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Cost-optimal energy performance renovation measures of educational buildings in cold climate

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HIGHLIGHTS

- The proposed national nZEB target can be cost-effectively achieved in renovations.
- Energy saving potential of HVAC systems is significant compared to the building envelope.
- Modern renewable energy production technologies are cost-efficient and recommendable.
- Improving the indoor climate conditions in deep renovations is recommendable.
- Simulation-based optimization method is efficient in building performance analyzes.

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ABSTRACT

The paper discusses cost-efficient energy performance renovation measures for typical educational buildings built in the 1960s and 1970s in cold climate regions. The study analyzes the impact of different energy renovation measures on the energy efficiency and economic viability in a Finnish case study educational building located in Lappeenranta University of Technology (LUT) campus area. The main objective of the study was to determine the cost-optimal energy performance renovation measures to meet the proposed national nearly zero-energy building (nZEB) requirements, which are defined according to the primary energy consumption of buildings. The main research method of the study was simulation-based optimization (SBO) analysis, which was used to determine the cost-optimal renovation solutions. The results of the study indicate that the minimum national energy performance requirement of new educational buildings ($E_{primary} \leqslant 170\ kWh/(m^2,a)$) can be cost-effectively achieved in deep renovations of educational buildings. In addition, the proposed national nZEB-targets are also well achievable, while improving the indoor climate (thermal comfort and indoor air quality) conditions significantly at the same time. Cost-effective solutions included renovation of the original ventilation system, a ground source heat pump system with relatively small dimensioning power output, new energy efficient windows and a relatively large area of PV-panels for solar-based electricity production. The results and conclusions of this study can be generalized to similar climates and techno-economic environments.

1. Introduction

The energy saving potential of existing buildings is significant compared to new buildings in the EU region [1]. The existing buildings account as high as 40% of the total energy consumption in the EU area [2]. The European Commission states that improvements in energy performance must not undermine the indoor climate conditions of buildings [3]. The recast Energy Performance of Buildings-directive (EPBD) requires the implementation of significant changes in building regulations of the member states [2].

The requirements of the recast EPBD-directive apply to new buildings, but the directive states that the energy efficiency of existing buildings should also be improved, when deep renovations are conducted [2]. According to the EPBD-directive, the technical, functional and economical aspects should always be taken into account, when the energy performance of buildings is improved in renovations [2]. Furthermore, a large share of the energy demand of nearly zero-energy buildings should be covered by using renewable energy sources (RES), e.g. solar energy and heat

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pump systems, to improve the primary energy efficiency and cost-effectiveness of energy performance measures to meet the EU 2020 energy efficiency targets [2,4]. The best way to encourage deep energy performance improving renovations is to set national energy efficiency targets, to develop economically viable renovation concepts and to demonstrate functional and cost-effective low-energy building and renewable energy production technologies to meet the national nZEB requirements of the EPBD-directive [2,5,6].

Multiple studies related to the learning and productivity of students and teachers, indoor climate and energy efficiency of schools and educational buildings have been conducted during the last two decades [7–20]. The main conclusions of these studies indicate that there is a connection between the productivity, learning performance and indoor climate conditions, including thermal comfort level and indoor air quality (IAQ), which is highly determined by the ventilation rates applied in educational buildings during operation time [14–20]. When energy efficiency of educational buildings is discussed, it is often relatively difficult to maintain excellent indoor climate conditions energy and cost-effectively, as indoor climate conditions and energy efficiency are conflicting objectives [13–15]. This creates a problem in designing both new educational buildings and also in renovating existing buildings, as the indoor climate conditions are typically improved in renovations, in addition to improving the energy performance of the buildings [13–15].

The previous studies have been conducted using a conventional research method, where typically only individual measures or concepts including a few different measures have been studied. This research method is always limited in the total number of predefined cases, which limits the number of studied energy performance measures and makes it impossible to determine, if the discovered cost-optimal solution is the global optimum solution [13–15]. In addition, the cost-effectiveness of modern renewable energy production systems has not been extensively studied in renovations of existing educational buildings located in cold climate regions. According to recent studies, correctly dimensioned and designed renewable energy production systems are possibly cost-efficient measures, depending heavily on the case, but more research has to be conducted to determine their economic feasibility as energy performance improving measures in deep renovations of buildings located in Nordic climate [21,22]. In Finland and in many other EU member countries, the nZEB is defined as standardized primary energy consumption of a specific building type. The proposed nZEB target level of educational buildings is 104 $kWh_E/(m^2,a)$ defined in the recent FInZEB project [23]. Previous studies have not come up with cost-optimal solutions to renovate the existing educational buildings located in cold climate to nearly zero-energy buildings, while improving or maintaining excellent indoor climate conditions at the same time. The main reason for this is that the previous studies have typically been limited to a limited number of the more commonly carried out renovation measures. Furthermore, the studied measures don't usually include new technologies and their comparison to the more popular renovation measures.

All of the applicable renovation measures that can be conducted in existing brick educational buildings are taken into account in this study. The ground source heat pump system and solar-based electrical and thermal energy production systems were also studied as RES-based energy systems. Furthermore, the main research method of the study is simulation-based multi-objective optimization analysis, which was used to determine the cost-optimal renovation measures. The optimization engine of the SBO analysis was MOBO, a new software developed for building performance optimization analyzes [24,25]. The number of measures and renovation solutions is not limited by using the SBO analysis, which makes it a very efficient method to study multiple conflicting objectives and a large number of different measures simultaneously.

The main objective of this study is to determine cost-efficient renovation solutions for typical educational buildings built in the 1960s and 1970s that are located in cold climate regions. A key target of the study is also to determine cost-optimal renovation solutions to meet the proposed national nZEB energy performance target level of new educational buildings and to determine, if it is reasonable to renovate the existing educational buildings built during the 1960s and 1970s to nZEBs. A primary objective of the study is to provide economically viable energy performance measures to meet different energy performance criteria and to reduce both the primary and the delivered energy consumption and also the environmental impact of the existing educational building stock.

This study presents the global cost optimum renovation solutions of educational buildings, including a GSHP and on-site electricity production system in addition to the more commonly used renovation measures regarding the building envelope and technical systems, for the first time. The research method used in the study, the simulation-based multi-objective optimization analysis, has not been previously used in any studies to determine the cost-optimal renovation measures in deep renovations of educational buildings. Global optimum solutions cannot be determined by conventional methods, where a few individual energy efficiency measures or concepts are simulated and compared, as deep renovations of buildings typically include thousands or even millions of potential solution combinations. Furthermore, this study presents optimal renovation solutions in educational buildings located in cold climate conditions to also reach higher energy performance criteria in addition to the cost-optimal renovation solutions, while improving the indoor climate conditions at the same time. A large set of alternative and cost-optimal renovation measures to help the educational building owners to meet different energy performance targets cost-effectively and to develop cost-efficient renovation concepts have not been presented before. The results and conclusions of this study can be generalized to similar climates and techno-economic environments, when deep renovations of educational buildings are conducted.

2. Methods

2.1. Studied building

2.1.1. Selection of the case study building

The study focuses on the cost effective renovation of typical educational buildings located in cold climate areas. A Finnish educational building located in Lappeenranta University of Technology (LUT) campus area was selected as a case study building of this study. Fig. 1 presents the distribution of educational buildings by the total floor area according to the construction year (right) in addition to the total number and floor area of educational buildings (left) [26]. Fig. 1 shows that the educational buildings built before the 1980s represent the largest share (68%) of the Finnish educational building stock. The share is even larger (73%), when the total number of educational buildings is discussed (see Fig. 1). Furthermore, the educational building stock built before 1976 also possesses a significant energy efficiency improvement potential, due to their age and the fact that there were no building regulations in Finland before 1976 to set minimum requirements for energy performance of buildings. The studied building also represents typical educational buildings built during the same era and located in similar cold climate conditions, such as educational buildings built in the Scandinavian countries and in Estonia [11–