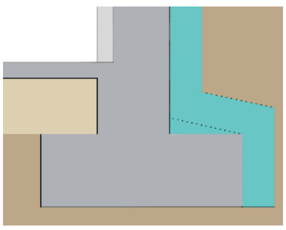
Floor	External wall	Roof	Window/Door	Airtightness
≤ 0.18 W/(m²·K)	≤ 0.22 W/(m²·K)	≤ 0.18 W/(m²·K)	≤ 1.2 W/(m²·K)	≤ 1.5 1/h

Two main façade retrofitting alternatives were selected to be investigated. Both include the removal of some of the existing structures and materials used, the installation of new façade components, and the exchange of the current windows, as described in the following two sections.

3.2. Alternative 1, Exterior insulation

The first retrofit alternative with exterior insulation shown in Table 3, was selected based on the primary studies, and supported by simulations carried out in the thermal simulation tool THERM. The table shows detail drawings for both the existing construction and proposed changes. The choice of materials and their thickness, however, is a subject of further investigations and optimizations. This approach was considered the most usual and is expected to be the best performing (building physically). The minimum energy requirements given by the Norwegian building code, TEK17 [7] can easily be achieved. Constraints are given by the fact that additional materials are placed on the exterior surface of the existing façade that might be under heritage protection.

Table 3. Retrofit alternatives.

Description existing	Details existing (+ Alternative 2 marked "red")	Details retrofit Alternative 1	Description retrofit
Detail 1a: Roof Prefabricated concrete; exterior/interior insulation; mineral wool; vapor barrier between concrete and insulation; wooden construction on the top of the roof.			Detail 1b: Roof Exterior insulation; vapor barrier inside in the roof construction only; no wooden construction on the top of the roof.
Detail 2a: External wall Prefabricated concrete; interior insulation; mineral wool; cellulose based divider between concrete/insulation; vapor barrier inside.			Detail 2b: External wall Exterior insulation; no interior insulation; no cellulose-based divider; no wooden construction or cork materials inside; no vapor barrier inside; climate screen outside.
Detail 3a: Floor Poured concrete; interior insulation; mineral wool; no radon/moisture barrier.			Detail 3b: Floor Exterior insulation of the wall only; radon/moisture barrier in the floor only; no interior insulation.

3.3. Alternative 2, Interior insulation combined with exterior insulation

Interior insulation is often considered "unwanted" (as unusual and expected to be a difficult approach) but sometimes a necessity due to exterior constraints such as the heritage value. Following measures (mostly on the interior) are proposed as "heritage-friendly alternative", as only some of the measures are applied to the exterior surface:

- Existing interior insulation must be increased by additional insulation in the existing external wall, as shown with a red dot-line in details existing, in Table 3.
- Interior insulation must be completed by a thin layer of material with insulation function externally, as well, to meet the minimum energy requirements and, considering heritage requirements, unifying the visual appearance of the existing prefabricated concrete plates. Preferably and probably necessarily, the external prefabricated façade-plates of concrete

should be replaced with new components, such as alkali-activated concrete (ACC), with insulation function.

- Cellulose-based material must be removed from the external wall construction and replaced with a non-organic and well-performing material to avoid risk for condensation between concrete and interior insulation after retrofitting.
- The existing vapor-barrier must be removed and replaced with an another one made of flexible and well-performing material, such as a smart-vapor-barrier, after investigating this solution theoretically first.

This is where it is appropriate to mention that additional insulation can contribute to a lower quality of indoor environment in terms of access to daylight and views as mentioned in the introduction. This issue is rather poorly addressed in the Norwegian technical requirements TEK17 (Chapter 13 Indoor climate and health, paragraph 13-8) where only generally formulated requirements regarding access to daylight and view can be found [7]. However, the occupant's well-being, including both physical and mental comfort, is depending on a sense of connection and a feeling of security within the exterior environment, including a view of the three layers of sky, built and natural environment, and ground [22], which is not specified further in Norwegian regulations where it is only specified that sufficient quality of views must be ensured.

4. Discussion

Looking back at the ambition of the European Green Deal to improve human health and well-being, among others through the Renovation Wave, this study aims to link a case of energy retrofitting to the indoor environment. Typically, retrofitting projects are associated with a windows' change, in the first step, while by installing new windows in the same position the outcome can be negative, as additional insulation might reduce views and daylight. Exterior façade design should therefore aim for more flexible solutions, including window size, to achieve better performance and benefit for the new materials and components used. Other aspects to consider are the façade`s orientation as that might require multiple façade solutions, as well as other relevant conditions including the protection of aesthetical and heritage values. Increasing the rate of retrofitting projects can be considered the most usual and efficient (also, in many cases, economically) approach to achieve significant energy, climate gas and demolition-related waste reduction, in long term. However, these kinds of projects are often impeded or opted out due to missing detailed solutions, recommendations, and reference projects. Especially, the concrete-based constructions potential of retrofitting having heritage constraints should not be underestimated and wasted. Both alternatives displayed depend on the addition of insulation material. The added thickness can lead to decreased views of the outdoor, that in turn can influence productivity. Window openings in both alternatives must therefore at least be of the same quality as in the current stage. The German code DIN EN 17037 [22] as example gives guidance on how to assess and ensure good quality of view as a combination of horizontal and vertical angles and layers of view, and the distance of views. This also depends on the elevation of the individual floors and room, resulting in lower quality of the low-rise buildings of this case. Alternative 1 and external insulation in general is considered favourable due to less risk for moisture within the construction, while alternative 2 must be considered if heritage restrictions apply only. It is more difficult to achieve due to the significant risk for condensation inside the existing external wall construction what can lead to a mold growth. This could result in a significant reduction of the indoor air quality and might introduce health-problems for long-term users. The complex showed to have great energy-related retrofitting potential of 2.69 GWh/a (-42 %) meetings Norwegian regulations, and up to 5.12 GWh/a (-80 %) according to very ambitious goals as found in reference projects.

To test whether the year 2021 is a representative year, the two months January and February were compared for 2021 and 2022 to see if large unknown Covid-19-related deviations show. This initial comparison showed no major difference in energy consumption. For the entire complex, the 2022 usage was at 102 % in January 2022 and at 97 % in February 2022 compared to the same months in 2021, see Figure 6.

That in mind, used 2021 energy data might be slightly higher than during other years but is considered sufficient for the estimates performed here. These two months of 2022 were the only ones available for comparison. Other parameters such as indoor temperature, outdoor weather conditions, and data from more years must be included to establish a reference year.

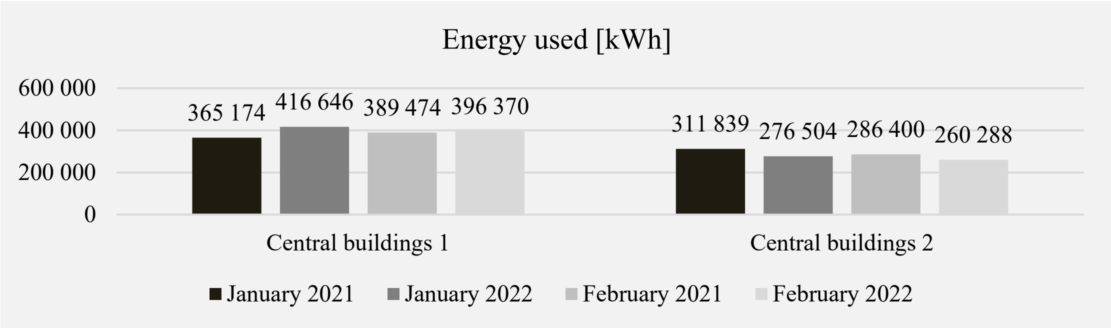


Figure 6. Energy use in the entire complex, comparison between January and February in 2021 and 2022. [figure by the authors]

Future retrofit propositions will be done in cooperation with other departments at NTNU to establish detailed HVAC definitions and will include user surveys. The fact that the user group is already known is considered an advantage of retrofit projects, as it is easier to compare pre and post-retrofit surveys and user participation in general. Both proposed alternatives are subject to ongoing analysis. More information and detailed drawings will be presented in separate studies after consulting the Directorate of Cultural Heritage. Some retrofit requirements must be met regardless of the chosen alternative. As mentioned in the introduction, good and ideally increased productivity of the occupants is one of the main goals, apart from energy and emission reductions. During the replacement of windows and providing additional insulation, following requirements must be met:

- Same or larger window openings, especially regarding Alternative 1, as smaller windows or reduced effective windows' area restrict both the access to natural daylight, views of the outdoors, and ventilation openings which is expected to decrease productivity.
- Windows of at least the same physical quality as worse windows negatively impact visual tasks and thermal conditions of the interior which is expected to decrease productivity.

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