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From Energy to Health: Role of the Ventilation Systems in Energy-Retrofitted Buildings

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Abstract

The transition towards zero-energy buildings by 2050 has driven retrofitting initiatives across Europe, focusing on renovating existing buildings through improving insulation, solar panel installations, window replacements, and implementation of heat pump systems. While these retrofitting strategies contribute to energy efficiency, they also introduce new challenges related to indoor air quality and occupant health, particularly in highly insulated, and airtight buildings. This paper aims to investigate the intersection of energy retrofitting of buildings and occupants' health, with a specific focus on mechanical ventilation systems. By reviewing relevant literature on health issues and energy retrofitting in buildings, building-related illness is explored. The results highlight that while enhanced insulation and airtightness improve energy efficiency, they necessitate appropriate ventilation systems and informed end-user engagement. This study emphasizes the critical role of manufacturers and installers in providing clear ventilation system manuals for end-users. This research contributes to healthy indoor environments by increasing awareness towards building-related illnesses associated with energy efficiency initiatives.

Keywords

Energy retrofitting, Occupants' health, Ventilation system

1 Introduction

Buildings contribute to 40% of the European Union's final energy consumption and 36% of its energy-related greenhouse gas emissions, with 75% of the Union's building stock remaining energy-inefficient (Union, 2024). The Global Roadmap identified retrofitting existing buildings as one of the key steps for energy efficiency and low GHG emissions (Global Alliance for Buildings and Construction, 2016). In response, the revised Energy Performance of Buildings Directive (EPBD) in 2018 mandates all EU member states to develop long-term retrofitting strategies aimed at achieving a highly efficient and fully decarbonized building stock by 2050 (Union, 2018). Efforts to enhance the energy performance of buildings should consider climatic conditions, not only climate change adaptation, local contexts, and cost-effectiveness, but also indoor environment quality (Union, 2024). Three types of high-efficiency buildings include passive houses, Nearly Zero Energy Buildings (NZEBs) and deep-retrofitted buildings that consume significantly less energy compared to conventional buildings and have non-energy benefits as well. For instance, 80% of indoor exposure to air pollutants can be avoided in high-efficiency buildings, which results in health and productivity benefits (Bonetta et al., 2010, Chatterjee and Ürge-Vorsatz, 2021). The strategies of high-efficiency buildings such as building

insulation, Heating, Ventilation and Air conditioning (HVAC) systems with filtration, control, and determine indoor air quality (Chatterjee and Ürge-Vorsatz, 2021). The mechanical HVAC system plays a significant role in improving the environment by providing fresh air to individual rooms and extracting polluted air, which reduces moisture and improves thermal comfort level as well (Li et al., 2007). Some studies (Asikainen et al., 2016, Organization, 2016) show that adequate air exchange can reduce humidity and exposure to other indoor pollutants such as Carbon dioxide (CO₂).

On the other hand, the findings show that in practice, energy-retrofitted buildings cause risks for Indoor Environmental Quality (IEQ) and, consequently, for the health and comfort of occupants (Ortiz et al., 2020). Although few studies have been carried out on IEQ and possible health effects in retrofitted buildings, the results show that the retrofitting of the buildings can lead to complaints about mold growth, built-up of pollutants (including radon), and a range of health problems. Underperformance of mechanical ventilation and heat recovery systems and air source heat pumps is a result of insufficient commissioning and maintenance procedures and poor end-user control due to complex control interfaces (Ortiz et al., 2020). This study aims to explore the health issues as a consequence of energy retrofitting, the role of the ventilation systems, and their proper use.

2 Methodology

This study is a critical review exploring the effects of energy retrofitting on occupant health using a scoping review approach. A scoping review is useful for determining the scope and coverage of literature on a given topic and identifying the types of available evidence within a field (Munn et al., 2018). The study follows the methodological framework developed by Arksey and O'Malley (2005) for conducting scoping reviews.

2.1. Selection of articles

The selection of articles was conducted in three stages:

- 1) *Initial database search*: the search was conducted on October 15, 2024, yielding 326 studies. First, a comprehensive search was performed in Scopus and Scholar Google using the search keywords: energy-retrofitting AND health risks OR post-occupancy behaviour OR zero-energy buildings OR indoor air quality OR behavioural change. These terms were chosen to obtain studies examining health risks in energy-retrofitted buildings during post-. To ensure a broad disciplinary perspective, variations of “energy-retrofitting” and “post-occupancy behaviors” were included, drawing from health risks and behavioral literature rather than focusing solely on energy efficiency studies. This approach facilitated the exploration of the key effects of energy-retrofitted buildings on health risks linked to occupant behaviors.
- 2) *Screening process*: The selection process involved two levels of screening:
 - a) Inclusion criteria: peer-reviewed academic work and energy-retrofitted related health risks as a central focus of the study.
 - b) Exclusion criteria: studies where health risks were not a primary concern, studies not related to energy retrofitting, and studies not focused on buildings-related health risks.
- 3) *Final selection*: 65 articles were selected for full-text review after the initial screening. Following this, 16 articles were excluded, leading to a final dataset of 49 studies for data extraction and analysis.

2.2. Data analysis

The analysis used a deductive approach: 1) *Initial coding* categories were derived deductively based on the research questions. The main research question guiding this review was: “What are the health risks associated with energy-retrofitted buildings?” 2) The study examined the sources and effects of

building-related health risks, particularly those rising during post-occupancy. *A critical interpretive analysis* was conducted to identify the key risks and sources and develop recommendations for mitigating these risks in energy-retrofitted buildings.

3 Building-Related Illness Associated with Energy-retrofitting

The health risks can be traced to three retrofitting strategies: building insulation, HVAC systems, and end-user behaviors. Air-tightness and more thermally insulated retrofitted buildings lead to humidity problems, build-up of pollutants, and overheating. Installing HVAC systems and issues within (ducts, filters, maintenance) may also affect IEQ. Some indications show that certain retrofits increase the risk of health problems, particularly for airways, skin, and eyes (Ortiz et al., 2020). Therefore, most of the health effects of highly efficient buildings depend on the operation of the mechanical HVAC system and an airtight building envelope with high thermal insulation (Chatterjee and Üрге-Vorsatz, 2021). The HVAC system has two effects: 1) reducing indoor pollutant concentration (such as allergens, formaldehyde, micro-organisms, and fungal spores) by maintaining an adequate and constant air exchange rate (Che et al., 2019, Levetin et al., 1995), and 2) causing an unintended inflow of outdoor pollutants, which can include particulates of biological origin (e.g., microorganisms or pollen), particulate matter, ozone (O₃), and nitrogen oxides (NO_x) (Asikainen et al., 2016). Hence, filtration is often installed in the HVAC system to prevent the intrusion of outdoor pollutants indoors. Moreover, buildings with high levels of thermal insulation and inadequate air exchange increase indoor humidity and moisture, leading to higher microbial growth and dust mites. Consequently, breathing in mold spores and volatile organic compounds (VOCs) produced by mold contributes to a high ‘burden of disease’ (Chen et al., 2018, Fernandes et al., 2009, Fisk and Rosenfeld, 1997, Mondal and Paul, 2020, Nagendra and Harika, 2010). HVAC systems in less airtight conventional buildings have a minimum effect on human health as outdoor pollutants, such as particulate matter and NO_x, can enter through the envelope cracks, which could result in building-related illnesses (BRI) (Hänninen and Asikainen, 2013). BRIs due to poor indoor building conditions consist of various diseases, which are shown in Table 1 (Asikainen et al., 2016, Jones, 1999, Redlich et al., 1997, Crook and Burton, 2010, Kreiss, 2005). The relationship between energy retrofitting, building insulation, and the installation of mechanical systems, along with end-user behaviors such as maintenance and system understanding, is presented in Table 2.

Table 1. Building-related illnesses associated with energy retrofitting

Effective factors	How	Building-related illnesses
Mechanical system	Installing HVAC systems and issues within (ducts, filters, maintenance)	-Risk of health problems, particularly for airways, skin, and eyes (Ortiz et al., 2020)
	The HVAC system causes an inflow of outdoor pollutants (Asikainen et al., 2016)	-Increases indoor humidity and moisture, resulting in higher microbial growth and dust mites (Chen et al., 2018, Fernandes et al., 2009, Fisk and Rosenfeld, 1997, Mondal and Paul, 2020, Nagendra and Harika, 2010).
Building insulation	Air-tighter and more thermally insulated (Chatterjee and Üрге-Vorsatz, 2021) and inadequate air exchange	-Diseases including asthma, cold and flu, lung cancer, and cardiovascular diseases, especially ischemic heart disease (Asikainen et al., 2016, Jones, 1999, Redlich et al., 1997).
End-user behavior	Higher exposure time and occupancy rate	-Influenza types cold and flu, and eye infections in the tertiary buildings (Crook and Burton, 2010, Kreiss, 2005).

Table 2. The relationship between retrofitting of the buildings and health issues

Effective factor	Main cause	Health risks	Key solutions
Building insulation	<ul style="list-style-type: none"> - Thermal bridging & condensation (Vinha et al., 2018) - Moisture/dampness (Bornehag et al., 2005) - Reduced ventilation (Marlow, 2012) - Overheating in well-insulated buildings (Tink et al., 2018) 	<ul style="list-style-type: none"> - Mold-related respiratory issues (Adan and Samson, 2011) - Allergic reactions (Takaoka et al., 2016, Sun et al., 2018) - Skin symptoms (Bornehag et al., 2005, Sun and Sundell, 2013, Zhang et al., 2019) - Heart problems (from overheating) (Kovats et al., 2008) - Systemic inflammation (Mustonen et al., 2016) 	<ul style="list-style-type: none"> - Increased ventilation - Regular cleaning - Moisture control - Window opening (Ortiz et al., 2020)
Mechanical ventilation systems	<ul style="list-style-type: none"> - Poor maintenance (Mendell et al., 2003) - Dirty filters/ducts (Withers, 2019) - Lack of cleaning (Coelho et al., 2005) - Limited user control (de Dear et al., 2013, Boerstra, 2016) 	<ul style="list-style-type: none"> - Respiratory tract issues (Mendell et al., 2003) - Mucous membrane symptoms (Withers, 2019) - Anxiety, fatigue, allergies and asthma (McClellan and Hamilton, 2010) 	<ul style="list-style-type: none"> - Regular system maintenance (Bluyssen, 2019) - Personalized control systems and user-friendly interfaces (Hellwig and Boerstra, 2017, Ortiz et al., 2020, Hellwig and Boerstra, 2018)

4 Improving Indoor Air Quality in Energy-retrofitted Buildings

As aforementioned, the main effects of using a highly efficient building and corresponding ventilation system lead to improvement of the indoor air quality level. Indeed, the appropriate ventilation rate decreases indoor pollutant concentrations and simultaneously filters outdoor pollutants, while high insulation levels minimise infiltration of outdoor pollutants indoors. Therefore, the indoor air quality in any highly efficient building is better than in any low retrofitted building. A lower concentration of pollutants contributes to improved health levels as the risk of certain diseases would be reduced due to less exposure to indoor and outdoor pollutants. The impact of these various factors in providing good indoor air quality in an energy-efficient building is shown in Figure 1 (Chatterjee and Üрге-Vorsatz, 2021). It is important to note that good indoor air quality starts with source control, which involves minimizing materials, machines, and other items that could negatively impact the air quality (Bluyssen et al., 2016, Marlow, 2012, Bhat, 2024, Alapieti et al., 2020, Jones, 1999, Dehghani et al., 2024). This can be achieved by avoiding indoor sources of pollutants, avoiding high occupancy levels, and using low-emission interior materials (e.g. placing printers outside workspaces). In summary, the recommendations for improving the intervention quality in ERBs are indicated in Table 3.

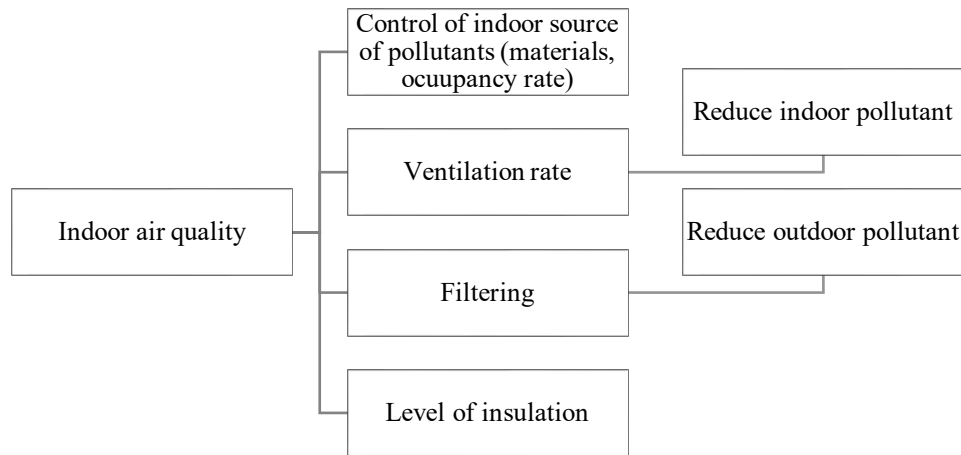


Figure 1. The effective factors on indoor air quality in an energy-efficient building (Chatterjee, S., & Ürge-Vorsatz, D., 2021)

Table 3. The suggested improvement for increasing indoor air quality

Improving people-related behaviors	References
Opening/closing a window or door	(Langevin et al., 2013)
A good knowledge of the operation of energy-consuming equipment and how it works	
Increasing homeowners’ participation	(Ma et al., 2021)
Simplicity and the user-friendliness of control systems	(Boerstra, 2016)
Detailed information provision about the ventilation systems including initial oral instructions and written manuals	(Mlecnik et al., 2012)
Improving building-related condition	
Better ventilation and reducing condensation	(Ebrahimigharebaghi et al., 2019)
Well-designed buildings with proper moisture management (e.g. Avoid cold bridges that can lead to mould growth)	(Mlecnik et al., 2012, Boerstra, 2016, Dehghani et al., 2024)
Using low-emission materials	
Filtering and high levels of insulation	(Chatterjee and Ürge-Vorsatz, 2021)

Therefore, a multi-dimensional strategy is recommended to avoid building-related illness in energy-retrofitted buildings, including:

- Education: Provide comprehensive user guides, interactive training materials, and continuous learning opportunities about IEQ;
- Technology: Provide control interfaces, simple monitoring systems, and user-friendly design;
- Support: Provide ongoing technical support, community knowledge sharing, and personalized guidance (Figure 2).

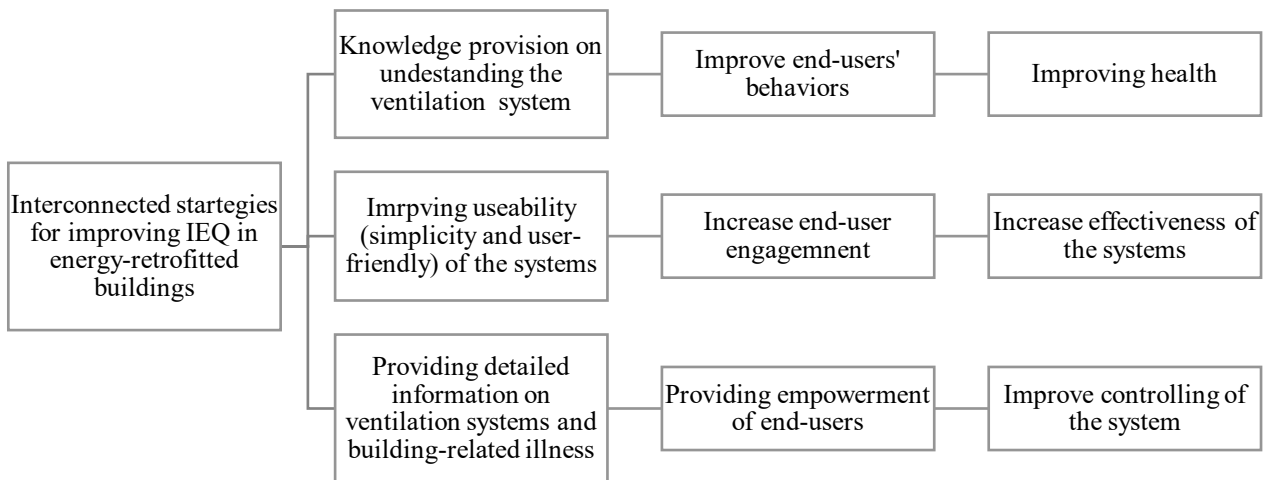


Figure 2. Interconnected strategies to improve IEQ in energy-retrofitted buildings.

5 Conclusion

This study aims to show the relationship between energy retrofitting and indoor air quality. The findings highlight the role of proper use of ventilation systems and end-users' knowledge of systems' operation and control directly impacts indoor air quality. Moreover, the study shows that improving indoor air quality can be achieved simultaneously alongside energy efficiency goals by addressing the sources of indoor pollutants, such as low-emission building materials and furnishings, as well as improving occupant behaviors. It can be concluded that:

- End-users behavioral change is crucial for improving IEQ and health in energy-retrofitted buildings;
- User knowledge directly impacts mechanical ventilation system effectiveness;
- Simplicity and information of ventilation systems are key to engaging end-users;
- A holistic approach combining indoor resources, technology, education, and support is needed to provide good indoor air quality.

The research suggests that key stakeholders, including manufacturers, installers, and energy communities within neighborhoods need to provide user-friendliness systems and effective information to support learning on proper system use. These stakeholders can help bridge the current knowledge gap and improve end-users' understanding of their retrofitted building systems. Future research can focus on evaluating existing informational packages for end-users, identifying gaps related to health in current information systems, and developing and testing specific infographic content and formats. The findings contribute to the growing knowledge on the intersection of energy efficiency and occupant health in retrofitted buildings.

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