Indoor environmental quality and energy performance: Reviewing the case of council homes in London

In the UK, exposure to air pollution constitutes the most significant environmental risk to public health, particularly for low-income groups residing in council homes. These occupants often live in smaller flats at higher densities, which are typically located in areas with higher levels of air pollution. Consequently, their health and well-being are negatively impacted. Moreover, in the quest for improving indoor thermal comfort and energy efficiency, the levels of airtightness increased, and the ventilation rates decreased, which have further worsened indoor air quality. Therefore, this paper critically reviews the trade-offs between airtightness, indoor air quality (IAQ), thermal comfort, and their impacts on building occupants' health and well-being. The paper focuses on the case of London, where action plans and retrofitting strategies of council homes are reviewed. The review aims to explore strategies to optimize and balance between energy efficiency, indoor thermal comfort, and indoor air quality. Based on the review, the paper proposes the adoption of the social approach, in addition to the physical measures, through the consideration of the occupants' behaviour and altering their behaviours to optimize the use of energy and improve their indoor living conditions. The paper also recommends different mitigation strategies and design guidelines to promote healthier and more energy efficient buildings.

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1. Introduction

In 2021, the residential sector in the UK accounted for approximately 16 per cent of greenhouse gas emissions, with roughly 97% of the gases attributed to carbon dioxide [1]. In addition, the indoor environment in these households can have a significant impact on people's health due to the extended duration spent in these microenvironments. In developed countries like the United Kingdom, people spend around 90% of their time indoors [2], with around two-thirds of their overall time spent within residential buildings [3]. According to the World Health Organization [4], in 2020, household air pollution was responsible for approximately 3.2 million deaths. Furthermore, indoor air pollution has been identified as the third leading cause of disability-adjusted life years worldwide [5]. Focusing on the United Kingdom, air pollution exposure represents the most significant environmental health threat, resulting in 28,000–36,000 premature deaths annually. In London, poor air quality is also linked to approximately 9,400 premature deaths annually due to elevated levels of PM2.5 and NO2, resulting in a financial burden of £1.4 to £3.7 billion on the healthcare system [2, 6, 7].

Various adverse health outcomes are also associated with these elevated exposure levels to air pollution, including respiratory and cardiovascular complications, birth defects, childhood asthma cases, and sudden infant deaths. Additionally, air pollution has been estimated to have a detrimental impact on cognitive functions, leading to cognitive impairment and an increased risk of dementia [2]. The impact of air pollution in homes on human health and well-being occurs through various environmental pathways, including: (1) household air pollution originating from activities such as cooking, heating, and lighting, especially when reliant on rudimentary biomass, heating stoves, and coal cooking; (2) indoor air quality affected by dust or gases emitted by hazardous building materials and radon, as well as exposure to extreme temperatures (either hot or cold); (3) exposure to disease-carrying vectors, including pests and insects; (4) exposure to dampness and mould; and (5) utilization of unsafe construction materials and inadequate construction practices [5, 8].

Given these severe impacts, concerns over indoor environmental quality (IEQ) and energy efficiency in residential buildings have gained greater importance and the reduction of emissions from residential buildings became inevitable. Energy efficiency in buildings aims to minimize energy consumption while ensuring occupants can perform their daily activities, all while maintaining an optimal indoor environmental quality. Indoor environmental quality, simultaneously, refers to the physical and psychological aspects of indoor environments that influence the well-being, comfort, and contentment of occupants. Therefore, it is imperative to implement energy-efficient strategies and other measures that aim at mitigating indoor air pollution and emissions in the residential sector. This can also contribute to the mitigation of other problems like fuel poverty, household energy insecurity, and the negative health impacts associated with winter and cold conditions, including mortality and morbidity [9].

The significance of both indoor environmental quality and energy efficiency in residential buildings cannot be overstated. They are crucial for safeguarding the health, well-being, and productivity of occupants, while simultaneously reducing carbon emissions and energy expenses associated with buildings. These problems are particularly challenging for low-income groups residing in council homes. These occupants inhabit smaller flats with higher population densities, often located in areas characterized by elevated levels of air pollution. Consequently, their physical health and overall well-being are negatively impacted. In addition, efforts to enhance indoor thermal comfort and energy efficiency have resulted in increased levels of airtightness and decreased ventilation rates, which further exacerbated indoor air quality issues.

Thus, this paper aims to comprehensively understand the various synergies and trade-offs between airtightness, indoor air quality (IAQ), and thermal comfort, and their respective impacts on the health and well-being of building occupants. An overview of the circumstances in London is presented, examining the diverse factors that contribute to low-income households experiencing higher levels of indoor air pollution compared to the general population. This analysis is based on studies and models specific to London. Based on the review, strategies for balancing energy efficiency, indoor thermal comfort, and indoor air quality are presented. The paper recommends the adoption of the social approach in addition to the physical measures in building retrofits and energy simulations. This encompasses the consideration of occupants' behaviours and modifying their habits to optimize the use of energy and enhance their indoor living conditions.

2. Indoor environmental quality, and energy efficiency: Synergies & trade-offs

In the pursuit of enhancing indoor thermal comfort and energy efficiency, there has been a significant rise in airtightness levels and a corresponding decrease in the ventilation rates. However, these measures have adversely aggravated the issue of indoor air quality. This section aims to examine the effects of increased thermal insulation and air tightness on the overall indoor environmental quality and energy performance of residential buildings.

Thermal conditions and air quality were considered by the occupants to be two of the most important indoor environmental parameters determining comfort [10]. In today's buildings, thermal comfort is directly related to indoor air quality (IAQ), which in turn depends on envelope airtightness in buildings with no active ventilation systems [11]. Envelope airtightness and thermal insulation are used to help in: 1) reducing the amount of energy consumed for heating/cooling by limiting the number of air changes, 2) ensuring conditions for indoor thermal comfort, and 3) controlling moisture [12, 13]. The term "insulate-air tightening" was used by Yoshino [12] to refer to thermal insulation and air tightening in one word.

However, reducing air permeability in buildings by implementing highly airtight building envelopes can have significant implications for indoor air quality. This reduction in air infiltration leads to an increase in the concentration of water vapor and carbon dioxide, which are byproducts of human metabolism and considered major contributors to indoor environmental issues. In residential dwellings, occupants' behaviour can exacerbate these problems. For instance, when residents use cooking appliances with open flames to warm the interior, the indoor air experiences elevated moisture content and concentrations of harmful gases, including carbon monoxide and dioxide [13].

Furthermore, it is important to note that thermal insulation alone does not always result in a better indoor environment [12]. A recent study conducted in the UK revealed that improved building performance, while increasing thermal insulation and airtightness, can potentially lead to over insulated building envelopes that are more prone to overheating during warmer seasons, especially when subjected to direct solar radiation. These findings underscore the significance of considering occupancy scenarios for different households to accurately predict overheating risks and prevent complications in retrofit interventions, which will be discussed in section 5 [14].

In addition, insufficient ventilation in indoor spaces is a significant factor in the prevalence of sick house syndrome (SBS). SBS refers to the negative impact on the comfort and well-being of individuals in a building. Apart from its detrimental effects on occupants, a sick building is often associated with low energy efficiency, which can be attributed to various design, implementation, and operational flaws in the building and its systems. These issues highlight the importance of addressing ventilation deficiencies and improving overall building performance to ensure healthier and more energy-efficient living environments [13].

The sick house phenomenon can be attributed to several factors, including reduced natural ventilation resulting from a tightly sealed building envelope. Additionally, the use of certain building materials, furniture, and everyday items containing chemicals, as well as the presence of substances like mothballs and air fresheners, and other pollutants contribute to the problem. These factors collectively contribute to the development of an unhealthy indoor environment with potential negative impacts on occupants' well-being [12].

As a result, ventilation is imperatively important in the design of residential buildings. Firstly, ventilation aims to prevent the build-up of air pollutants such as chemical substances, carbon dioxide, nitrogen oxides, and unpleasant odours. Secondly, it serves to remove excess moisture from enclosed spaces. Lastly, ventilation plays a crucial role in supplying an adequate amount of oxygen to combustion devices. To achieve effective ventilation, it is essential to ensure the airtight performance of the building. This can be accomplished by introducing outdoor air through properly designed air supply inlets, allowing it to circulate through all areas of the indoor spaces, and efficiently expelling it through exhaust systems. Particularly in spaces where chemical emissions may occur, the introduction of fresh outdoor air to all areas becomes paramount [12].

Finding the optimal ventilation rate in residential dwellings is a trade-off between minimizing heat loss for meeting greenhouse gas emission targets and minimizing adverse health effects caused by exposure to cold temperatures and pollutants from both indoor and outdoor sources. In a preliminary application of the methods to a typical flat and detached house in the UK [15], it was observed that the optimal ventilation rate can vary depending on the building form. The analysis indicates that the flat may require a higher ventilation rate compared to the detached house. By employing a generalized multi-objective optimisation approach with equal weightings given to health impacts and energy savings, an optimal annual air changes per hour (ACHyr) of 0.4/h for the house and 0.7/h for the flat was determined. These values include purge ventilation during periods of indoor PM2.5 and moisture generation, corresponding to average ventilation rates of 0.3 l/s/m2 for the house and 0.4 l/s/m2 for the flat [15].

Effective control of moisture, carbon dioxide (CO2), and airborne pollutants necessitates a balance between introducing fresh air from the outside and extracting stale air from the indoors. Retrofitting measures are often implemented to enhance energy efficiency by improving airtightness in homes. However, as homes become more airtight, it becomes imperative to install controllable ventilation systems to ensure consistently high air quality. A recent study conducted by the London Councils [16] identified heating systems, and mechanical ventilation with heat recovery (MVHR), to have the greatest impact on occupants' health (based on subjective assessment of the impact of retrofit measures on the second-order effects). Consequently, it is of utmost importance to prioritize the development of ventilation systems in building retrofitting plans to enhance both health and indoor air quality.

3. Indoor air quality & socioeconomic disparities: Reviewing the case in the UK

Numerous studies have focused on investigating the associations between environmental inequality and health [2, 17-20]. These studies have recognised the significant links between pollution, deprivation, and health. Within the field of environmental health, this phenomenon is commonly referred to as the 'triple jeopardy' effect. The ‘triple jeopardy’ phenomenon states that communities with lower socioeconomic status (SES) residing in deprived areas face a threefold challenge. They experience elevated exposure to air pollutants and other environmental hazards, such as air pollution. Besides, they display an increased susceptibility to poor health, primarily due to elevated psychosocial stressors, including discrimination and chronic stress, limited opportunities to engage in health promoting behaviours, and overall poorer health status. As a result, these circumstances lead to the emergence of health disparities that are primarily driven by environmental factors [2, 21].

In the UK, extensive research has long acknowledged the links between low socioeconomic status (SES) and poor IAQ. The two UK studies conducted by Pearce, Richardson [22] and Fecht, Fischer [23] have found that individuals from low SES groups tend to experience poorer air quality compared to their counterparts. Furthermore, in England, the gap in health inequalities has widened between 2001 and 2016 (Bennett et al. 2018), where occupants residing in the most deprived areas of the country face a threefold higher risk of death from preventable health conditions compared to those residing in the least deprived areas, according to data from the Office for National Statistics in 2019 [2]. The exposure to air pollution has been explicitly highlighted in the 2019 Public Health England's (PHE) remit letter as one of the leading factors contributing to preventable health issues (Ferguson, Taylor et al., 2021). Thus, the reduction of environmental inequalities shall be prioritized.

Ferguson, Taylor [2] in their paper examine the factors that contribute to higher levels of indoor air pollution in low-income households compared to the general population, using models and datasets for London. The study has outlined five important factors driving indoor air pollution exposure disparities. These factors include:

1. Living in deprived areas with often higher levels of outdoor air pollution.
2. Inadequate housing conditions:
    a. Low socioeconomic status groups tend to live in smaller dwellings with limited external facades, hindering the removal of both outdoor-sourced and indoor-generated pollutants.

    b. Indoor sources of pollutants, such as gas cookers, heating systems, smoking, and cooking styles, further contribute to indoor pollution.

    c. Increased airtightness in low-income housing reduces the removal of indoor-generated pollutants.

    d. The physical layout of buildings also plays a role, as smaller volumes lead to higher concentrations of pollutants without sufficient ventilation. Low-income households face challenges in maintaining proper ventilation systems. Besides, living in flats with shared walls and floors increases the risk of pollutants from neighboring dwellings entering the home, especially in high-density housing.
3. Occupant behaviour also plays a crucial role in indoor air pollution levels. For instance, low-income households are characterised by longer cooking durations resulting in substantially higher indoor air pollution levels.
4. Additionally, residents of low-income households spend more time at home, often due to unemployment or security concerns in their neighborhoods. Overcrowding and high occupant density further contribute to poor indoor air quality.
5. Underlying health issues; respiratory and cardiovascular diseases have been identified as major contributors to the increasing health disparities between the most and least deprived regions in the UK over the past two decades. These diseases are more prevalent in areas of lower socioeconomic status, intensifying the adverse effects of air pollution exposure on health.

In conclusion, low-income groups face a triple jeopardy situation where they experience higher levels of indoor air pollution due to factors such as the physical properties of the household, their socioeconomic status, their behaviours, and their preexisting health conditions that further exacerbate the health impacts of exposure compared to those without such conditions. As their health deteriorates, individuals may be compelled to spend more time indoors, leading to an increased exposure to air pollution within the domestic environment.

4. Energy-efficient retrofitting of council housing: Reviewing the case in London

This section reviews the national and local initiatives for building retrofitting in London and the

UK. The current retrofitting strategies and efforts within council homes are outlined. In addition, the barriers and enablers to energy efficiency retrofitting of social housing in London are demonstrated.
National and local scale initiatives for energy efficiency in the UK

In England and the UK, national level initiatives have been proposed to address energy efficiency in buildings. These initiatives involve:

a) Policy measures for the private rented sector (minimum Energy Performance Certificate (EPC) rating of C by 2030) and for mortgage lenders as well,
b) The Construction Leadership Council has drafted a National Retrofit Strategy that emphasises local leadership and collaboration through partnerships for effective implementation,
c) Funding initiatives have also been introduced, such as the Green Homes Grant Local Authority Delivery scheme and energy efficiency projects supported by the Department for Business, Energy and Industrial Strategy (BEIS).

Furthermore, local initiatives and guidance plans are also in place. For instance, Nottingham Deep Retrofit Energy Model, Greater Manchester Combined Authority: People Powered Retrofit with URBED & Carbon Coop, and UKGBC Accelerator Cities Programme, including the Retrofit Playbook. These initiatives collectively aim to drive sustainable retrofit programs, improve energy performance, and promote the adoption of energy-efficient practices in the built environment [16].
Buildings in London have a significant impact on the city's carbon emissions, contributing to almost 80 percent of the total. Additionally, these buildings emit pollutants like nitrogen dioxide and particulate matter, which have direct health implications for the residents of London. Therefore, enhancing thermal comfort and indoor air quality can significantly benefit health, particularly for vulnerable populations. According to the International Energy Agency (IEA) and the Organisation for Economic Co-operation and Development (OECD), health improvements may contribute up to 75% of the overall value derived from enhancing the energy efficiency of buildings. Additionally, HACT's Social Return on Investment calculator indicates that a 3-point improvement in Energy Performance Certificate (EPC) ratings in London can lead to enhanced well-being for individuals, amounting to an estimated £651 per year. Therefore, it is crucial to assess home retrofitting not only in terms of energy conservation but also in terms of positive health effects and other associated benefits, often referred to as co-benefits [16]. Accordingly, tackling air pollution and energy efficiency have been prioritised in London’s plans and policies [24].

Current initiatives and retrofitting progress in London Boroughs

London boroughs have a significant level of control over their own housing stock. This level of control provides an opportunity to implement large-scale retrofitting initiatives over the next decade and beyond. Nearly all London boroughs are actively engaged in the development of effective retrofit initiatives, aiming to establish and promote best practices, as shown in Table 1. These initiatives encompass a wide range of projects, including demonstration projects for both individual houses and blocks of flats [16].

Table 1. Examples of London borough initiatives as of April 2021; adapted from: [16]

Demonstrator Project	Delivery, skills, supply chain
Houses: Brent, Enfield, Lewisham, Newham, Richmond, Sutotn, Wandsworth, Waltham Forest Block of flats: City of London, Enfield, Greenwich, Hackney, Haringey, Kensington & Chelsea, Redbridge, Richmond & Wandswort, Sutton	Skills: Camden's stakeholder engagement event Energiesprong: Enfield, Haringey, Sutton Window manufacturing: Newham Parity Projects' Ecofurb

Additionally, there is a specific focus on activities related to heat decarbonisation, renewable energy generation, demand flexibility, and strategic endeavours related to delivery, cost assessment, funding, stock assessment, and modelling. These comprehensive efforts reflect the commitment of London boroughs to advance sustainable retrofitting practices and drive positive change in the built environment. Moreover, the Retrofit Accelerator - Homes programme was developed to assist London boroughs and housing associations in implementing large-scale energy efficiency projects. The programme offers technical and commercial solutions to support the development of these initiatives. Furthermore, homeowners and professionals in London have various resources to support energy efficiency initiatives. These resources include reports published by the Greater London Authority (GLA) on topics such as heat pump retrofit in London (2020) and Building Renovation Passports (2021). By incorporating energy-efficient retrofit measures into the ongoing maintenance programs and establishing clear and measurable targets, London local authorities can effectively drive the progress towards achieving low-energy standards in their housing stock [16]. The London Councils [16] have also developed a set of recommended actions to retrofit the councils' own stock, as demonstrated in Table 2

Table 2. Recommended action to retrofit the councils' own stock by the London Councils [16]

1	Improve the building fabric of London's inefficient homes
2	Develop a plan for retrofitting ventilation systems to improve health and air quality
3	Electrify heat
4	Deliver smart meters and demand flexibility (controls, storage) in retrofitted homes
5	Increase solar energy generation on London homes
6	Map out each building's journey towards lower energy costs and Net Zero
7	Review current maintenance programmes and identify retrofit opportunities
8	Facilitate procurement of materials and services at a larger scale
9	Enable planning to facilitate low carbon retrofit, including in Conservation Areas
10	Develop retrofit skills actively across London
11	Set up a clear and consistent system to report and monitor progress (and success)
12	Establish the cost of retrofit, business case and funding gap for the different tenures
13	Maximise capital finance for council-owned stock (and eligible homes)
14	Create a 'Finance for retrofit' taskforce with finance experts
15	Social housing: engage with tenants, leaseholders and other registered providers
16	Continually develop and implement the Action Plan together

Though huge efforts were demonstrated in the field of energy retrofitting to residential buildings in London, it was still recognised that there were not enough retrofits. It is critically important to understand the key barriers to residential retrofitting in London. One of the main attributed reasons was the lack of regulatory framework [16]. The current regulatory framework lacks adequate support for improving the energy efficiency of existing homes, transitioning away from gas boilers, and implementing solar PV systems for electricity generation. It falls short in promoting comprehensive whole house retrofitting and decarbonisation of heating systems. Besides, supportive initiatives remain very limited in scale and primarily focus on individual measures rather than adopting a holistic approach to retrofitting. As a result, they have not yet reached the necessary scale to make a significant impact [16].

Other challenges are also faced throughout the different retrofitting stages. In that sense, two significant studies were concerned with overviewing the key challenges. First, the report conducted by the London Councils [16] categorized the challenges into four main groups, as follows:

- Technical:

  The complexity of retrofitting requires tailored solutions for each home and household, striking a balance between simplification and specificity. However, the current approach fails to achieve this balance, leading to confusion and inadequate recommendations for homeowners and landlords.

- Finance:

  The majority of landlords and homeowners face financial constraints that prevent them from undertaking whole-house low carbon retrofit in a single phase. This challenge extends to occupants of social housing as well. Local authorities have the potential to facilitate finance for all properties within their jurisdiction, including non-council owned social housing. However, limited resources pose significant obstacles, hindering the funding of retrofit projects even for their own housing stock.

  o London's local authorities have made a collective commitment to retrofit the city's building stock to achieve an average Energy Performance Certificate (EPC) rating of B by 2030. Furthermore, many authorities have declared a climate emergency and set a target of achieving net-zero emissions by the same year. However, the challenges of financing and limited resources pose significant obstacles for local authorities, who are under immense pressure. Mobilizing substantial amounts of public and private finance is crucial for successful retrofitting efforts, and achieving this requires effective coordination at both local and regional levels.

- Delivery and supply:

  Meeting various obligations and priorities, such as affordable housing provision, building safety improvements, and post-Covid-19 recovery, creates additional complexities in the delivery of retrofit projects. Once homeowners and landlords have determined their retrofit plans, the challenge lies in accessing a reliable and high quality supply chain capable of effectively implementing the proposed measures.

- Demand and take-up:

  As individuals and organizations increasingly recognise the importance of contributing to Net Zero Carbon goals, there is a reasonable expectation for higher demand in retrofitting homes. However, the lack of clear regulatory drivers and robust data leaves homeowners and landlords unaware of the potential and requirements of retrofitting. Addressing this information gap is crucial to stimulate demand and promote widespread adoption of retrofit measures.

Second, Peel, Ahmed [25] were concerned with investigating the barriers and enablers to energy efficiency retrofitting in social housing in London, UK. Based on literature review, interviews and surveys with key stakeholders within the housing stock, they grouped the barriers and enablers into seven categories. These are: financial matters, Technical, IT, Government policy and regulation, social factors (including awareness of the energy efficiency agenda), quality of workmanship and disruption to residents. Similar to the findings of London Councils [16], financial issues, technical complexities, and government policy and regulation were identified as the primary significant barriers and enablers to energy efficient retrofitting in social housing (EERSH).

5. Discussion

The key findings derived from this study highlight the need for collaborative efforts between government, its agencies, and professional bodies to address knowledge gaps and implement technological interventions. Incentivisation is identified as an important tool to improve poor indoor environments. In addition, based on the results from this study, various potential interventions, and strategies for improving indoor environments and retrofitting residential buildings are also proposed. These interventions can be categorized into three main areas: improving outdoor environments, enhancing housing quality and urban form, and changing the behaviour of occupants.

First, improving outdoor environments involves reducing emissions from outdoor sources, increasing green infrastructure, and improving access to high-quality, safe, and low-traffic outdoor spaces. These interventions have multiple benefits, including reducing outdoor air pollution levels and its subsequent infiltration indoors, promoting physical activity and reducing underlying health issues, and potentially increasing the use of natural ventilation to remove indoor-generated pollutants. However, it is important to note that spending more time outdoors may not lead to an absolute reduction in air pollution exposure unless outdoor concentrations are significantly reduced. Moreover, investments in infrastructure are needed to reduce outdoor air pollution and traffic, improve local green spaces, safety, and amenities. This can encourage residents to spend more time outdoors and subsequently reduce indoor pollution levels. Inadequate access to green infrastructure has been identified as a driver of health inequalities, and investing in infrastructure that promotes walking can increase physical activity across different socioeconomic groups. These principles are also aligned with initiatives such as the NHS's Healthy New Towns Programme.

Second, improving housing quality and urban form involves several measures such as enhancing airtightness and insulation, implementing effective ventilation systems for local moisture/fume extraction and recirculation, utilizing filtration methods, and installing alarming systems. Additionally, the study emphasizes the importance of analyzing and ensuring the functionality of natural ventilation systems when increasing the air tightness of building envelopes. It is also suggested that energy efficient retrofitting is a long-term solution for reducing heating energy use and improving the overall performance of buildings. These measures aim to improve indoor air quality and overall living conditions.

Third, this study highlights the importance of occupant behaviour in building performance and energy consumption. Variations in energy consumption behaviour among households with similar characteristics pose challenges in predicting the energy-saving potential of retrofit interventions. This variability adds complexity to the task of improving energy efficiency in residential homes. Changing the behaviour of occupants is another important aspect of improving indoor environments. This includes addressing the use of chemical-emitting consumer products, combustion appliances, and optimizing the use of windows, trickle vents, and extractor fans. Raising awareness and providing education about healthy indoor environments can also contribute to behaviour change among occupants.

In the context of the social housing sector, several recommendations are proposed, including the introduction of legally binding national energy efficiency targets, stability in government policies and funding, increased grant funding for energy efficiency works, and research into innovative solutions for hard-to-treat properties. It is also suggested that engaging with tenants, leaseholders, and other registered providers, as well as developing action plans, communication tools, and coordination among stakeholders, can facilitate more efficient and effective retrofitting efforts.

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