A dissertation submitted to Cardiff University in partial fulfilment of the requirements for the degree of Master of Science

Abstract

The post-war stock in the UK that includes high-rise apartment buildings (built taking place in the 1950s-1970s) is the highly inefficient source of energy and produces a substantial carbon portion. The deep retrofitting plans are needed to reach the net-zero since almost 80 percent of the current homes would still be in use in 2050 (Azeem et al., 2025). This dissertation examines the concept of applying the principles of circular economy (CE) and Design for Deconstruction (DfD) to undertaking the cleaning up of the facade of Sleaford House as a preparatory example of post-war social housing.

The research involves a mixed approaches design, including policy analysis, case study assessment and the performance simulation construction using DesignBuilder. The comparative scenarios consider the operational and embodied carbon, the possibility of implementing bio-based, recycled, and demountable facade systems within the frames of Design for Disassembly (DfD) principles, and feasibility. The paper presents the primary functions of interdisciplinary research, as well as bottom-up and top-down projects as helping to make the shift to so-called circular buildings. (Pomponi and Moncaster, 2017)

According to simulation outcomes, it is possible to make rainscreen cladding systems using recycled-content aluminum panels and mineral-wool insulation and reduce the energy utilized to operate a building to achieve fire safety standards (Jensen et al., 2023). Aluminum is also relatively high in embodied carbon, and it can be recycled and is also compatible with modular rainscreen assemblies, so it will never be wasted (Moncaster and Pomponi, 2017). Heritage restrictions on listed towers such as Trellick complicate the provision of new features, whereas non-listed estates such as Sleaford provide more of a range of fabric upgrades considering the prevailing policy frameworks (Historic England, 2023; BEIS, 2024).

This dissertation enhances retrofit research by introducing a decision-making framework for high-rise facades that amalgamates Circular Economy (CE) and Design for Disassembly (DfD) principles with simulation-based performance assessment. It says that using rainscreen systems that can be taken apart, recycled, and are safe from fire can save a lot of carbon and make the UK's aging social housing last longer.

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1. Introduction

1.1 Overview

The UK's commitment to achieving net-zero greenhouse gas emissions by 2050 was introduced through an amendment to the Climate Change Act in 2019. The act established the UK as the first major economy to legislate such an ambitious target. This legislation was further made concrete with the publication of Net Zero Strategy:

Build Back Greener (UK Government, 2021), which highlights the pathways for sector-specific decarbonisation. The impact of the built environment has a direct control of 25% of the GHG emissions. If we include transport emissions due to embodied carbon, the total emissions rise to 42% (UK Green Building Council, 2021). The estimated percentage of existing buildings that will be in use until 2050 is 70%, underscoring the need for deep retrofitting to improve the thermal performance of the existing stock (Department for Energy Security and Net Zero, 2021).

Retrofitting is a viable solution compared to demolition and new buildings. Operational emissions can be reduced, and the embodied carbon that is enticed in structural elements may be preserved. The most recent policies have been increasingly coming to the point where the whole-life carbon thinking is necessary to take. This not only takes into account emission due to the use of energy but also material production and construction. (UK Green Building Council, 2021).

1.2 Residential Sector and its need for Retrofitting

Among the sectors, the housing stock has been the most significant contributor to the GHG emissions, while also showing a slight increase of 3% in 2024 (Department for Energy Security and Net Zero, 2024). The main concern for this increase has been the ease of access to gas, which has led to the rise in energy systems to maintain comfortable temperatures, despite similar outdoor temperatures in both years.

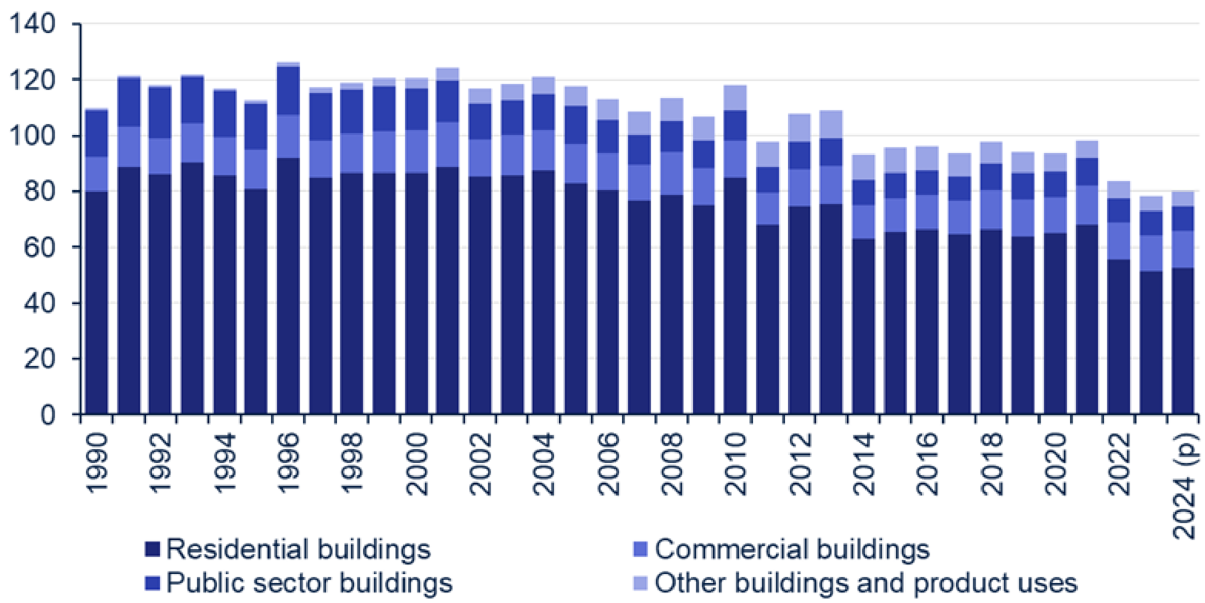


Figure 1: Annual territorial greenhouse gas emissions in the UK by building type (MtCO2e) (Source: Department for Energy Security and Net Zero 2025)

Figure 1, emphasises the importance of extensive retrofitting needed in residential buildings. The data mainly comes from fuel combustion in buildings, such as the use of natural gas and other fuels for heating and cooking, as well as appliances like refrigerators and air conditioning. Additionally, the UK housing stock has a renewal rate of less than 1%. This indicates that deep retrofitting of existing homes is essential rather than optional (SDC, 2007). The indoor environment includes a tremendous number of spaces encircled or somewhat encircled by human-constructed buildings. An interest in enclosure is not new to political ecologists who look into the technologies and power relationships, which are enrolled in the delimitation of zones of conservation and production (Day Biehler, 2011). Additionally, research shows that individuals spend 90% of their time indoors, with 69% at home.   (Booker et al., 2025). This emphasises the crucial role a house can have in achieving carbon savings and health benefits (UKGBS, 2021).

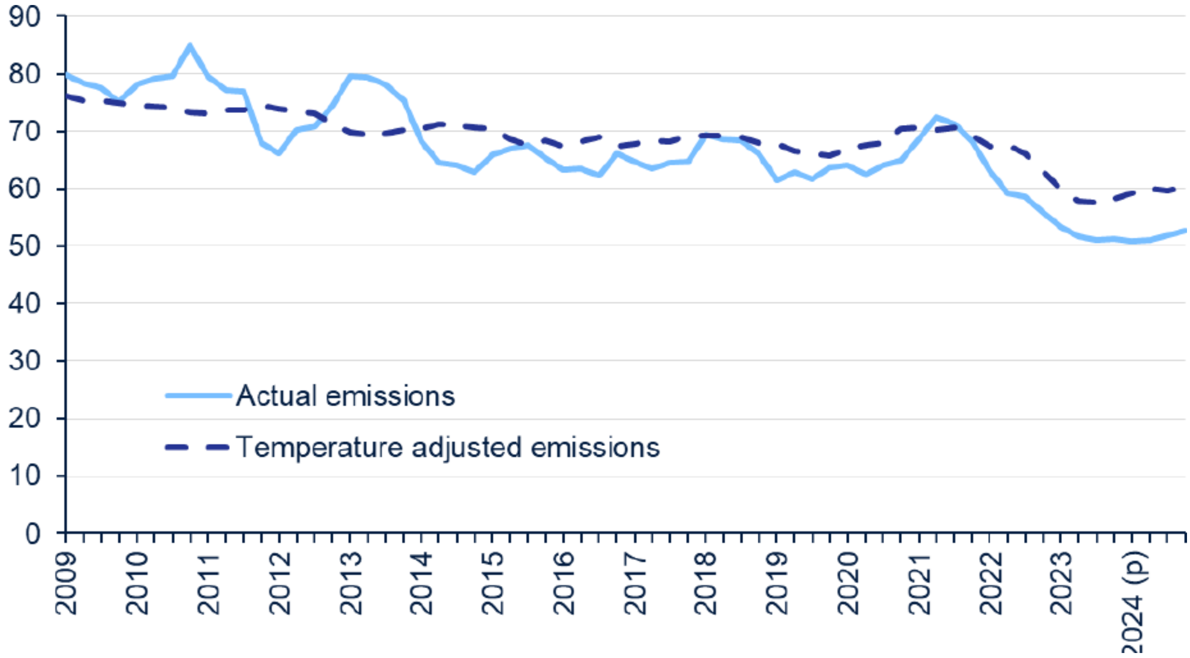


Figure 2: Actual and temperature-adjusted greenhouse gas emissions from residential buildings, UK (MtCO2e) (Source: Department for Energy Security and Net Zero 2025)

1.2.1 Boom of High-Rise Residential Buildings post WW2

The rise of high-rise residential buildings across post-WW2 Britain was not merely an architectural trend; it was a large-scale, government-led response to a severe national housing crisis. For three decades (from the late 1940s to the 1970s), thousands of tower blocks emerged across UK cities, driven by urgent social needs, political aims, and technological optimism. This phenomenon fundamentally changed urban landscapes and left a lasting impact on British housing policy.

Within the aftermath of the Second World War, the UK had to grapple with a housing crisis of disastrous magnitudes. The Blitz had destroyed or badly damaged over 2 million houses and almost six years of war had stopped construction and repair countrywide (Ravetz, 2001). The situation deteriorated in 1951 and England and Wales were facing a deficit of about 750,000 dwellings (Power, 1993). A significant part of the existing housing stock, comprising mostly of the pre-WW2 dwellings, were so deficient in the essentials like indoor bath, or target insulation (English Heritage, 2014).

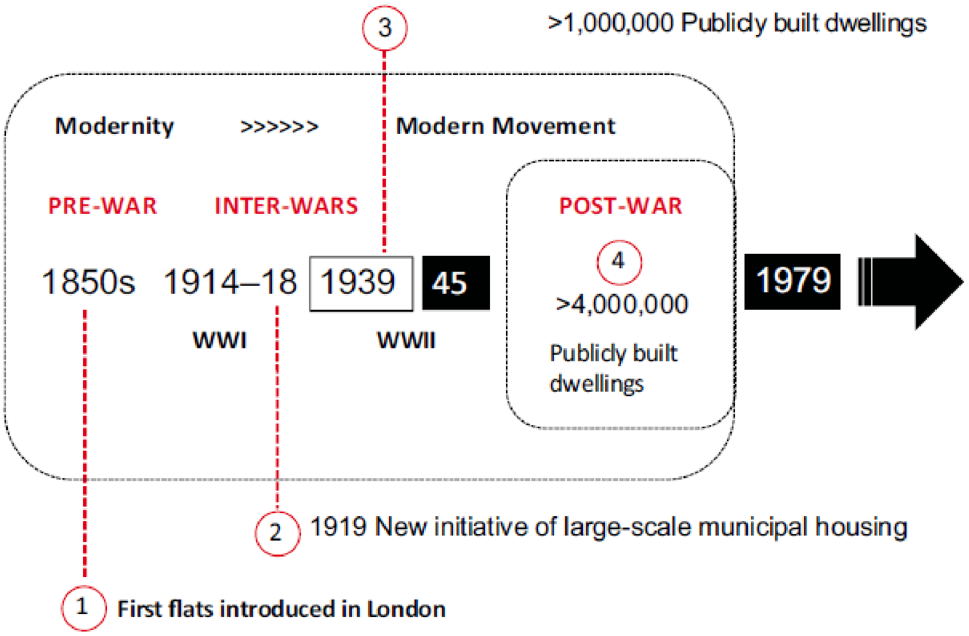


Figure 3: Public high-rise homes from 1850 to 1S45 (Source: Sustainable Retrofits: Post War Residential Towers in Britain)

The solution was being high-rise buildings which was both practical and symbolic. They replicated the modernist European concepts of architecture, particularly the idea of Le Corbusier, a vertical dwelling. Lawn in Harlow was the first residential tower built in Britain in 1951 and set a precedent to future residential towers (Historic England, n.d.). Towards the 1960s, high-rise buildings were a prevalent form of construction in metropolitan areas, including Birmingham, Glasgow, and London where hundreds of buildings were constructed to serve growing urban populations (Boughton, 2018).

The high-rise boom was a complex and ambitious part of the British housing history, after all. Despite the fact that ideal was later undermined by technological constraints and social consequences, the attempt to employ architecture as a means of equity and development remains one of the most unique aspects of mid-20th -century Britain.

1.2.2 Demand for Retrofitting in Residential Buildings

Residential housing in the UK encompasses millions of houses dating back to the immediate aftermath of the World War II, particularly, 1950 to 1970 periods, which are currently considered energy-inefficient and rich in carbon monoxide. About 20 per cent of the total UK carbon Emissions comprise residential buildings. Retrofitting initiatives, like the use of fabric-first schemes, comprising wall, floor, and loft insulation, high-performance windows, and air-tightness amendments, have demonstrated to reduce space heating desires by far. An example would be that Wright et al. (2012) discovered that post-war social housing-envelopes and heating systems retrofits will reduce energy consumption by 40-60 percent. According to Lingard (2021), these retrofits can be optimised towards.

low-carbon technologies including heat pumps, they offer inexpensive cuts in emissions plus numerous long-term savings. Renovating old buildings and listed ones is a way not only to help the environment but also provide professional work in traditional crafts and renovation practice.

According to Correia and Fazion (2023), the UK can create over 200,000 jobs each year with a proper scaling up of sustainable retrofit efforts throughout the whole UK. In the case of listed properties, this will necessitate creative policy instruments, such as specific grants, green heritage retrofit centers, and streamlined planning procedures, in order to break down the current impediments amongst building proprietors.

1.3 What is Design for Deconstruction (DfD)

Design for Deconstruction (DfD) refers to a construction method, a strategy, enabling elements of a building to be assembled and disassembled in a safe, efficient way. This method promotes the reuse of components, recycling, and the reuse of a circular flow of materials. DfD also enhances the efficiency of the material used by developing a comprehensive database about their property, reuse of the material, designing their end of life and the structural characteristics of the material. Central to centralised Design for Deconstruction (DfD) are the following principles; modularity, a non-destructive reversible connection, material traceability and layer construction (Durmisevic, 2006). This enhances the minimization of embodied carbon, and storage of material value which is necessary in achieving the net- zero carbon targets of the UK (Rios, Chong, and Grau, 2015).

Figure 4: Design for Deconstruction (Source: https://parametric-architecture.com/design-for- deconstruction-transforming-architecture-with-sustainable-approaches-and-real-world- examples/)

1.3.1 Scope of DfD in the UK

The shift towards a circular economy, as an approach to reaching the goal of net-zero emissions, is rapidly becoming an increasingly popular trend in the UK. There are a lot of economic, environmental, and social benefits of moving toward a circular approach. At present, more than 60 percent of the building industry materials are used and 1/3 of total waste in the UK is produced by the built environment (UK Green Building Council, 2021). That is why it is necessary to introduce low-impact retrofitting measures, particularly to houses. Facades and non-structural elements should be made out of modular, demountable and reusable materials, which can reduce a lifecycle carbon emission, by large (Moncaster, 2017).

Although not a requirement or an obligatory energy label as required by the UK building regulations, DfD is becoming more popular in the policy landscape such as - Construction Playbook (Cabinet Office, 2022), Whole Life Carbon Roadmap developed by the UK Green Building Council (UK Green Building Council, 2021), and the RIBA Circular Economy Guide (RIBA, 2021).

The current housing stock in the UK especially the buildings constructed before 1960s has potential on the implementation of the DfD strategy. These buildings have to be retrofitted, and using DfD will be central in lowering the number of carbon emissions and having net-zero by 2050. DfD can significantly reduce embodied and operational carbon by integrating this tool into the design efforts.

1.4 Aim

To explore the integration of circular economy principles into retrofitting strategies for post-war high-rise residential buildings, aiming to lower their total life-cycle carbon emissions.

1.5 Objectives

1. Identify the construction typologies and retrofit requirements of UK residential buildings built before 1960, emphasising thermal inefficiency and outdated facades.

2. Review UK policies, case studies, and academic frameworks that support circular economy principles and design-for-deconstruction (DfD) approaches in retrofit initiatives.

3. Compare different facade systems based on embodied carbon, durability, reusability, and compatibility with DfD focusing on recycled, and demountable systems.

4. Employ building performance modelling tools to evaluate the entire-life carbon footprint (embodied plus operational emissions) of traditional versus circular retrofit strategies.

5. Develop a facade retrofit design scheme or material palette that takes into consideration the concept of the circular economy and DfD, and focuses on the possible carbon savings and adaptable design choices in the UK residential market.

1.6 Dissertation Overview

This dissertation explores the potential of Circular Economy (CE) and Design for Deconstruction (DfD) principles to transform façade retrofitting methods in the UK's post-war residential high-rises. It works towards having a replicable framework which integrates sustainable use of materials, adaptability of design and energy efficiency to facilitate the UK 2050 net-zero targets.

Two different case studies are considered in the study, Trellick Tower is a Grade II* listed heritage building whereas Sleaford House is a post-war social block of housing, which is not listed. These examples highlight the two main challenges faced in retrofitting the nation's housing stock: balancing adaptability with preservation constraints.

The research evaluates operational carbon (energy use) and embodied carbon (materials manufacturing and transportation) through DesignBuilder simulations (using EnergyPlus) and an analysis of policy and literature. It discusses how rainscreen enclosures and, in particular, those made with recycled aluminium panels and mineral wool, can improve the energy-saving and comply with the fire and dismantling laws.

The carbon effect of different facade arrangements has been quantified in the study utilizing the Environmental Product Declarations (EPDs) and Inventory of Carbon and Energy (ICE) database. It is done by creating a carbon payback model, which illustrates how recycled aluminium systems could recover their carbon cost (within a period of ten years) due to high cost-reduction in their operational costs and due to their easy recycling nature.

Finally, the dissertation suggests a way to make decisions on the facade retrofits based on environmental, material and policy parameters. It focuses on circularity due to modular shapes, mechanical fittings and reversible connections. It has the consequence of producing facades that are energy efficient, flexible to the future and resource conscious.

2. Literature Review

The literature analysis will be conducted in the selection of the particular building components to be retrofitted and the rationale. It will also determine what type of buildings can be retrofitted and what opportunities and challenges it may experience.

In addition, it will shed light on the way that the circular economy can be incorporated into the retrofitting procedure. Different materials and their properties will be analysed, with one material ultimately selected to serve as the basis for the model. After the modelling phase, a comparison between the base model and the upgraded model will be made to highlight the savings in operational and embodied energy.

2.1 Facade Retrofitting

The external facade of a residential building acts as the main interface between indoor spaces and outdoor climate conditions. Therefore, modifications to the facade can significantly enhance energy efficiency. Studies consistently show that external walls contribute about 40–60% of heat loss in post-war UK homes, with windows adding another 20–30% (Palmer and Cooper, 2013). Consequently, retrofitting the building envelope through insulation improvements and better glazing is regarded as the most effective “fabric-first” approach to lower space heating needs and reduce carbon emissions.

The international examples demonstrate the effectiveness of the facades retrofitting in radically changing the energy performance and in lengthening the useful life of post-war housing. Prefabricated facade panels with airtightness and insulation built into them have proven to achieve near net-zero energy performance, in addition to producing appealing and contemporary exteriors, in the Netherlands through large-scale retrofit programmes. The same methodology is tested in Germany through application of deep retrofit projects which apply the tenets of passive houses. The results of such interventions are typically triple-glazed windows, insulated outer envelopes and elimination of thermal bridges, hundreds of percent of heating needs saved, and a precedent of retrofitting buildings in Europe in the future set.

There also are the facades retrofits which are expanding their opportunities with the help of technological advancements. Photovoltaic facades also allow the exterior dressing to operate in two modes to improve thermal performance and, concurrently, to generate renewable electricity. This kind of integration will reduce the carbon operation and cover the power bills of the residents (Durmisevic, 2006). Ventilated facade systems are another useful tip. The systems stabilise the situations indoors, improve moisture control and make the building more resistant, creating an insulation air cavity between the outer cladding and the insulation. Those can also be combined with the modular construction methods, and, therefore, they can be utilized effectively when the needed application is in a circular economy where disassembly and reuse in the future are necessary.

A key debated aspect of retrofit practice concerns whether interventions should follow a *fabric-first* or a *technology-first* approach. The fabric-first strategy emphasises on the building envelope improvement involving such objects as insulation, airtightness, and high-performance glazing, before installation of mechanical or digital systems and minimising long-term energy usage and heating loss at the source (Palmer and Cooper, 2013; Rosenow and Eyre, 2016). In contrast, with technology-first strategies, it places significant consideration on the application of technologies such as smart energy management, mechanical ventilation, or low-carbon heating technologies that can offer rapid efficiency payoffs but cannot be effective on low-thermal-cladded buildings (Eyre, 2023). Retrofit programs in the UK have indicated that although technology-based actions can be useful in the short run, their performance and competitiveness become very limited where the performance of the underlying fabric is poor. As a result, a balanced and increasingly accepted approach in the UK positions robust fabric upgrades-particularly façade and envelope improvements-as the essential foundation upon which advanced technologies can be integrated efficiently, delivering durable energy savings and improved occupant comfort (Rosenow and Eyre, 2016; UGBC, 2021).

Regarding sustainability, the old facade components are conserved to maintain the same. Constituted carbon into the initial construction, and exploited their permanence rather than breaking it down and building up. Mocaster (2017) emphasizes that sustainable facade retrofits are capable of increasing building life duration, reducing wastage of materials and ensuring that they follow environmental goals in lifecycle. Moreover, the integration of the concepts of circular design, i.e., the application of removable and recyclable assembly systems, can contribute to the reduction of resources consumption and simplify the tasks of changing them in the future (Akinade et al., 2015; Durmisevic, 2019).

The major post-war residential construction is dominated by cement and concrete, but their reuse at the end of the life has been significantly dominated by downcycling out of hand items as opposed to actual recycling. Downcycling is a protocol where re-use of materials is utilized in some other form of use that is less value adding and leads to a decrease in both the functionality and material quality. Cement and concrete dominate the structural systems of post-war UK high-rise residential buildings, particularly those constructed using reinforced concrete panel. Downcycling refers to the process whereby materials are reused in applications of lower value or reduced performance compared to their original function. In the case of demolished concrete, structural elements are commonly crushed and reused as low-grade aggregate in road sub-bases, general fill, or landscaping works rather than being reincorporated into new structural concrete of equivalent quality. The cement-based materials are not always reused as a new structural concrete but instead as low-grade aggregate in road sub-bases/backfill or general construction fill, in the form of demolished concrete that is crushed down and-reused (Geyer et al., 2016; UKGBC, 2021).

Facade retrofits beyond enhancing thermal performance are necessary to offer opportunities to achieve airtightness, moisture control, and adopt modern ventilation systems. Comprehensive external interventions allow insulation, controlled ventilation, and building services—such as photovoltaic systems—to be installed simultaneously, making façade-led upgrades more efficient than piecemeal internal retrofits, particularly in occupied residential buildings (Palmer and Cooper, 2013; Rosenow and Eyre, 2016). Additionally, the design of facade has a direct impact on daylighting, solar gains, and acoustic performance. The retrofit solutions thought through might make a tremendous difference in terms of the quality of the indoor environment, as well as the energy efficiency performance (UK Green Building Council, 2021).

The major path of heat transfer in post-war residential buildings is the facade, as the external walls are not insulated properly and the air-in-filtration is high. As a result, façade interventions are widely regarded as the most effective means of achieving substantial reductions in space heating demand. Evidence from UK and European pilot projects indicates that external façade retrofits deliver greater improvements in thermal performance, airtightness, and whole-life carbon outcomes than incremental, internally focused measures, while also minimising disruption to occupants (Palmer and Cooper, 2013; Rosenow and Eyre, 2016).

The study focuses on the topic of sustainability renovation of residential buildings by emphasizing multi-functional measures of retrofit beyond thermal upgrades. The paper highlights the fact that to ensure high performance in the refurbishment process, combination solutions to the quality of daylight, acoustic comfort and indoor environmental state are to be supported with the solutions to energy efficiency. Renovation patterns that enhance facade insulation and glazing do not only minimize heat loss but also allow access to natural light and reduction of glare (when managed appropriately) that will ensure the wellbeing of the occupants (Konstantinou, 2015). Equally, better envelope systems would enhance acoustic performance by reducing the external delivery of noise, which is an important aspect in residential areas (pure dense urban settings). Also discussed in the research are prefabricated façades elements as modern retrofit delivery because factory-built elements may offer several functions, including insulation, daylight maximisation and integrated service conduits, and lessen on-site disturbance and enhance building quality. The integration of mechanical ventilation with heat recovery (MVHR) systems has been noted as a way to ensure a good indoor air quality, to save on energy requirements, through recycling heat contained in the exhaust air streams during high performance retrofit. The article, using case studies and performance simulations indicates that a combination of prefabricated structures, improved acoustics, better daylighting, and heat recovery technologies result in overall increases of sustainability results and occupant comfort during the renovation of the building stock (Sharma *et al.*, 2022).

Façade retrofit interventions can be categorised into a set of distinct strategic approaches. (Bystedt *et al.* (2016) identify five principal façade retrofit strategies based on the degree of intervention and the relationship between the existing envelope and the new system: *replace*, *add-in*, *wrap-it*, *add-on*, and *cover-it*.

The add-in approach is generally used in places where external modification of the facade is limited or impracticable, including those buildings which are subjected to planning or heritage restrictions. Under this method, the performance is optimized internally with the internal wall being insulated through other means such as secondary glazing, internal wall insulation or increases in internal airtightness layers (Van Den Bossche et al., 2012). Add-in strategies can enhance thermal effects, but may decrease transferring floor, and must be combined with precaution when it pertains to moisture management, as this issue may lead to condensation in direction of post-war concrete building (Bystedt et al., 2016).

The wrap-it approaches, which entails the insulation of the existing building envelope in a new exterior layer, is typically conducted with use of external wall insulation systems or ventilated secondary-skin exterior. By placing insulation externally, this approach minimises thermal bridging and preserves internal living space, making it particularly suitable for high-rise residential retrofits (Mayouf *et al.*, 2022). Wrap-it strategies can be implemented with limited disruption to occupants; however, their application may be constrained in listed buildings or conservation areas due to planning restrictions on façade appearance (Bystedt *et al.*, 2016).

Add-on strategy involves introduction of new elements of the building, like extensions, more floors, balconies, or even second layer of facades used. The additions provide new envelope components that comply with modern thermal standards and had the potential to enhance the performance of energy and the comfort of dwelling. However, add-on interventions frequently necessitate rap-on retrofit procedures to address the effectiveness of the current building cover, and such that energy inefficiencies are not pushed aside but pumped away (Bystedt et al., 2016).

The cover-it method is the envelopment of existing facades, courtyards or atria with a new lightweight structure usually glazed, to create a thermal buffer zone between the interior and the outer environment. The solution will help minimize the heat loss and shield the original facade with the weather exposure and preserve the old architectural material. Cover-it strategies are not as widespread as usingendant to dense high-rise residential buildings, regardless of their effectiveness and suitability in certain building typologies, due to limitations in terms of access to daylight, massing, and planning permission (Bystedt et al., 2016).

The research paper reviews the role of retrofit to reduce fuel poverty and to improve the quality of life of occupants in UK housing social unit, which has a direct bearing on the building Sleaford House. The study targets households with low-income earning levels and who occupy thermally-weak structures and buildings, which have poor insulation, heavy heat loss, and antiquated services that lead to disproportionate heavy energy bills over household income levels. As the research is based on a mixed-method design that incorporates the results of resident questionnaires, interviews, building audit and energy simulations, it can be shown that improper building fabric not only promotes energy consumption but also harms thermal comfort and mental health.

The results are especially relevant to the post-war high-rise buildings such as the Sleaford House that were built with little regard to the energy efficiency and have continued to leave their inhabitants vulnerable to the danger of fuel poverty. The research considers fabric-first retrofit works, which consist of improving the insulation to the facade, airtightness, and ventilation works such as mechanical ventilation with heat recovery. These solutions achieve a great depletion of energy requirements, decrease of residential energy expenditures, and enhancement of indoor air quality.

Critically, the role of resident participation and communication in the success of retrofits is noted to be significant in the study since social acceptance and expected improvement in perceived comfort are essential results in addition to energy savings. In the case of such buildings as Sleaford House, its research justifies the use of facade-based, modular retrofit strategies as a productive tool of pursuing environmental performance and social inequality in UK social housing. (Shwashreh *et al.*, 2024)

2.2 Facade Retrofitting Parameters

Thermal Performance (U-values):

The majority of post-war residential houses in the UK had been built with either uninsulated cavity or solid wall assemblies, which accorded them poor thermal performance according to modern standards. U-values of external walls in these buildings are usually higher than 1.5 W/m 2 K, which leads to high space-heating requirements and thermally uncomfortable conditions. Retrofit programmes demonstrate that the application of external wall insulation or façade-based insulation systems can significantly improve thermal performance, with upgraded wall U-values typically in the range required to meet current energy efficiency standards (Doran and Lomas, 2021; Palmer and Cooper, 2013).

Similarly, the replacement of single-glazed windows with high-performance double or triple glazing substantially reduces heat loss through transparent elements. Window upgrades are widely recognised as a key component of fabric-first retrofit strategies, contributing to lower heating demand and improved indoor comfort in post-war housing stock (Palmer and Cooper, 2013; UK Green Building Council, 2021).

Airtightness

Airtightness is a critical determinant of heat loss in post-war high-rise residential buildings, where poor construction tolerances, ageing concrete panels, and degraded façade junctions often result in high levels of uncontrolled air infiltration. Strategies of retrofit that predominantly use faacade painting, especially with continuous layers of external insulation and junction improvement detailing, have been identified to significantly reduce air pollution. Enhanced airtightness does not only reduce the space-heating demand but improves thermal comfort and minimizes the possibility of surface and interstitial condensation under the condition of employing sufficient ventilation measures to ensure the quality of indoor air (Palmer and Cooper, 2013; UK Green Building Council, 2021).

Embodied carbon considerations

While façade upgrades are primarily undertaken to reduce operational carbon emissions, their embodied carbon implications are increasingly recognised as a critical component of retrofit decision-making. The embodied carbon through such aspects of the building can be preserved by continuing to use the existing structural frame and updating the aspects of the exterior instead of demolishing and replacing spent up to a significant percentage. The whole-life carbon can also be mitigated by using prefabricated (or even recycled) facade systems and material with a recycled content, especially when measured through the lifecycle lenses (UK Green Building Council, 2021; Moncaster and Pomponi, 2017).

Whole-life effect may be used to reduce carbon and other effects on the environment by cancelling waste production on the site, improving the accuracy of the construction and recycling the structural frames that remain intact. The research concentrates on the concept that it is feasible to either maintain the original fabric and modernise the facade systems to keep the embodied carbon in a building by preserving a significant portion of it, namely in large retrofit ventures, where the total savings can be substantial (Lević et al., 2023; UK Green Building Council, 2021). According to lifecycle assessment studies, insulation materials based on bio-based substances (i.e., hemp-lime and wood fibreboard, among others) are typically lower in embodied carbon than the traditional petrochemical-based insulation products, which can offer substantial reductions when measured at the production, use, and end-of-life phases (Moncaster and Pomponi, 2017; LETI, 2020).

Façade retrofit interventions have the potential to provide broader performance benefits with respect to acoustics, ventilation and energy recovery. These modernized exterior structures will go a long way in improving the acoustic insulation that will lessen the influx of outside noise in the crowded urban areas and allow people to enjoy their comfort within the buildings. Daylight penetration in architectural designs is also affected by careful planning of the range of openings, the proportion of glazing, and shading tools. It assists in augmenting natural light besides regulating glare and unwanted sunlight intake (Capeluto, 2019).

Mechanical ventilation and heat recovery into the facade helps in achieving energy efficiency by recovery of heat in the exhaust air, as well as release of fresh air with minimum energy dissipation. Prefabricated facades give performance functions in a number of ways. This involves insulation, airtightness, acoustic control as well as ventilation features (Salvalai, 2025).

The integration of material passports within façade systems enhances traceability by recording material composition, embodied carbon data, and disassembly pathways. When applied to façade or multi-layer building components, material passports support future reuse and recycling by treating buildings as material banks rather than disposable assets, thereby strengthening circular economy outcomes over the building lifecycle (UK Green Building Council, 2021; Arup, 2022).

Besides thermal performance, when design choices are made holistically at the envelope level, facade retrofits can enhance many levels of indoor environmental quality, such as daylight availability, acoustic comfort, and indoor air quality. The designed interventions of the facades have a positive impact on a solar-controlled building, possible ventilation, and noise reduction, resulting in the creation of healthier and more comfortable living conditions and the enhancement of energy efficiency (UK Green Building Council, 2021).

Advance facade systems can also support renewable energy technology or green-built ventilation systems, e.g. photovoltaic cladding or the mechanical ventilating system with heat recovery. With effective cloth upgrades, the systems may lead to substantial cuts in space-heating call in the large-rise residential retrofit, although their effectiveness relies on relevant combination (as opposed to unilateral implementation) with the building envelope (Palmer and Cooper, 2013; Rosenow and Eyre, 2016).

In general, facades are strategically valuable focus on interventions of retrofitting post-war residential buildings. Facades-led upgrades have the highest potential in terms of minimized energy demand in operations and retained embodied carbon, better indoor environmental quality, and scalable applications of the principles of the circular economy. Facade retrofitting is, therefore, offering an urgent route to provide long term carbon savings and long-term improvements of performance in the UK residential market (Radić et al., 2019).

2.2.1 UK's Post-War Residential Building Stock

The development of high-rise residential buildings in post-war Britain was fuelled by the necessity to respond to severe housing shortages and to conduct the mass-construction urgently. These constructions were often deployed with industrialised forms of construction, like concrete panel and system-built methods, which focused on speed and costs instead of long-term durability and thermal performance. Energy efficiency standards were either non-existent or primitive at the time of construction, which led to a vast number of housings that will not stand a test against current standards (Ravetz, 2001; Palmer and Cooper, 2013).

Most of the flaws that come with this type of building stock are still present in the modern days and have great social consequences. Low thermal envelopes, the extensive heat loss, and dependence on old fashioned heating systems make people living in the post-war high-rise social housing in the UK disproportional victims of the phenomenon of fuel poverty. Consequently, they tend to raise the energy bills, decrease thermal comfort and poor indoor environmental conditions in households, which only contributes to disparities between older social housing and new residential developments (Boardman, 2010; Department for Energy Security and Net Zero, 2023).

Fuel poverty has a disproportionate impact on the low-income households residing in social housing, which is mostly explained by poor thermal performance, ineffective building fabric, and the lack of control of the retrofit decisions. The majority of the social housing estates built post-war are poorly insulated, damaged, and leaky, and because of that, the residents of the older housing spend a bigger part of their income on the energy bills than the residents of more recent or privately-owned houses (Pollard et al., 2019) do.

With poor earnings and high bills, tenants are usually in a twofold command of low income and high energy bills which makes them susceptible to cold health hazards and financial pressures. The UK research findings reveal that social housing tenants continuously face disproportionately large energy bills despite living in a smaller home, thus demonstrating structural inequalities immanent to the current housing stock. Deep and facade-led retrofits are not only an environmental requirement but also a societal imperative since lowering energy requirements is a direct support to affordability, thermal comfort, and wellbeing of the vulnerable building occupants (Wang, 2022).

From an environmental perspective, post-war housing continues to represent one of the most carbon-intensive segments of the UK residential stock. A substantial proportion of these dwellings fail to meet modern energy performance standards, and retrofit interventions to date have often been limited to incremental measures such as window replacement or heating system upgrades. Evidence from UK retrofit programmes indicates that such partial interventions frequently underperform in practice, with notable discrepancies between predicted and actual energy savings. These performance shortfalls demonstrate that holistic, not focused on isolated upgrades, fabric-based retrofit solutions are necessary that consider the facade and envelope performance as a whole (Palmer and Cooper, 2013; Rosenow and Eyre, 2016).

To address these issues, this paper explores two high-rise residential case studies in London that were built in the 60s and 70s, when the post-war housing of the 1960s was at its peak. The comparison of their physical features, regulation settings, and impact on retrofit possibilities brings a clear ground on which building to choose as the lead case study in thorough assessment of facades retrofit.

2.2.2 Case Study Selection Rationale

Sleaford House and Trellick Tower have some key similarities that qualify them as suitably comparative case studies within the context of post-war high-rise residential development in the UK. Both structures were built in the post-Second World War boom in housing and are heavily based on reinforced concrete structural systems that focused more on quick construction and standardisation rather than on thermal performance in the long-run. This has also led to the fact that both structures have features typical of post-war high-rise residential properties, such as lack of envelope insulation, excessive demand on space-heating, and operational unproductivity when compared to current energy performance standards (Palmer and Cooper, 2013; Ravetz, 2001).

In addition, both buildings accommodate dense residential populations and face challenges typical of high-rise housing, such as elevated energy consumption and increased exposure to fuel affordability pressures among residents. These issues are particularly acute in older social housing stock, where inefficient building fabric contributes to higher energy bills and reduced thermal comfort, reinforcing social and environmental inequalities (Boardman, 2010; Department for Energy Security and Net Zero, 2023).

Irrespective of these similarities, the two case studies entail opposing regulatory and technical conditions, which are extremely informative to the decarbonisation agenda in the UK. Trellick Tower shows the limitations which come with retrofitting listed post-war high-rise buildings and Sleaford House shows the possibilities which exist when working at a large scale and undertaking a socially-inclusive retrofit intervention in non-listed social housing.

Trellick Tower is a Grade II+ Brutalist landmark that was designed by Ernö Goldfinger and built in the early 1970s. The fact that it has the heritage designation under the Planning (Listed Buildings and Conservation Areas) Act 1990 greatly restricts the modification of the outward appearance and the areas that can be represented by fabric-based retrofit interventions. Consequently, the building illustrates the issues of heritage retrofit as complicated negotiations between stakeholders, strict approval procedures, and increased intervention costs, which restrict the use of the principles of the circular economy and Design for Deconstruction (DfD) (Historic England, 2024).

In comparison, Sleaford House is a post-war social housing tower that is not under heritage protection and whose thermal performance has been proven poor. The absence of listing constraints provides greater technical flexibility for façade replacement or over-cladding strategies. Moreover, being a social housing property, Sleaford House conforms to the existing UK retrofit policy interventions, including the Energy Company Obligation (ECO4) and the Social Housing Decarbonisation Fund (SHDF), which consider fabric-first improvements to inefficient housing stock. Sleaford House provides a very appropriate policy context to discuss scalable facade retrofit, which accounts for the principles of a circular economy and Design for

Deconstruction, such as the use of prefabricated facade systems (Preece et al., 2023; UK Government, 2023).

2.2.3 Lincoln Estate - Sleaford House

Figure 5: Sleaford House (Souce : Alamy)

Lincoln Estate, Tower Hamlets, East London is a post war development by the London County Council (LCC) which was a part of the post-war programme to elevate the high-rise social housing. The Slieford House, which was built in 1967, is a part of this estate, and consists of a 19 storey residential tower comprised of about 100 flats (Layers of London, 2023). The construction is done with a reinforced concrete frame and slab, which has been a common form of typology used throughout the mid-twentieth century trying to provide a timely and cost-effective delivery of housing.

In 1998, the Lincoln Estate came under the management of Poplar HARCA as a larger regeneration project (Poplar HARCA, 2023). Since this conveyance, Sleaford House has been subject to several refurbishment works. It is worth noting that some of the projects that were carried out in the late 1990s involved the replacement of windows, internal insulation, and balconies, and external finishes on render (Tower Hamlets Council, 2003). Although these interventions have contributed to the aspects of building condition and occupant comfort, they were not a thorough fabric-based retrofit to make any significant difference, such as a common reduction in operational carbon emissions or a wholesome-faenza thermal performance.

Sleaford House, like most of the high-rise social housing blocks in the Denmark and UK, was constructed during an era when the energy regulation was minimal. It causes insulated façades, heat loss and dependency on energy and intensive heating systems. Even refurbishment interventions that occurred in the late 90s were not a deep, fabric-based retrofit. As a result, the building is still performing moderately regarding energy when measured against current standards, and residents are still exposed to high-energy consumption and related fuel expenses (Rahla, 2021).

Unlike a number of Danish residential retrofit programmes, the retrofit of UK social housing has been more incremental historically. Prefabricated and modular facades Prefabricated and modular facades have gained popularity in the Danish residential retrofit programmes as they allow large-scale energy upgrades to be realized, with limited resident disruption. Being a non listed building, Sleaford House has considerable potential in pursuing such modular retrofit strategies currently being marketed in the UK through funding schemes like the Social Housing Decarbonisation Fund (Shwashreh, 2024). The standardised geometry and repetitive facade arrangement of the estate are especially appropriate in prefabricated programs that incorporate insulation, airtightness, and service upgrades. Sleaford House is an archetypal, though strategically significant, case in the UK. A post-war social housing tower that is technically flexible enough to experiment with scalable, modular, and low carbon retrofit options and is designed to solve broader social issues, including fuel poverty and resident wellbeing.

Available evidence indicates that the energy performance of dwellings within Sleaford House remains moderate when assessed against current standards. The building, similar to most social housing stock built after the war, still has constraints related to ageing fabric, full-coverage of insulation, and pre-historic construction detailing. These features imply that further retrofit of the facade, boosting performance, airtightness, and carbon reduction are still possible in the future.

Being a non-listed social housing property, the Sleaford House is highly compatible with the current UK retrofit policy framework, such as the Social Housing Decarbonisation Fund (SHDF) and the Energy Company Obligation (ECO4), which focuses on fabric-first retrofit of thermally inefficient housing. The standardised aspect of construction and no heritage restrictions allowed in this policy context make Sleaford House a good case study to explore scalable strategies of retrofitting new facades using the principles of circular economy and Design for Deconstruction (DfD).

2.2.4 Trellick Tower

Figure c: Trellick Tower (Source : Historic England Archive)

Trellick Tower is a 31-storey residential high-rise located in North Kensington, London, and is a prominent example of post-war Brutalist architecture. The tower was built by architect Ernst Goldfinger and finished in the early 1970s as part of the greater post-war housing programme to solve acute housing shortages in the capital. The open concrete facade and the separate service tower are the distinguishing features of the building, which bring it its architectural value. In 1998, Trellick Tower was designated as a Grade II* listed building by Historic England in recognition of its special architectural and historical interest.

Social housing requires technical solutions to deliver the retrofit, but it is also a matter of thorough communication and active involvement of stakeholders. The residents, housing associations, local authorities and contractors are all very crucial in determining the results of retrofitting. In busy buildings like Sleaford House, there should be a transparent communication with occupants so as to control expectations, reduce inconveniences and grow trust between them throughout the construction stage. The results of UK social housing retrofit programmes indicate that early engagement and the maintenance of ongoing dialogue enhance resident acceptance, fewer complaints and a higher level of satisfaction with the results of retrofit. Policy makers are facilitated by housing providers who balance policy needs, funding limits, and needs of residents, and a coordinated stakeholder effort will enhance a smoother implementation process and long-term effectiveness of retrofit measures (Hasheminasab et al., 2022).

Since listing, the building has undergone a series of borough-led refurbishment programmes that have focused primarily on internal upgrades, including services, dwellings, and common areas (Royal Borough of Kensington and Chelsea, 2015). However, the external façade has remained largely unchanged in order to preserve the building's listed character. As a result, opportunities for extensive fabric-led façade retrofits are significantly constrained by heritage protection requirements.

In the UK planning system, listed buildings have a broad tendency towards retrofit interventions which pursue a soft retrofit strategy that maximises in both physical and aesthetic effect on historic fabric incorporation. Historic England guidance and other studies highlight the importance of finding the right balance between energy efficiecy efforts and architectural significance preservation that frequently restricts the options concerning outside insulation, recladding, and significant changes in the facade systems (Wise et al., 2021; Historic England, 2024). While elements of circular economy thinking—such as material longevity and careful maintenance—may be compatible with heritage conservation, the application of Design for Deconstruction (DfD) principles at the façade scale is typically restricted in listed high-rise buildings.

The Tower of Trellick, in this work, thus serves as a significant counter example, where regulatory, technical, and preservation constitute the issues that emerge in retrofitting listed post-war high-rise housing. Its incorporation supports the reason as to why such buildings are typically less effective in terms of DfD-enabled façade retrofitting than non-listed social housing towers, including Sleaford House, where regulatory flexibility can enable more radical and widespread retrofit interventions.

2.2.5 Opportunities and Challenges

The lack of heritage restraint and the comparatively uniform slab-block structure of Sleaford House offer more possibilities when it comes to accommodating the implementation of circular economy, such as componentised cladding, prefabricated facade elements, and Design for Deconstruction (DfD). Despite the late 1990s refurbishment interventions, the building still appears to have thermal performance constraints as it can be evaluated against current energy efficiency standards, which suggests another opportunity of fabric-based retrofit actions. Being a social housing property, Sleaford House is constrained by budgetary limits as well, which affect decision making, and the retrofit interventions are generally fitted in to national funding regimes and policy settings. Moreover, the role of the Poplar HARCA as the managing organisation implies that the residents, housing providers and public authorities need to make sure that retrofit interventions are socially acceptable and operationally viable.

Retrofitting of post-war residential buildings on a large scale is also a tremendous opportunity in the decarbonisation agenda of the UK. Policy wise, national retrofit programmes of social housing and models of funding that local authorities and housing associations can gain access to are a means of piloting new facilities in regards to facade and whole-building retrofit solutions. Such efforts have not only facilitated the reduction of operational carbon emissions but also have broader co-benefits, such as skill building and job creation in the retrofit, manufacturing and building industry (UK Green Building Council, 2021; Piantanida et al., 2023).

Social acceptance is another chance of the successful delivery of retrofit. There is also evidence that co-benefits to energy savings associated with building fabric can be achieved through better insulation, better facades, and better ventilation strategies which provide much also to thermal comfort, indoor air quality and general wellbeing. The higher the visible benefits in the form of reduced energy bills and improved health regardless of the living environment, the more will be the participation in retrofit programmes. Participatory retrofit or community-based methods could also contribute to acceptance by making residents part of decision-making and dealing with disruption and safety of buildings concerns (Korniyenko, 2021).

Although these opportunities are there there are still a number of obstacles. The major issue is financing due to the fact that initial capital expenses of deep retrofit interventions may be difficult to bear by housing providers even in cases where long term savings are expected. Also, policy frameworks regarding retrofit can change and this poses a risk to the long-term investment planning. The real-life problems that come up in the course of construction include disturbance of the residents, decanting, and logistical limitations in tall buildings to the high-rise buildings, which become major hindrances. Lastly, the affordability, technical achievability, and regulatory considerations, especially in the heritage setting, remain the element that constrains the scope of such an all-encompassing retrofit plan to be carried out on the post-war housing stock.

This analysis is referred to in the results chapter which compares Sleaford House and Trellick Tower in order to understand which one of these buildings should be subjected to retrofit modelling and assessment in most detail. Although the two buildings provide an insight into varying facets of the high-rise housing legacy used in the UK following the period of the war, both buildings exist in different regulatory and technical environments. The comparative evaluation will look into aspects such as enhancement of thermal efficiency, operational carbon emissions reduction, whole-life carbon implication and the possibility of implementing DfD strategies. Working off of the triangulation of these technical, policy, and social standards, the paper will form a solid foundation of a primary case study, which represents an effective and significant implementation of the principles of circular economy retrofit in the UK high-rise residential sector.

2.3 Circular Economy Integration in Residential Buildings

The circular economy (CE) is the alternative approach to the built environment, where linear trends of resource extraction, use, and disposal are replaced by the approaches that would ensure minimal waste, increase the lifestyles of materials, and consume fewer finite resources (Ellen MacArthur Foundation, 2019). In buildings, in the given context, applying this method means a complete re-evaluation of the whole lifecycle of a building, i.e. the design and building, its use, adjustment, and finally demolition.

The application of the principles of the circular economy in the UK construction industry has received a slow pace of momentum, in the context of the retrofitting of residential properties built after the war. Traditional building projects build more or less on a take– make- Dispose paradigm; and circular methods rely on reuse, repair and recycling of materials and components to ensure value is maintained over time. Penetrating retrofit requires here Design for Deconstruction (DfD), the production of material catalogues and the incorporation of prefabricated systems that can be disassemled and reassembled with the minimum amount of waste production (Ellen MacArthur Foundation, 2019; UK Green Building Council, 2021). Though there is an increase in the incorporation of these principles in planning frameworks, pilot projects and industry-led initiatives, uptake by regions and housing providers is still uneven.

One of the new bio-based materials is mycelium, which is being developed as an alternative to the current case of the circular economy of the built environment. Made by using fungal networks which are cultivated on agricultural waste mycelium composites provide low embodied carbon, biodegradability, and even regenerative resource cycles. Mycelium has been investigated in non-structural use, on a non-brokerage basis, as insulation panels, acoustic treatments and interior envelope elements in a retrofit setting, because of the present restriction concerning moisture resistance, durability and fire behavior. Although its application to high-rise facades is yet to be sustainable, mycelium has considerable possibilities in the future of prefabrication and modular retrofit solutions, especially in cases where circularity and material recovery and lower environmental impact are a priority. It will need extensive research and standardisation as well as adoption cannot be widespread in residential retrofit projects in the UK (Attias et al., 2020).

In the example of circular retrofit strategies at large scale, international precedents are used to show their potential. The implementation of prefabricated facade systems and combined renewable systems in large-scale social housing programmes in some countries, including the Netherlands, shows that prefabricated facades enable the implementation of building performance at a scale, and reduces construction waste. Equally, Nordic nations have developed lifecycle-based strategies by incorporating matters of whole-life carbon analysis and reuse of materials in the construction policy and practice. These illustrations underscore the power of regulation, industry capability, and cultural acceptance to drive cyclic changes. In comparison, the UK developments in the area have been relatively incremental as most of the circulatory construction’s efforts are voluntary, and most are still regionally fragmented (UK Green Building Council, 2021).

Besides bio-based innovation, like mycelium, other materials like bamboo and recycled plastics are also considered as a part of moving towards a circular economy in the built environment. Bamboo has good strength: weight ratio, fast renewability and less embodied carbon, compared to conventional timber products. This gives it applicability in modular components, finishes and lightweight facade components where the structural requirements are minimal. Cladding panels, insulation products and composite facades are being involved in recycling using plastic materials, which are recycled plastic materials of post-consumer or industrial waste streams, which contribute to reduction of waste and resource efficiency. Plastic parts that are recycled and made in a way that allows them to be easily put back together again can maintain material value over several life cycles. High-rise residential applications pose critical limitations on performance considerations, UV stability, and long-term weathering, and specification and regulation enforcement are necessary in the UK (Van Der Lugt et al., 2006).

There are several obstacles that still limit the broader implementation of retrofit retrofit strategies. The issue of economics is one of the biggest issues as deep retrofit and circular solutions can be associated with greater initial costs of the capital, even though they can provide saves in the long term in terms of the lifecycle of the solution. Financing solutions and project acquisition frameworks often focus on short-term cost-effectiveness at the expense of entire life, constraining investments in more aggressive retrofit policies.

Secondly, there are still regulatory gaps, especially when it comes to material passport requirements, disassembly planning, and the lifecycle performance reporting. Overcoming these obstacles will entail the need to pose greater policymaking, better regulatory indicators, and prolonged long-term investment to aid industry shift (UK Green Building Council, 2021).

The participation of stakeholders will be fundamental to effective provision of circular economy retrofits in housing as well. Retrofit interventions include direct influence on the everyday life, money, and living conditions of the residents, which is why the active participation and communication are vital. The successful involvement can be used to minimize disruption, deal, and enhance acceptance of retrofit measures. Housing associations have the pivotal role of connecting policy goals, financial limits and demands of the residents with balancing their social roles and long-term viability of the asset management. Simultaneously, policymakers have the role of designing regulatory protocols that facilitate integration among citizens, housing chiefs and players in the industry. The stakeholders groups need to act synchronously to close the gap between a vision of a circular economy and its application on a grand scale in residential retrofit programmes.

2.3.1 Principles of Circular Economy

The circular economy has three principles that are interrelated. To begin with, it aims at removing wastage and pollution by focusing on long-term stability, versatility, and a low carbon footprint. Second, it will reduce resource wastage through encouraging reuse, repair, refurbishment and recycling of materials and components. Third, it aims to restore the natural systems by promoting the utilization of bio-based material and practices to aid in ecological restoration (Ellen MacArthur Foundation, 2019; UK Green Building Council, 2021).

The operationalising of these principles is in form of various design, procurement and construction strategies. Design for Deconstruction (DfD) encourages applying reversible mechanical attachments, including bolted or screwed fasteners, instead of permanent adhesatives or composite so that components of the building may be disassembled and reused (ISO, 2020). Material Passports also contribute to circularity by offering digitalized records of material origin, composition, and possible reuse opportunities, enabling buildings to act as material banks and make further harvesting of end-of-life resources possible (Madaster, 2023).

Product-as-a-Service (PaaS) models are a different mode of ownership where the manufacturers do not give up control of their products, i.e. lighting or building services, but include leasing arrangements. These models can encourage durability, upgradability, and material recovery through holding maintenance, performance, and end-of-life recovery accountable, although the use of these models in residential retrofit is still in the early stages (BSI, 2020).

Another enabler of circular construction is prefabrication, which has enhanced quality control and minimized material waste, compared to conventional construction techniques that were based on construction on site. With the addition of the DfD concepts, factory-based production of modular facade and building elements can minimize construction waste and enhance precision, and promote dismantling and reuse (WRAP, 2022). Simultaneously, bio-based or recycled substances, including timber-based products, hemp-lime insulation, or recycled aluminium, could decrease the effects of embodied carbon, as they are evaluated over their life cycle, especially in comparison to other conventional alternatives containing petrochemicals or virgin materials (LETI, 2020).

The two complementary loops are generally used to describe material flows in the circular economy. Biological loops help biodegradable substances like timber and cork to be deposited back to a natural system and help replenish natural capital. Technical loops, centered on the restoration of the value of non-biological materials (steel, glass, and aluminium) through reuse, remanufacturing, and high quality-recycling in industrial systems (Ellen MacArthur Foundation, 2019; Circle Economy, 2023).

Whole Life Carbon (WLC) assessment models also contribute to accountability by incorporating both embodied carbon, i.e., the carbon associated with the extraction, manufacture, and construction of materials and operational carbon, i.e., the carbon generated by the use of energy throughout the life of a building. WLC assessment offers a more detailed foundation on which decarbonisation strategies in the built environment can be analysed through the considerations of emissions across the lifecycle stages (RIBA, 2020).

The role of policy and industry structures is critical in enhancing the process of circular economic principle adoption. London The London Plan Structure has mandated Circular Economy Statements on major developments in London, which would require designers to show how resource efficiency and material recovery have been addressed (Greater London Authority, 2021). Best practice in the lifecycle management of carbon and lifecycle disassembly-ready design is further elucidated through sector-led initiatives like the RIBA 2030 Climate Challenge and the embodied carbon targets of LETI. Façade interventions in retrofit settings present effective possibilities of deploying circular principles that include modular panels, reversible attachments, cladding materials made with recycling, and bio-based insulation, which have made it possible to retain the structure, minimize embodied carbon, and provide long-term flexibility to the post-war residential fabric (Arup, 2022).

2.3.2 Application of DfD

The main strategies of retrofit adopted when it comes to key circles involve incorporation of reversible construction methods like bolted or screwed fixations instead of welded or permanently bonded components, and modular elements of buildings like prefabricated floor cassettes and demountable partitions. These strategies allow dismantling without serious losses of material and enhancing the possibility of rescuing parts and reusing them after the end of the service of a building (BSI, 2020; ISO, 2020).

Despite the specific disadvantages of high-rise buildings in the context of circular implementation with regard to the scale and structural complexity of high-rise constructions, Design for Deconstruction (DfD) principles are capable of alleviating the mentioned limitations, allowing the implementation of the disassembly procedures clearer sequencing, minimizing the use of destructive methods of building demolition, and limiting the amount of waste in end-of-life intervention.

2.3.3 Case Study: 100 Liverpool Street, London (Milton s Shire House Retrofit)

Figure 7: 100 Liverpool Street (Source: Soltech)

Project Overview

A 22-storey commercial development in the City of London, originally finished in 1980 but retrofitted in 202022 as part of a large-scale refurbishment, the Milton Court / 100 Liverpool Street is now mentioned as a prime illustration of the principles of a circular economy in high rises. The Arup-led project in partnership with Bloomberg involved offering the full reuse of the structural frame in place instead of destroying and recreating it. The building's original steel superstructure was saved in around 95 percent which greatly minimised material usage and proved the relevance of Design for Deconstruction (DfD) principles at large scale in ageing high-rise constructions (Arup, 2022).

Key Design for Deconstruction (DfD) Strategies

Structural adaptation:

The steel beams that were in place were used and the beams were refurbished and added with bolted mechanical joints, as opposed to welded joints. It enhanced the performance of the structures and still retained the possibility of reuse in the future.

Modular façade systems:

The retrofit introduced prefabricated aluminium façade panels with high recycled content, mechanically fixed to allow removal, replacement, or upgrading without destructive intervention.

Material traceability:

Digital material documentation systems were incorporated to record material composition, embodied carbon data, and disassembly guidance, supporting long-term asset management and future material recovery (Arup, 2022).

Circular Outcomes

This project provided significant whole-life carbon savings through the prevention of the demolition process and structural reuse. Recycling the frame made of steel avoided tens of thousands of tonnes of carbon dioxide equivalent emissions that were produced during new steel production while a large percentage of the construction and demolition waste was redirected out of landfill and recycled and reused through recycling and reuse processes. Along with this, the retention-based retrofit strategy showed that the concept of circular interventions can be cost-effective compared to the traditional demolition-and-rebuild, and be beneficial to the environment and programmatically (Arup, 2022).

Policy Relevance

The project would be very useful regarding London Plan goals, including its assertion of whole-life cut of carbon, resource productivity and circular economy claims to big developments. In that way, it offers a demonstrative model of how the practice of circular retrofit can be implemented in the dense urban environment of the UK, based on structural reuse, modular design and DfD.

2.4 Materials for Circular Economy

Traditional building practice remains largely linear in terms of extracting resources, their use and disposal, making them very resource wasteful and carbon embodied. In comparison, circular building strategies focus on reusing, recovering, and re-purposing of building elements through several building lifecycles. This change is more pronounced in the issue of retrofit of high-rise due to the fact that these materials: facade systems, insulation layers and key structural elements, present meaningful flows of materials and carbon. The shift to the principles of the circular economy in the construction sphere is closely connected with converting the materials with lower embodied carbon and a better ability to reuse (Ellen MacArthur Foundation, 2019; UK Green Building Council, 2021).

There is a growing interest in the use of bio-based and recycled materials in this regard because they could result in positive environmental outcomes. Mycelium-based composites have been examined in applications outside of structural functionality as non-structural materials in interior finishes and lightweight insulation since they are biodegradable and have low embodied carbon profiles. Nevertheless, they are still only used to a very limited extent in the facade system, and are currently restricted by performance, durability and regulatory concerns. Likewise, products made out of bamboo have given good strength to weight and speedful renewing properties, and have been used in modular and component-based construction, albeit limited in UK high-rise facades by fire performance standards and standardisation issues.

Polymer recycled materials are also finding application in construction works like insulation boards, cladding panels and modular components which allow the coveting of waste streams and minimise the use of virgin petrochemical resources. On the one hand, these materials can become part of circular material flows in case they are designed to be durable and recycleable, on the other hand, their environmental performance is strongly related to the product design, lifecycle assessment, and end-of-life management strategies (UK Green Building Council, 2021; LETI, 2020).

2.4.1 Design for End-Of-life

End-of-life design is another fundamental concept of the circular system of construction, making sure that the materials and parts of the building can be separated, recovered, and reused in case of an element alteration, or in case of a final tear-down of the building. The given method focuses on thinking ahead during the design phase, which allows flexibility in the future instead of disposal at a young age (Teicher, 2023). The plans to assist this goal would be modular construction, reversible fastening, as well as, non-destructive connection systems that conserve material integrity in repeated cycles of use.

Prefabricated panel-based retrofit systems which are based on mechanical fasteners like bolts instead of permanent adhesive can help selectively replace, upgrade or remove facade-based parts with little waste production in the context of a retrofit facade. These methods enhance flexibility throughout the building life and minimize the destructive demolition process in case of interventions in the future (Wei et al., 2024).

In the context of circular economy, biological and technical cycles are generally identified among the material flows. Regenerative end-of-life paths can be pursued with bio-based and organic materials, in this case timber, hemp, cork, etc., either by means of biodegradation or selective reintegration into biological processes when specified suitably. Non-organic materials, on the other hand, like steel and aluminium can be kept in technical loops via design to be disassembled in order to be re-used or to be high-value-recycled so as to avoid downcycling in products of lower value. These measures combine to contribute to material value retention and lower the entire life environmental impact of the facade retrofit scheme.

2.4.2 Material Passport

Material passports are a computerised list of materials recording the properties, provenance, and reuse of building products and components throughout their lifecycle. When applied to the context of façade retrofit, the material passport can be useful to improve transparency by documenting the data regarding embodied carbon, material composition, chemical content, and disassembly procedures, thus enabling an informed decision-making process in the show of further interventions (Amarasinghe et al., 2025). Material passports allow the buildings to be visualised as material depositories instead of end-of-life streams of waste through consolidating such information.

Material passport systems have been of growing interest due to new advances in digital construction technologies because they enhance the continuity of data throughout the lifecycle of a building. The provision of available and consistent material information after the building stage is becoming identified as a critical measure that can be used to facilitate wise end-of-life decision-making and the decrease of whole-life carbon impacts. According to Wang et al. (2024), the existing lifecycle carbon assessment practices have a lot of gap especially in the area covering demolition, material recycling, and waste management, which implies the necessity to bring the information flows of all lifecycle phases closer to one another. In that sense, technological solutions such as material passport and the support of digital construction platforms can provide a possible direction towards these constraints to enhance the traceability of materials over time and contribute to circular economy goals.

In large-scale retrofit programmes, material passports can function as enabling tools for circular procurement by supporting compliance with emerging policy frameworks, improving traceability of materials, and facilitating new asset-management and service-based business models. While their effectiveness depends on consistent data standards and long-term governance, material passports represent a key mechanism for retaining material value and operationalising circular economy principles within high-rise residential retrofit contexts.

2.5 Conclusion

There is solid evidence in terms of the integrated body of knowledge on the facade retrofit strategies and the framework of running a circular economy, as well as the fresh material innovations, that testify to their high degree of interdependence. Façade based interventions can be regarded as one of the best and fastest solutions towards enhancing thermal performance and lowering operational energy needs in post-war housing. The principles of the circular economy will guarantee that a group of such performance improvements is attained without supporting the construction practice based on linear and waste-intensive systems. With the incorporation of recycled materials and bio-based materials, technological tools like material passports and lifecycle data systems, retrofitted buildings can serve as permanent material re-Depositories and not as temporary resource sinks. A combination of these strategies can help minimise the volume of operational and embodied carbon pollution, increase the lifespan of buildings, and improve occupant comfort and wellbeing.

Regardless of this possibility, there are still great gaps in research. Scalable models with the potential to provide deep, facade-based retrofits of the varied typologies of post-war housing stock are scarce, and the actual performance of post-retrofit is often worse than which is predicted at design stage. The difference in performance between the expected and the achieved energy and carbon performance has not been adequately investigated, especially where high-rise social housing is involved. To overcome these issues, the closer integration of material science, digitalisation and policy alignment is needed, so that the retrofit strategies based on circular retrofitting should no longer be isolated pilot projects but become standard, replicable practice. It is based on this need that the current study aims at evaluating the facade-led circular retrofit strategies by using a complex case-based study foundations on the basis of technical, social, and regulatory facts.

3. Methodology

This chapter identifies the methodological approach to be used to state and respond to the research objective to assess the concept of circular economy-oriented polishing strategies of post-Second World War residential high-rise buildings in the UK. The research paper stands against the backdrop of overall national sustainability goals, specifically the UK pledge to realize net-zero carbon emissions by 2050.

It uses a mixed-methods research design at the intersection of quantitative and qualitative methods to come up with a holistic evaluation of circular retrofit performance. The quantitative analysis concentration is on the material reuse potential, embodied and operational carbon analysis, and performance simulation in building performance on Design builder with retrofit scenarios influenced by Design for Deconstruction (DfD) principles. This allows comparative assessment of carbon outcomes relative to the current base-case scenario and the anticipated retrofit scenario involving the use of façade.

To supplement this, the qualitative analysis is done on architectural and contextual determinants of the feasibility of retrofit, such as policy frameworks, regulatory restraint, and end-of-life material management approaches. These approaches can be combined to offer a combination of quantitative performance measurement and critical analysis of the technical, regulatory, and material factors influencing the practical application of circular economy facade retrofit into UK high rises in housing.

3.1 Research Method

1. The combination of qualitative and quantitative research types in one study allows getting a more detailed and powerful picture of multifaceted built-environment problems. Mixed-method paradigms are especially useful to produce subtle information and reinforce the validity of the research results through the triangulation of numerical data with contextual and interpretive lecture (Amaratunga et al., 2002).

2. In this study, qualitative analysis is used to examine the broader contextual framework within which circular façade retrofits are delivered. This includes a review of UK retrofit and decarbonisation policies, strategies for achieving national net-zero targets, prevailing construction material practices, and key design principles associated with circular economy and Design for Deconstruction (DfD). This thread offers essential information about regulatory, institutional and architectural provisions, that determine the viability and expandability of circular retrofit measures.

3. The quantitative analysis is carried out with the help of the construction of performance simulations and carbon assessment. Design Builder is used to simulate energy performance of the current building condition (base-case) and the proposed retrofit building condition to estimate energy performance in terms of operational energy demand and carbon emission as a result. Simultaneously, embodied carbon is calculated on chosen construction and facade

materials, such as end-of-life conditions, in order to get the whole-life carbon implications. Comparative charting of operative and embodied carbon results will allow finding the possible carbon savings that can be attributed to the circular retrofit intervention in the form of fa facade.

3.2 Review of Literature and Policy

Literature and Policy Review

The study is supported by a systematized search of the academic sources and policy documents connected with the improvement of the UK high-rise residential buildings facades as a part of the circular economy. Databases such as Google Scholar, Web of Science, ScienceDirect, and Taylor and Francis Online were used to find scholarly sources where most peer-reviewed studies on the subjects of architecture, construction, sustainability, and building performance are found. The sources of government and institutional policies were obtained via the official UK ports and industry bodies.

The search terms have been chosen based on the technical and regulatory aspects of the topic of the research and contained such phrases as circular economy retrofit, high-rise retrofit UK, Design for Deconstruction, and limitations in work with listed buildings UK. Best practices The review made it possible to identify the current retrofit strategies, policy drivers, and implementation barriers in line with housing stock that had been demolished during the war.

Some of the important policy frameworks consulted are Historic England Advice Note 18 (instruction on energy efficiency of historic buildings), the Planning (Listed Buildings and Conservation Areas) Act of 1990 and energy company-financing schemes like the Social Housing Decarbonisation Fund (SHDF), and Energy Company Obligation (ECO4), and Home Upgrade Grant (HUG). Together, these documents provide the regulatory and financial context within which façade retrofit interventions in UK high-rise housing are delivered. The review process was used to identify both constraints and enabling conditions for circular retrofit implementation.

Analytical Framework for Retrofit Assessment

To enable systematic comparison of retrofit strategies applicable to high-rise residential buildings, four principal evaluation criteria were defined:

1. **Design for Deconstruction (DfD)** – assessing reversibility, modularity, and potential for future disassembly and reuse;
2. **Embodied carbon** – evaluating material-related emissions across production, construction, and end-of-life stages;
3. **Operational carbon** – assessing in-use energy demand and associated emissions;
4. **High-rise suitability** – considering constructability, disruption to occupants, regulatory constraints, and scalability.

Data informing these criteria were derived from peer-reviewed research papers, precedent case studies, industry reports, and recognised carbon databases.

Simulation Methodology

Subsequent to the comparative evaluation of Sleaford House and Trellick Tower, the digital building framework of the chosen primary case study was built with the aid of DesignBuilder with the help of the EnergyPlus as the simulation engine. The current building state was modelled and calibrated on the model of a baseline, relying on the available construction typology, material properties, and operational specifications.

To test the scenario of retrofit, alternatively to the scenario of the interventions based on the principles of the circular economy and Design for Deconstruction, the modelling of the intervention, which is facade-led, was organized. The simulations were employed to test the difference in the operational energy requirement, thermal performance, and operational carbon emission of the base-case and the retrofit.

Circular Economy and Design for Deconstruction Review

In order to facilitate the elaboration of circular retrofit situations, a specific examination of the secondary sources that covered the topics of circular economy strategies and Design for Deconstruction of high-rise retrofit situations was carried out. The sources considered in this review addressed such topics as reversible facades system, material passport, modular buildings, and life cycle adaptability.

The search terms were reusable facade systems UK retrofit, modular retrofit panels and DfD strategies in a high-rise building UK. The results were used to perform qualitative evaluation of circularity and in choosing the use of retrofit design strategies used in the simulation models.

Stages of Methodology

The overall research methodology is structured into four sequential stages, as illustrated in the methodology flowchart:

1. **Policy and literature review**

   Collection and analysis of secondary data from academic journals, government reports, and sector organisations, including Historic England and the UK Green Building Council. This stage established the policy, regulatory, and theoretical context for circular façade retrofitting.
2. **Case study selection**
   Choosing two representative post-war residential high-rise buildings to allow a comparison between retrofit scenarios with varying regulatory and heritage constraints: Sleaford House (non-listed: social housing) and Trellick Tower (Grade II* listed residential buildings).
3. **Simulation studies**
   Establishment of baseline and retrofit building models in DesignBuilder to assess operational energy use, thermal performance as well as operational carbon reductions.

4. **Embodied carbon and circularity assessment**

Establishment of baseline and retrofit building models in DesignBuilder to assess operational energy use, thermal performance as well as operational carbon reductions.

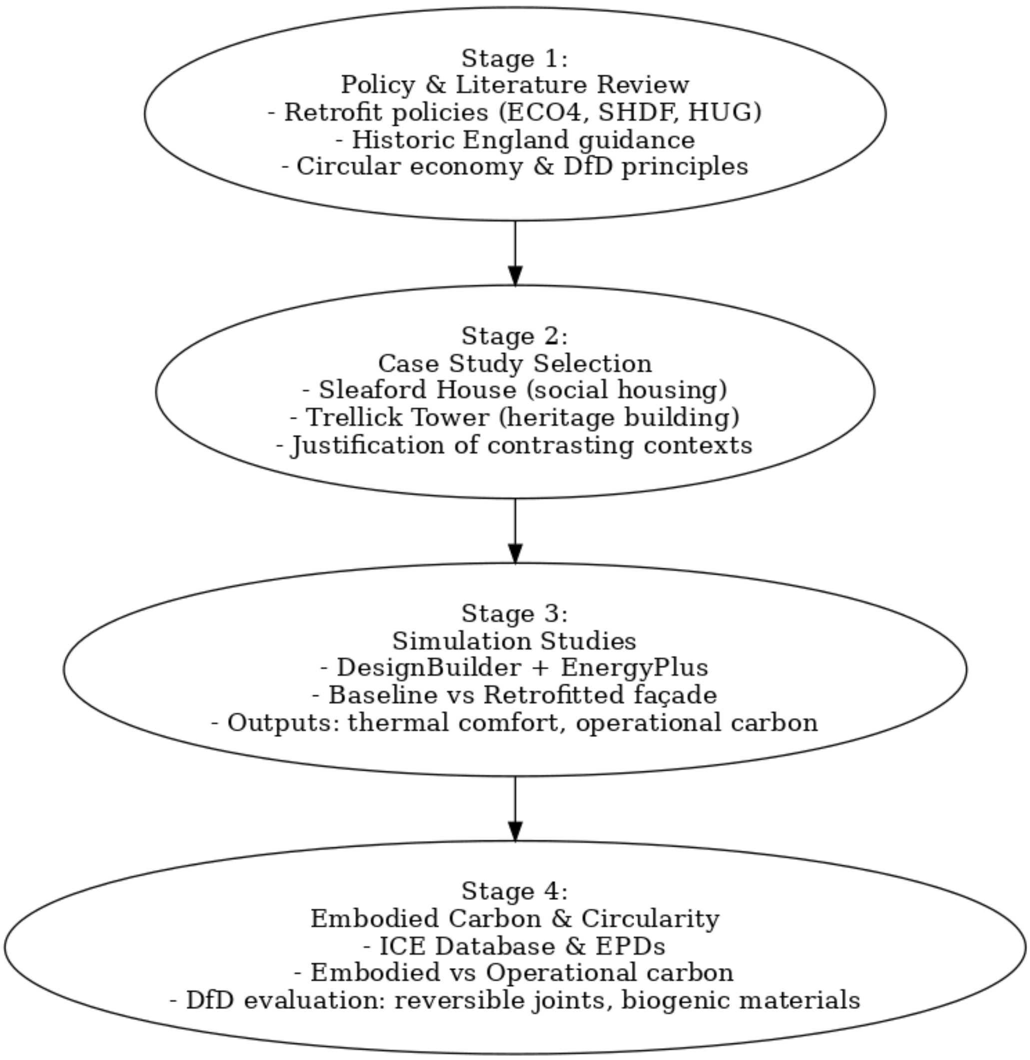


Figure 8: Flowchart for Methodology

3.3 Limitations

This research has a number of limitations that need to be taken into consideration when interpreting the results. The research is based on all secondary data found on peer reviewed journal articles, government reports, and environmental databases and documented case studies. Although this desk-based methodology allows the overall coverage of the current knowledge and policy frameworks, it also implies that the precision of the findings would be related to the quality, consistency, as well as comparability of the sources used. The differences in methodological tools, geographical settings, data clarification, and coverage of the reports in diverse studies can restrict the accuracy of the cross-comparative analysis and the certainty of some conclusions.

Two case studies Sleaford House and Trellick Tower are used to offer two opposing views on the potential of retrofit of non-listed social housing and heritage-protected high-rise buildings. Nevertheless the conclusions reached based on such cases can not be extrapolated to the whole of post-war high rise housing in the UK as there is immense variation in the construction typologies, ownership arrangements, occupancy levels, as well as the regulatory settings across buildings.

The methodology also presents limitations by the simulation-based part. Because full original construction records were not available, assumptions needed to be made about envelope build-ups, infiltration and schedules of occupancies were also to be made. Even though these assumptions were guided by the known literature and standard modelling practice, they might not necessarily be representative of the actual behaviour in the real world of buildings, which may influence the validity of the performance outcomes that have been predicted. Moreover, DesignBuilder does not provide the flexibility to depict some details in construction pertinent to Design for Deconstruction, including the special mechanical fixings and connection systems; hence, constraining the accuracy with which some of the circular retrofit strategies can be represented.

The paper also includes policy and regulatory frameworks that are expected to be put into practice starting in the year 2025. Consequently, the long-term applicability of the conclusions may be affected by modifications of government funding systems, retrofit schemes, or construction standards. Lastly, the study lacks an express determination of financial viability or stakeholder attitudes such as disturbances among residents, social adoption, upkeep over time, or operational management issues. These socio-economic dimensions to which these strategies are proposed are lacking and limit the assessment of the entire practical viability of the intended retrofit strategies.

Although these constraints are present, the methodology still offers an adequate, ordered and reproducible methodology of examining the impact of facade-led retrofit intercession in a circular economy framework. The method will provide a solid foundation on comparative analysis, also a basis on subsequent research involving use of primary data collection, cost analysis and involvement of stakeholders.

4. Results
4.1 Policy Rationale

A strategic sample of policy frameworks was chosen, to indicate two opposites of the UK retrofit practice, the regulatory environment constrained by heritage, and those that both enable and promote social housing retrofit. The chosen policies are Historic England Advice Note 18 (HEAN), Planning (Listed Buildings and Conservation Areas) Act 1990, the Social Housing Decarbonisation Fund (SHDF), the Energy Company Obligation (ECO4), and the Home Upgrade Grant (HUG). These instruments mutually reflect the regulatory and financial environment defining the process of retrofit decision-making in high-rise residential buildings of post-war.

The Planning Act and the guidance of Historic England represent an example of restrictions placed on listed buildings in which retrofit interventions have to strike a balance between increasing energy performance and the protection of architectural and historic values, including that of Trellick Tower. These systems are often limiting of exterior facade modifications, demand reversible and non-invasive action, and call for prolonged permitting with a multiplicity of interested parties. As a result, the plans of retrofit buildings are easily compromised between conservation and energy efficiency goals (Sevim, Taki, and Abuzeinab, 2025).

Conversely, policy and funding processes including SHDF, ECO4 and HUG are the main instruments used in the UK to decarbonise the social housing industry on a faster scale. Such programmes prioritize thermally inefficient housing to be retained in the post-second world war housing stock, promote fabric-first strategies of retrofit, and mass-scale interventions in line with national net-zero targets.. Their design also allows housing providers to be able to go further in retrofit actions in cases where regulatory and heritage limitations exist, and the environment is freer to test circular economy and Design for Deconstruction arrangements (Preece et al., 2023).

The combination of these policy factors represents the range of retrofit policy conditions considered in this paper. A case study is influenced by complexity of ownership and conservation based regulatory restrictions, whereas the other is facilitated by the specific financing schemes and higher technical flexibility. This dichotomy offers a systematic foundation on which the operation of policy regimes through constraints and facilitation of the adoption of circular economy facade retrofit approaches to UK high-rise residential sector may be explored.

4.2 Historical Building Regulations

A significant proportion of the stock of housing has been recorded as being of historic and architectural value in the UK where the housing portfolio is among the most developed in Europe (Historic England, 2024). The total number of listed buildings in the country is approximately 400,000, which is a statutory protection of buildings as a part of the UK planning law (Panakaduwa et al., 2024). These preservations are largely designed with Planning (Listed Buildings and Conservation Areas) Act 1990 which in addition to trying to safeguard cultural and architectural heritage of the country, also tries to regulate the alterations that have taken place in the historical buildings of great significance.

In the UK there are a wide variety of heritage assets which include; World Heritage Sites, scheduled monuments, registered parks and gardens, and registered battlefields. Listed buildings constitute a particular category of heritage assets and are given one of three grades based on the level of interest: Grade I, which indicates buildings of particularly extraordinary interest; Grade II, which indicates buildings of more than special interest of considerable interest; and Grade II, which indicates buildings of special interest and which should be preserved. The classifications determine the extent of the allowable change and level of scrutiny used to appraise the retrofit and renovation plans.

The potential of historic buildings in the UK to be used efficiently on energy saving is quite large, but retrofit interventions may be treated with caution because of concerns regarding preservation of architectural integrity and historical value. As El-Darwish (2017) illustrate, various types of retrofit strategies, including the improvement of the performance of walls, the optimization of HVAC, as well as the minimally invasive renewable energy sources can significantly decrease energy usage as well as carbon emissions without the loss of heritage importance. Their results emphasize that high quality interventions are possible that are sensitive and well designed, which can bring significant environment impact, and it is not necessary to stray into architectural limits. Nevertheless, the research also reveals a general unawareness of the building owners in terms of relevant regulations, grants presently available, and viable energy-saving solutions, this still narrows the application of proven retrofit solutions in old buildings.

Historic England, the public body responsible for the protection of England's historic environment, provides guidance on improving energy efficiency in historic buildings through Historic England Advice Note 18 (HEAN). It encourages a comprehensive approach to energy betterment of the entire building, which entails a comprehensive familiarity with the context, construction, material, condition, and patterns of use of a building, prior to interventions of any sort being considered. HEAN prioritises small-scale, low-risk, and reversible measures—such as draught-proofing or secondary glazing—before larger or more invasive interventions are pursued. While this approach reduces the risk of harm to historic fabric, it can also limit the magnitude of achievable energy performance improvements.

Besides technical limitations, heritage buildings are also subjected to significant challenges in respect to the procedures and policies. Majority of the proposals by retrofit is subject to some levels of approval including listed building permission, which can increase project durations and make it more costly. The Local Planning Authorities (LPAs) have to weigh up the expense of any benefits acquired through energy conservation and the heritage quality, with the former often winning out in the event of such a juxtaposition. This standpoint is supported in Approved Document L of the UK Building Regulation that says that in case of historic and traditional houses, energy efficiency requirements must not be met at the expense of unacceptably changing the character, appearance, or fabric of the building (UK Government (1)L, 2021, para. 0.14). Therefore, although the use of energy performance is an idea that is fostered, its use is regulated in heritage contexts with an authoritative approach to regulations and preservation.

4.3 Green Building Initiatives

To address climate change in the residential building sector, which significantly contributes to the UK's energy consumption and greenhouse gas emissions, the government has introduced several major green initiatives.

The UK introduced energy performance certificates (EPCs), which were later adopted by the European Performance of Buildings certification scheme in 2002. The EPCs became a new focus for energy efficiency in buildings, with the aim of reaching an EPC C-rating by 2030, according to the Clean Growth Strategy.

In 2013, the Green Deal was launched as one of the earliest initiatives to make energy-saving improvements in the UK. The deal enabled homeowners and tenants to make improvements without paying upfront costs, and repayments were made through savings in energy bills. The policy however failed to reach its predicted success due to its complexity, high interest rates and low consumer confidence (Rosenow a Eyre 2016).

Even though the policy failed, it helped to highlight the importance of green financing for encouraging large-scale retrofit adoption.

The decarbonisation instrument of Social housing in the UK government has come out to be one of the effective instruments of policy in improving energy efficiency in social housing with the decarbonisation Fund (SHDF) having in excess of PS3.8 billion as a source that supports the retrofit interventions by the year 2030. The scheme encourages the concept of fabric-first and aims at refurbishing the underperforming buildings to the minimum EPC band C standards. Although the SHDF is a policy and funding program, the broader benefits of the extensive retrofit measures are evidenced through the empirical research of social housing arrangements. As demonstrated by Shwashcreh et al. (2024), when properly and well-designed and of the necessary quantity, high-rise social housing can significantly increase thermal comfort with a thickness of the plans based on aggressive energy efficiency improvements and the structuring needs of the residents and serve to alleviate fuel poverty, which has significant social and environmental implications.

Energy Company Obligation (ECO) is in its 4 th phase. It is more of a supplier requirement plan in which the supplier will be charged with the costs of retrofitting homes to their customers in the form of electricity bills. ECO4 will run until 2026, targeting low-income and fuel-poor households. Under this scheme, energy suppliers are obligated to fund measures such as wall insulation and heating upgrades. The scheme prioritises homeowners and social housing tenants with an EPC rating of E, F, or G, aiming to upgrade them to Band D or higher (Preece et al. 2023). ECO4 encourages a fabric first, whole-house strategy and cost-effectiveness.

One such UK government initiative is Home Upgrade Grant (HUG) which may be provided to low-income earners, off-gas grid households with a middle EPC score of between D and G to ensure carbon emissions such as insulation, high-energy- efficiency windows and low-carbon heating systems are reduced. (Preece et al. 2023). HUG has a 1.4 billion budget and is a supplementary program to other programs, e.g., SHDF and ECO4. But it focuses on a more defined market - off-grid and fuel-poor families.

The Sleaford House, a post-war high-rise social housing block in Tower Hamlets portrays a classic reflection of the UK residential towers that have been erected. It employs standardised successively reinforced concrete systems and thermal performance is limited. Being a non-listed building as well, it is more flexible than serpent-retributed towers in the imposition of modular and prefabricated facade retrofit solutions. Modular design solutions can be fabricated off-site and cause less disturbance to the occupants of the social housing which is a significant concern in occupied social housing. These systems are enabled to absorb both the insulation and airtightness layers and service parts and allow future flexibility by designing-to-deconstruct concept. Modular facade retrofitting is a scalable solution to achieving energy efficiency, minimization of operational carbon, and fuel poverty issues in the residents of Sleaford House, as well as aligns with the current policies on de-carbonisation of social housing in the UK (Sustainablebuildinguk, 2025).

4.4 Case Study Selection

To assess whether Trellick Tower and Sleaford House are suitable for retrofit interventions, a comparison is made between the two buildings, focusing on DfD and the application of circular economy principles. These two London high-rise residential buildings serve as a useful starting point for analysis because they reflect different architectural typologies, ownership structures, and retrofit challenges.

The Trellick Tower is a brutalist building that became a Grade II+ in 2017 and was designed by Ernos Goldfinger in the 1970s and has gained fame due to its unique design and its significance to architecture. Nevertheless, its listed condition poses serious difficulties to the interventions of retrofit. Amendments to the exterior or interior of the building must be met with stern heritage approval procedures under the Planning (Listed Buildings and Conservation Areas) Act of 1990. This makes it incredibly limiting to deploy measures of deep retrofit like recladding or improved insulation, or installing photovoltaic panels. Also, the mixed-ownership form of the tower with council tenants and leaseholders makes it difficult to negotiate with them and to find the means.

Conversely, post-WW2 council housing developments in Tower Hamlets, including Sleaford House, offer a more adaptable framework for retrofit. These buildings are easier to upgrade technically because they are not listed and are built with more standardised concrete panels or bricks. They are also not subjected to much administrative and legal issues since they are under the complete control of the local government or housing association. They also receive priority on schemes such as SHDF and ECO4 because their thermal performance is less than EPC Band D (as is typical of all tenants) and because they are more prone to fuel poverty.

The customised detailing of Trellick Tower creates a very restricted opportunity of modularity or material separation when looking at it in a DfD perspective. In contrast, more modular building forms are available in Slieford House, which would be less harmful to the environment and thus can be changed or taken apart.

Trellick Tower throws light on the difficulties of doing retrofitting work in frameworks of heritage including the prospects of compromise in design, time require and costs involved, although it is a building of architectural and historical importance. Sleaford House is, on the other hand, a low bar, high impact site to prove that retrofit methods of circles, scale, and social inclusivity. Consequently, Sleaford House would become a more viable and relevant case study in this study, which is due to its feasibility to be retrofitted, the possibility of stakeholder involvement, and its compatibility with the goals of the circular economy.

Aspect	Trellick Tower	Sleaford House
Construction Period	Completed in 1972	Built in 1960s
Height and Typology	31-storey high-rise residential tower	19-storey high-rise
Architectural Significance	Brutalist icon by Erno Goldfinger	Standardised post-war housing block
Listing Status	Grade II* Listed Building	Non-listed
Construction Material	Concrete frame, precast panels	Brick infill and concrete frame
Current Condition	Partially refurbished; many heritage constraints	Generally poor energy performance, eligible for SHDF, ECO4
Occupant Profile	Mixed tenure, including social housing	Primarily social housing
Policy Constraints	Strict due to listed status; requires HEAN adherence	Fewer constraints; local authority flexibility
Retrofitting Complexity	High complexity due to listing and structure	Lower complexity; more adaptable for interventions
Suitability for DfD and Circular Economy	Limited scope due to heritage constraints; less DfD-compatible	High potential for DfD integration and material experimentation

Table 1: Trellick Tower vs Sleaford House

4.5 Systems Used in the UK for Retrofitting High-Rise Residential Buildings

A) Systems for External Wall Insulation (EWI)

The most used technique is External Wall Insulation (EWI), the mechanical attachment or glueing of insulation boards to the outside wall, e.g. mineral wool, expanded polystyrene (EPS), and phenolic foam. They are normally constructed to be clad or reinforced with render to shield them against the weather. In response to Calderon et al. (2018) investigated a high-rise tower in the UK that was insulated with 100 mm of mineral wool (density of 140 kg/m 2) and found that this insulation material provided more comfortable indoor climate, less heating, and less heat loss through the facade. It has generally been a requirement that any high-rise facade retrofit project undertaken involves the usage of mineral wool because mineral wool is incombustible, a factor that complies with safety protection requirements that the UK enforces on the use of the material following the Grenfell tower fire (Finish Facades, 2023).

A common method of retrofitting buildings is this one since it is fire-free and helps buildings to stay warm. Nonetheless, its Design for Deconstruction (DfD) capabilities are restricted as insulation boards are frequently glued and can hardly be taken off without damage, and the layers made of mineral wool can be polluted by or mesh material, making them more difficult to recycle (Göswein et al., 2022). As an embodied carbon impact, mineral wool is satisfactory and not as impactful as petrochemical foams. Nonetheless, the emissions are aggravated by adhesives or render closeures (Moncaster and Pomponi, 2019).

External wall insulation (EWI) has been demonstrated to substantially decrease the heat transfers via the building envelopes and use less energy to heat space in the case of retrofitting buildings. Research has shown that a significant reduction in heat loss through walls can be achieved by making changes in thermal insulation which can reduce operational energy use needed to heat buildings by a significant amount depending on the type of building, climate and the thickness of the insulation applied (Energy Saving Trust data suggests potential 85% reduction in heat loss through walls when properly installed EWI and research on insulation effects demonstrates possible drops of up to about 25-50% operational energy use in heating specific systems) depending on building type, climate and insulation thickness (Low Carbon Buildings, 2025).

High-rise residential retrofits with the use of mineral wool insulation become popular because of the insulation non-combustible properties to enable compliance with the advanced fire safety expectations after the Grenfell Tower fire. Although specific material-level fire performance requirements are distinguished in the framework of the regulation provided in the UK as opposed to their impacts on the specific academic research, the growing focus on fire safety has greatly affected the choice of facade materials in high-rise renovation projects. Stoops, Thorneycroft, and Touchie (2021) note that the existing policies and practices in renovation tend not to interpret buildings as systems, which may cause practical and logistical problems in the way retrofit delivery is delivered. In reality, the construction of mineral wool-based facade systems often require an extensive access system (full scaffolding) in addition raising the construction cost and the disturbance of occupied high rise buildings. It is also essential to note that fix strategies should be taken seriously during the facade system design so that they can perform well when they are under environmental loads characteristic of the tall structures.

Rainscreen Cladding

Ventilated rainscreen cladding systems, which create a ventilated space between the outer cladding panels and the insulation, are an alternate tactic. This design increases the durability of the facade while also improving weather resistance and lowering the risk of interstitial condensation. The effectiveness of rainscreen systems and insulation in Portsmouth tower blocks was highlighted by Aragón et al. (2018), who found that these systems reduced annual energy demand and enhanced occupant comfort. More design flexibility is another benefit of using rainscreen techniques, which is crucial for upholding planning and aesthetic standards in crowded urban settings. Portsmouth tower blocks retrofit project is frequently mentioned as one of the prominent instances of the deep retrofit application to the UK large-scale social housing. The intervention took place on two of the 1960s concrete high-rise blocks in Portsmouth to resolve some critical problems of poor thermal performance, occupant comfort, and energy needs typical of post-war concrete tower housing.

Ventilated Rainscreen Cladding Systems have a different balance. They are great for DfD because you can take off and replace mechanically fixed panels (aluminum, wood, or fiber-cement), and sub-frames are often recyclable (Akinade et al., 2015. Aluminum panels have a lot of embodied carbon, but recycling helps reduce this. Timber facade panel is considered to be a low-carbon material, which has the ability to store biogenic carbon throughout its service life and thus this makes it appealing in terms of whole-life carbon. Environmental Product Declarations (EPDs) show that biosourced products like timber could attain incredibly low to negative lift cycle carbon effects out of carbon capture throughout the growth. In residential high rise projects, however, external wall system usage of timber is heavily fire tightened thus may not be able to be utilized in regard to high rise buildings, facade arrangement and system test conformity. Consequently, their preference in higher buildings can be observed by non-combustible alternatives. Simultaneously, rainscreen ventilated facades are very vital in the thermal performance of insulations such as moisture management and condensation, which in turn are very important in the all-term thermal efficiency and sustainability.

Case studies in Portsmouth towers show that they lower heating needs and make people more comfortable (Aragón et al., 2018). Facade Rainscreen facade systems are commonly used in high-rise retrofits since in many cases, they can be mounted either with mast climbers or rope-access methods instead of full scaffolding, which impacts few discontinuities and less noise and on-site effects of the occupied building. Their sub-frame systems are designed to withstand the pressure of the wind generated by tall buildings and the choice of materials is limited by new and stricter fire safety standards in the UK. This means that corrugated timber (or combustible-laminated) would be usually limited in the use of high-rise facade applications. According to Stoops, Thorneycroft, and Touchie (2021), maneuvering such constraints of regulation and procedures is a major issue in the high-rise residential renovation practice.

Deep Retrofit and Whole-Facade Approaches

In larger projects, entire facades are demolished and rebuilt using high-performance prefabricated panels, sometimes in accordance with the EnerPHit standard. Extensive facade retrofits, including enhanced airtightness, enhanced glazing and external wall insulation, can lower demands on space-heating resources greatly and should also increase the service life of high-rise concrete edifices well into old age. Nevertheless, Stoops, Thorneycroft, and Touchie (2021) also show that the implementation of these integrated interventions in high-rise residential buildings is often impeded by systemic constraints, such as the separation of responsibilities, relative lack of focus on non-energy benefits, as well as the lack of the building-as-a-system approach. Practically, the massive refurbishment of tall occupied buildings at the facade is exacerbated with capital remunerations, displacement of tenants, and logistics issues with the use of scaffolding or mast climbers.

Deep retrofit with prefabricated facade panels is one of the most holistic retrofit approaches but is resource-intensive. Designing prefabricated panel systems has been seen as advantageous by Design-for-Deconstruction (DfD), as they can be designed in such a way that it has modular layers and mechanical fixings allowing them to be deassembled and replaced in future. These systems can also be further decreased through the addition of bio-based insulation materials, including hemp, straw or wood fibre, which use rapidly growing or waste-based biomass; with its favourable carbon sequestration properties (Goswein et al., 2022). But deep retrofit projects usually require replacing facades, insulation and windows which leads to fairly high initial embodied carbon although these might pay back in long-term operational energy bounds. Prefabrication reduces waste and emissions from transportation, but the material use remains high (Moncaster and Pomponi, 2017). The main benefit is in operational energy: deep retrofits can reduce heating demand by 50–70% by making buildings more airtight, eliminating thermal bridges, and adding high-performance glazing.

The case studies of high-rise residential retrofits in the UK show that when renovation strategies are well coordinated, it is possible to achieve high impacts as a result of changes in the energy performance, indoor environmental quality, and the longevity of the building. Such examples are used by Stoops, Thorrycroft and Touchie (2021) to emphasize the need to approach renovation in an integrated system-based approach beyond locally focused energy goals. Prefabricated panel systems used in the context of facade retrofitting can help keep the disturbance to inhabitants to the minimum since it is possible to pile up the panels over a short period, using short-term crane operations. This method is however usually best applicable in large scale regeneration, because it needs there to be a lot of site access, lifting capacity and strict fire co-ordination, so it is not applicable to smaller or piecemeal retrofit interventions.

4.6 Comparison Between Different Types of Methods

Method	Design for Deconstruction (DfD)	Embodied Carbon	Operational Energy	High-Rise Factors
EWI (Mineral Wool)	Limited DfD because insulation boards are often adhesively bonded, making removal destructive. Mechanical fixings are recoverable but they are less prevalent. Mineral wool is infected by render layers and meshes, making them difficult to recycle.	Moderate foams of carbon relative to petrochemicals. Adhesivals and render boost effects but are still less than aluminium rainscreens.	Savings vary between 30 and 40 percent of heating requirement in UK high-rise refurbishments, with enhanced comfort and less heat loss (Calderón et al., 2018). Fire safety is also met by the use of mineral wool. regulations.	Fire-safe (non-combustible), but installation requires scaffolding, which is expensive and disruptive at height.
Rainscreen Cladding	High compatibility with DfD since panels are mechanically fixed and sub-frames recyclable. Panels such as aluminium or timber can be reused or recycled.	Embodied carbon varies: aluminium panels are high but recyclable, timber is low with sequestration potential and fibre-cement is moderate. Sub-frames add impacts but are recyclable.	Ventilation cavity preserves insulation performance, reducing condensation risk.	Well-suited to towers using mast climbers for installation. Fire safety restricts panel choices (timber not permitted above 18 m).
Deep Retrofit Panels	**Highest DfD potential when prefabricated with modular layers and demountable fixings**.	**Very high upfront embodied carbon due to wholesale facade, window, and insulation replacement.** Prefabrication reduces waste but overall material intensity remains high.	**Delivers the largest energy savings**: airtightness, thermal bridge elimination, and glazing upgrades can reduce heating demand by 50–70%.	Highly effective for towers where large-scale renewal is planned.Minimally disruptive when installed, however, needs cranes and access to the site, which are expensive and complicated. Careful design is

				needed for fire safety.

Table 2: Comparison for different Facade Systems (Source: Self-developed)

The best balance of circularity, performance, and practicality for high-rise retrofits is found in rainscreen cladding. Rainscreens are mechanically fixed, unlike EWI that uses glue. This makes them work with design for deconstruction and material recovery at the end of their life (Akinade et al., 2015). They are flexible when it comes to embodied carbon. For example, while aluminum panels are carbon-intensive, alternatives like fiber-cement or bio-based composites can have less of an effect. Recycling can also help reduce emissions (Moncaster and Pomponi, 2017).

Ventilated facade envelopes are capable of sustaining sustainable thermal functions because they do not violate the insulation of moisture exposure and allow simplified control of the environment. The studies on high-rise retrofit in the UK demonstrate that the building envelope may be used to cut the heating demand by half and improve the comfort of occupants, but the typology of facades is not consistently specified (Aragon et al., 2018). In practice, rainscreen facade systems can effectively fit well into the retrofit of high-rise buildings, since they can usually be installed with the help of mast climbers instead of full scaffolding, making their installer less disruptive to occupied buildings. It has also been found that ventilated facades can be made to cater to the wind loading and to meet the fire safety standards when properly detailed (Stoops, Thorneycroft, and Touchie, 2021).

4.7 Aluminum Rainscreen Systems

Rainscreen cladding is a great choice for high-rise residential retrofits because it makes them more energy-efficient, controls moisture better, and lasts longer, all while supporting Design for Deconstruction (DfD). Rainscreens are fixed mechanically, so panels can be taken down, replaced, or recycled at the end of their life (Akinade et al., 2015). This is different from insulation that is based on glue.

In the UK, the more than 18 meters tall residential buildings are subject to strict fire safety measures, such as the prohibition of combustible materials when used to construct external walls, usually with the use of Euroclass A1 or A2 material. These demands may be met by facade systems of non-combustible cladding materials (fibre cement, aluminum, glass-reinforced concrete (GRC) panels) are employed together with mineral wool insulation, and yet it remains possible to support reversible construction strategies that facilitate disassembly in future (GOV.UK 2025). Sotech Optima and Rockwool ventilated cladding are two examples of commercial systems that have been tested by the CWCT and are designed to be replaced in modules, following the principles of a circular economy (Rockwool, 2023; Sotech, 2024).

As field research on high-rise residential retrofits proves, the renewal of building envelope may lead to a substantial drop in heating demand and the enhancement of thermal comfort of occupants (Aragon et al., 2018). Although the specific systems of the facades are not outlined in the study carried out by Aragon et al., the results indicate the general argument that the older tower blocks in the UK could get in the post-war period. Practically, where ventilated rain screen facades are required, they are frequently simply installed using mast climbers instead of full scaffold which can minimise on-site disturbance as well as enhancing the safety of installation in occupied premises. Such facade systems can provide an appropriate solution when aligned with prevailing fire regulations and the principles of the circular economy, to improve the performance, safety, and long-term flexibility during post-war high-rise retrofits in the UK.

Aluminum rainscreen systems have a higher embodied carbon when they are new than fibre cement systems, but they still integrate well with circular economy strategies. Virgin aluminum typically has an embodied carbon intensity of 8–10 kgCO_2e/kg (Hammond and Jones, 2011), which is significantly higher than fibre cement alternatives. It is possible to recycle aluminum repeatedly without losing quality. In fact, the recycling process only consumes about 5% of the energy required to produce it initially (European Aluminum

Association, 2020). This implies that aluminum cladding panels can be taken apart and re-introduced at the end of life with little or no further impact on the environment provided that they are designed with mechanical closing so that they can be taken apart.

Design-wise, Aluminum systems are superior to cement-based systems since they are typically assembled on subframe brackets and rails, which can be dismantled apart, breaking down and reused. Cement systems, conversely, tend to be downcycled (UK Green Building Council, 2021). Moreover, aluminum can be used in tall buildings as it weighs nothing much, is powerful and resistant to corrosion.

Wind loading, access of the facade and long-term maintenance are all factors to be considered. The retrofit also fulfills both fire safety regulations - A1/A2 non-combustible stop exterior wall requirement more than 18 m (MHCLG, 2018) and circular economy objectives by selecting an aluminum rainscreen system that contains much repurposed material and recommending reversible, mechanical fastening. The embodied carbon of fiber cement is low in the short run, whereas in the long run, aluminum is superior in terms of recovering, reusing and modifying materials since their life time.

5. Simulation Parameters

DesignBuilder was used to analyze retrofit options using a high-rise residential tower in London, Sleaford House, which was made as a digital model (simulation engine being EnergyPlus) of a tower constructed following the Second World War. The model will attempt to recreate the present-day baseline of the building and give an opportunity of experimenting with the facade activities in accordance with the principles of a circular economy.

Geometry and Building Envelope

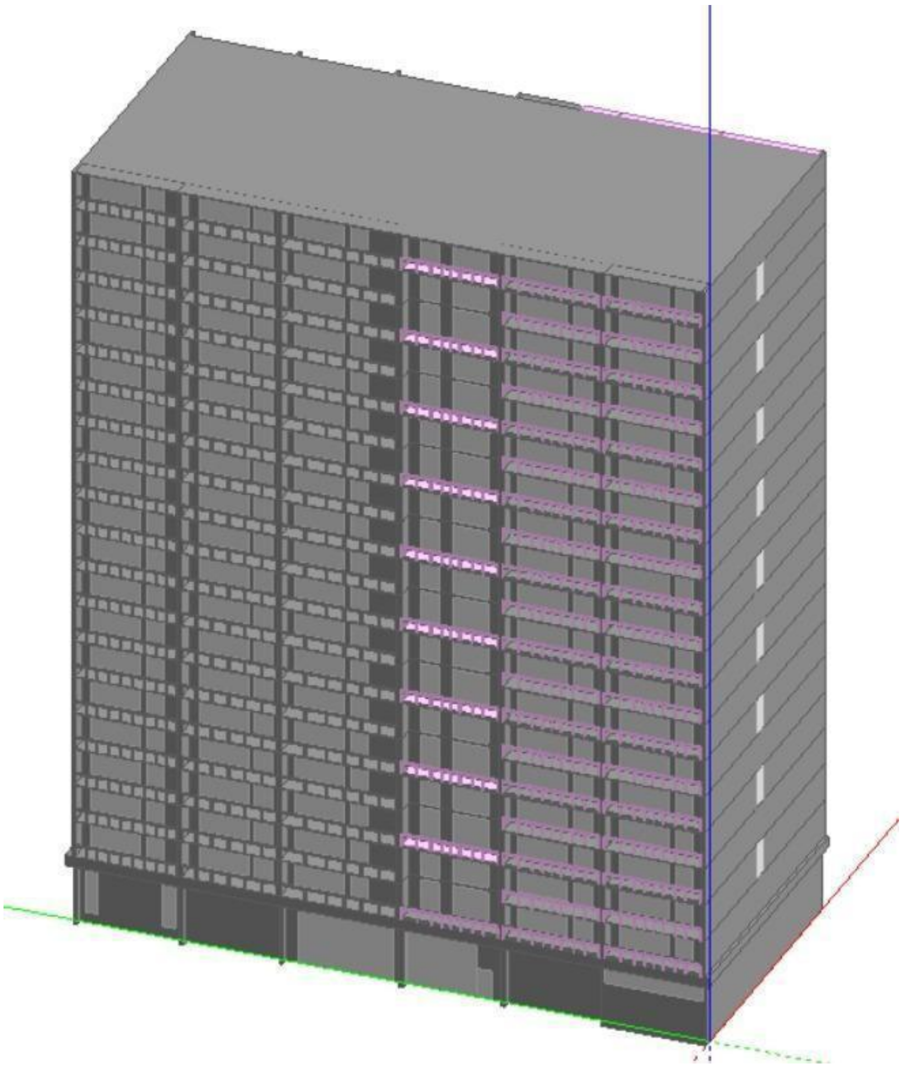


Figure S: Geometry and Building Envelope of Sleaford Tower (Source: DesignBuilder)

Geometrical design of the tower was reproduced and based on references and pictures of architecture and usual floor plans. Construction practices of the time used solid walls of the level of reinforcement outside and very little insulation on the inside, which is why the building was a reinforced concrete building.

External walls: The baseline external wall U-value in this model is 2.1 W/m²·K (Li et al., 2015; BEIS solid wall programme, 2016). This corresponds to the default value for uninsulated solid walls in UK stock modelling and EPC methods.

Glazing: Single-glazed metal-framed windows.

Roof and floor slabs: Concrete decks with minimal insulation.

These envelope parameters were entered to simulate thermal leakage and infiltration typical of buildings that are not retrofitted and belong to the post-WW2 housing stock from that era. Infiltration was set at 0.15–0.2 ACH to represent air permeability levels common in unrenovated high-rise blocks.

The remaining settings for occupational load, lighting schedule, metabolism rate, and DHW via electricity (common in post-World War II high-rise residential buildings) have been based on the existing DesignBuilder template, with adjustments made to the number of people and occupancy density.

- **Base Case Materials for Facade designed in DesignBuilder**

Figure 10: Base Case Materials (Source: DesignBuilder)

The cross-section above illustrates the basic wall construction of Sleaford House. It is typical of post-war high-rise buildings in the UK. It features a 15 mm thick layer of cement plaster on the exterior, a 300 mm thick reinforced concrete wall serving as the main structural element, and a 10 mm thick layer of lightweight plaster on the interior. Such solid wall assemblies without insulation were common in tower blocks built during the mid-20th century, when speed and structural efficiency took precedence over thermal performance. This layering results in a significant U-value, generally between 2.0 and 2.2 W/m²K, consistent with data on uninsulated concrete high-rise walls (Li et al., 2015; BEIS solid wall programme, 2016). The absence of insulation highlights how inefficiently the original design used energy and explains why post-war social housing blocks lose substantial heat. These characteristics make the baseline construction a useful reference for assessing how retrofit changes impact thermal performance and operational carbon emissions (UK Green Building Council UK Green Building Council, 2021).

- **Retrofitted Materials for Facade designed in DesignBuilder**

Figure 11: Retrofitted Facade Materials (Source: DesignBuilder)

The refitted wall construction incorporates a non-combustible aluminium rainscreen panel (3 mm) fitted to an air-ventilated cavity (50 mm) and secured by an outer layer of mineral wool insulation (120 mm). The software however limits the addition of hooks and screws used in mounting the insulation and panels.

It maintains the current construction of cement plaster (15 mm), dense reinforced concrete (300 mm) and internal plaster (10 mm). This accumulation significantly enhances thermal performance, reducing the U-value of the baseline at approximately 2.0 2.2 W/m 2K to an estimated 0.20 2.25 W/m 2K. The practice aligns with the case studies regarding high-rise residential renovation on the UK, indicating that heating consumption can be minimized and the thermal comfort can become improved through the modification of the building envelope (Aragon et al., 2018; BRE, 2016). Aragon et al. (2018) demonstrate that even the enhancements of the envelope to meet or even surpass Building Regulations may lower heating loads by more than 80 per cent, though they also point out that the overheating risks should be addressed with the help of proper ventilation and shading. Correlated studies show that additional moisture and condensation control are possible in using ventilated facade assemblies, which lead to superior durability and comfort among occupants (Stoops, Thorneycroft, and Touchie, 2021).

Both aluminium panels and mineral wool meet the A1/A2-s1, d0 non-combustibility standards for fire safety. This means they meet the post-Grenfell UK facade safety rules for buildings taller than 18 m (MHCLG, 2018). Design for Deconstruction (DfD) principles are facilitated by the implementation of mechanical fixings, by which facade components can be more easily separated, retrieved, and recycled at the end of their service ramification (Densley Tingley, 2022). This solution leads to a reuse of materials and minimum waste, which is a direct benefit towards the objectives of the circular economy regarding the facade retrofitting. The Net Zero Whole Life Carbon Roadmap (2021), created by the UK Green Building Council, puts it in all the strategies that embodied carbon is to be reduced and material efficiency should be increased at all building construction stages, operation, and end-of-life (UK Green Building Council, 2021). In spite of the fact that the roadmap does not prescribe the use of some forms of facade technologies, the aluminium rainscreen retrofit systems succeeded in meeting the criteria of the possibility of dismantling, and it is in this regard that meets the broader vision of decarbonising the built environment in the UK in terms of lifecycle performance and recoverability.

In this research, data gathering and the simulation results have been focused on one representative floor (middle) of the case study building being 19 storeys high. Middle floors were considered the most beneficial floors that provide the best results and representative findings on the study of high-rise buildings. This is due to the fact that they are not subject to extreme weather conditions and temperature conditions that normally impact on the top and ground floors.

Different boundary conditions normally occur in ground floors since they are in contact with the ground, they dissipate heat when people step in, and they are utilized differently among people. Instead, upper floors have increased sunlight, heat loss through the roof and wind exposure. An intermediate level, in its turn, has a more stable and homogenous thermal performance, which is rather similar to the work of the majority of the settled floors in the building.

This approach also increases the efficiency of calculations by reducing model complexity while still providing accurate and generalisable data on heating demand, thermal comfort, and carbon performance. The results from the middle floor offer a reliable basis for comparing baseline and retrofitted scenarios across the entire building.

5.1 Simulation Performance Indicators for Base Case vs Retrofitted Model

A comparative simulation between the base model of Sleaford House and its retrofitted variant using rain-screen cladding as external facade is done to assess the efficacy of facade retrofitting using circular materials. In addition to evaluating the design from a circular economy and DfD standpoint, the objective is to quantify improvements in thermal performance, operational carbon, and embodied carbon. DesignBuilder will be used for the simulations, with EnergyPlus serving as the simulation engine.

A) Thermal Performance

- **Base Case**

Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	4.145
R-Value (m2-K/W)	0.411
U-Value (W/m2-K)	**2.432**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.3250
Km - Internal heat capacity (KJ/m2-K)	179.8800
Upper resistance limit (m2-K/W)	0.411
Lower resistance limit (m2-K/W)	0.411
U-Value surface to surface (W/m2-K)	4.145
R-Value (m2-K/W)	0.411
U-Value (W/m2-K)	**2.432**

Figure 12: Thermal Performance of Base Case Façade (Source: DesignBuilder)

- **Retrofitted Model**

Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	0.266
R-Value (m2-K/W)	3.929
U-Value (W/m2-K)	**0.255**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.4980
Km - Internal heat capacity (KJ/m2-K)	179.8800
Upper resistance limit (m2-K/W)	3.929
Lower resistance limit (m2-K/W)	3.929
U-Value surface to surface (W/m2-K)	0.266
R-Value (m2-K/W)	3.929
U-Value (W/m2-K)	**0.255**

Figure 13: Thermal Performance of Retrofitted Case Façade (Source: DesignBuilder)

B) Operational Carbon

Operational Carbon ($kgCO_2e$) = Energy (kWh)×Carbon Factor ($kgCO_2e$/kWh)

For Sleaford House, the main mode of fuel type used is electricity for most of the appliances and heating. Assuming standard GHG conversion factor for UK electricity 0.22535 $kgCO_2e$/kWh (BEIS, 2024) consistent with the current SAP 10.2 methodology (BRE, 2022).

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	226933.70	200.96	200.96
Net Site Energy	226933.70	200.96	200.96

Figure 14: Total Site Energy of a Floor in Base Case (Source: DesignBuilder)

For base case the total site energy is 226,933.7 kWh (200.96 kWh/m^2), representing energy consumed directly on-site.

The Operation Carbon turn out to be **51,140 $kgCO_2e$/year** (≈51.1 tonnes CO_2e)

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	210609.15	187.66	187.66
Net Site Energy	210609.15	187.66	187.66

Figure 15: Total Site Energy of a Floor in Retrofitted Model (Source: DesignBuilder)

For the retrofitted model, the Operational Carbon comes out to be **47,460 $kgCO_2e$/year** (≈47.5 tonnes CO_2e)**,** marginally lower than the base case.

C) Embodied Carbon Calculation

Recycled Aluminium	14.352 tonnes CO2e
Mineral Wool Insulation	9.059 tonnes CO2e

Figure 1c: Embodied Carbon Calculation (Source: EC Calculator)

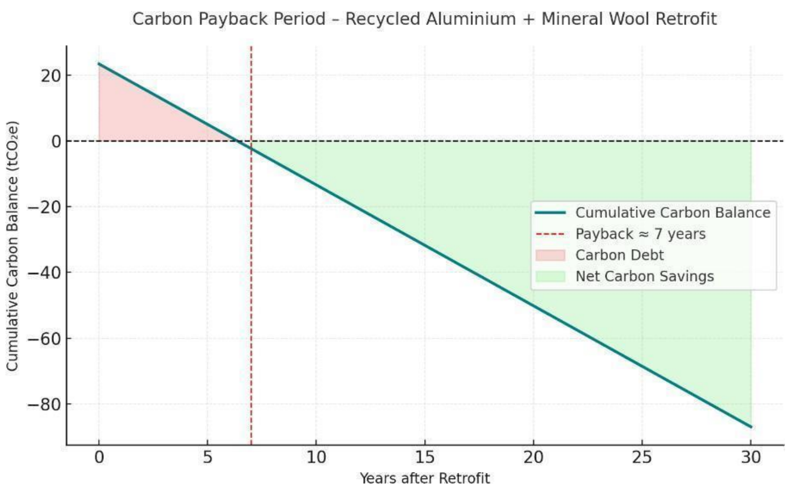
Here, the embodied carbon is calculated for the production of recycled aluminium and mineral wool insulation using the EC calculator. Since fasteners and other fixings were not included in the operational carbon calculation, they have not been added here.

D) Carbon Payback

Parameter	**Value**	**Unit**
Recycled Aluminium embodied carbon (A1–A4)	14.352	tCO_2e
Mineral Wool Insulation embodied carbon (A1–A4)	9.059	tCO_2e
Total Embodied Carbon of Retrofit	14.352 + 9.059 = 23.411	tCO_2e
Annual Operational Carbon Saving	3,680	$kgCO_2e/yr = 3.68\ tCO_2e/yr$

Table 3: Carbon Payback Table

Carbon Payback Period = 6.36 years



5.2 Design for Deconstruction and the Circular Economy

The DfD approach in the UK construction industry aligns with regulations such as the London Plan Circular Economy Statements (GLA, 2021) and ISO 20887:2020, which establish clear standards for the use of adaptable and dismountable materials. DfD for aluminium facades employs mechanical fixings like bolts, rails, or clips instead of adhesives or welded joints. This allows panels to be removed from the subframes without damaging the structure (Stacey, 2015; Sotech, 2024). The Sotech Optima rainscreen exemplifies a reversible and repairable design. It utilises modular aluminium cassettes mounted on removable rails. For high-rise retrofits, these systems comply with fire safety standards by meeting the A1/A2 non-combustibility requirements for façades over 18 m, as specified in the Building (Amendment) Regulations 2018 (MHCLG, 2018).

When the host building's service life ends, DfD ensures that aluminium panels can be removed quickly and with minimal damage to the material. The deconstruction process adheres to the life-cycle assessment (LCA) module outlined in BS EN 15978:2011.
These are stages C1-C4 (deconstruction, transport, processing, and disposal) and Module D which studies the advantages of recycling and reusing materials. At stage C1, the panels are unbolted to the subframe using mechanical tools or automated building facades. This ensures that the panels are safely removed with minimal contamination from sealants or insulation residues. Subsequently, the panels are transported to regional recycling centres like Hydro Aluminium or Novelis Latchford. Both centres process significant quantities of post-consumer aluminium scrap from UK construction sites (Hydro, 2023).

The processing is the C3 stage at which recovered panels are shredded and melted in rotary furnaces of low carbon. This uses approximately 0.7kWh/kg (95 times less energy than new aluminium production) (Hammond and Jones, 2008; BEIS, 2024). The resulting secondary ingots will be melted and re-extruded again to form new sheets that will be used again to build the exteriors of buildings. This recycling is closed loop and keeps the metal.

Structure of aluminium and lowers the embodied carbon values to as low as 0.49 kgCO_2e/kg, compared to 9.16 kgCO_2e/kg for new material (Hammond and Jones, 2008). Hydro (2023) states that their "CIRCAL" aluminium, which contains at least 75% post-
consumer scrap, has an average embodied carbon of 2.3 kgCO_2e/kg. This demonstrates that high-performance façade systems with minimal carbon impact are achievable.

If the panels are still structurally sound, direct reuse is a more environmentally friendly option than recycling. Panels can be cleaned, repaired, and reinstalled on other buildings, like low-rise extensions, social housing retrofits, or inside buildings, like partition walls and ceilings. Studies show that direct reuse doesn't require any remelting energy, which means that carbon emissions can be as low as 0.15 kgCO_2e/kg (European Aluminium, 2020). Stacey (2015) says that reusing one tonne of facade-grad aluminium can stop about 8.5 tonnes of CO_2e from being released into the air compared to making new material. This is the same as the emissions from almost 1,700 kWh of UK grid electricity (BEIS, 2024).

Design for Deconstruction also highly depends on effective information management. Akinade et al. (2015) claim that it is possible to track and retrieve the items in the future with the help of Digital Material Passports, their databases that store the origin of each panel, the type of alloy, and the coating aspect. This method combined with Building Information Modelling (BIM), might convert the facade into a bank of documented materials. The deconstruction teams in future will be in a position to scan QR codes located on panels to determine their mechanical properties, and strategize how they can be better used or recycled. The scheme for Extended Producer Responsibility (2023) introduced by DEFRA requires manufacturers to assume responsibility of materials during the entire lifecycle management. This scheme is based on this traceability framework.

The ease at which it interacts with mineral wool insulation systems is another factor that should be taken into consideration. Non-combustible mineral wool (class A1) is typically used in the UK as the aluminium facades helped in keeping the building warm and free of fire (Rockwool, 2023). Thus, a DfD-friendly facade should allow removing insulation slabs and aluminium panels without befriending. To ensure that the materials are capable of self-recycling and separation, mechanical retainers and dry-joint detailing are used. This may be evidenced by a project that Rockwool plans to undertake one day: Rocketcycle (2023), which involves use of stone wool used, then melted down into insulation items again. This forms a consecutive circular pattern whereby the cladding as well as the insulation is recycled into the manufacturing process.

From a carbon-accounting point of view, each loop of reuse or recycling makes a measurable difference under Module D of the whole-life carbon framework (RICS, 2023). Because aluminium can be recycled so easily, the environmental benefits add up over many generations of buildings. For instance, melting down one tonne of aluminium scrap saves about 13 MWh of energy and keeps 9 tonnes of CO_2e from being released (European Aluminium, 2020). If this is done systematically across the entire housing stock, it could save up to 1.5 $MtCO_2e$ of carbon over the 60-year lifespan of a typical UK high-rise (BEIS, 2024).

Despite the obvious advantages of DfD, as well as circular reuse, they are challenging to install. According to Stopps, Thorneycroft, and Touchie (2021), the consequence of a disrupted supply chain and not planning to break it down leads to contamination of materials or early scraping. The UK has limited standardisation of systems used to track alloys, coatings and fixings. There is these days an ISO 20887 (2020) that offers a formal structure to evaluate the adaptability and deconstructible nature of a product. In addition, economic disincentives do exist since most contractors would rather focus on the short-term cost reductions rather than on the long-term value of resources (Pomponi and Moncaster, 2017). These problems underline the necessity of fire laws, circular economy objectives, and procurement standards to be in agreement with each other.

New technologies are beginning to address these issues. AI-based material tracking and BIM can schedule maintenance and recovery in advance. Recent research has revealed the usefulness of optimisation of retrofit measures in the minimisation of the environmental impact of the current stock of buildings with systematic and versatile intervention. Piantanida et al. (2023) also focus on retrofitting methods to make the operation less energy-intensive and focus on making buildings part of larger energy networks, showing that a well-thought-out facade and envelope upgrades can reduce the anthropogenic impact to a considerable degree. Within the UK setting, these strategies can aid the shift to more versatile and resource-saving facade systems, especially in combination with design strategies that will enable future adjustment and material recycling. This is in line with Whole Life Carbon Roadmap of the UK Green Building Council (2021), which suggests measures of recoverable and adaptable technologies of facades as a source of reduction of lifecycle carbon emissions and enhancement of long-term sustainability.

To conclude, designing is where an outline is designed to be recycled rather than disposed of as a finite lifecycle, as in the case of recycled aluminum panels. Through reversible fixings, modular panelisation, digital material passports, and closed-loop recycling systems, aluminum cladding can be converted into a net resource asset, rather than being a high-carbon product. UK-specific frameworks such as the London Plan (2021), the RICS Whole Life Carbon Assessment (2023), and ISO 20887 (2020) offer a good guide to the ways of implementing such methods across the construction sector. One of the innovations that the UK can introduce to us when it comes to designing sustainable retrofitting is to think of buildings not as generators of waste but as material banks. As an example, consider today recycled aluminum panels which might become the foundation of tomorrow low-carbon buildings.

5.3 Conclusions

- The study shows that applying Circular Economy and DfD concepts in façade retrofitting can significantly reduce the carbon footprints of both the buildings and the work involved afterwards, especially after the war.
- Recycled aluminium rainscreen panels and mineral wool insulation work together to achieve the best balance between performance, durability, and recyclability. This enables designing for deconstruction without compromising fire safety.
- The carbon footprint of the proposed retrofit system will be compensated in approximately 6 7 years. Subsequently, it will become carbon-positive, i.e. will contribute to the improvement of the environment within the next 30-50 years.
- Social policy analysis reveals that such a framework as SHDF, ECO4, and HUG help to decarbonise social housing. But it is true that buildings in the heritage list are limited by conservation regulations that make profound retrofitting difficult.
- The DesignBuilder simulation method demonstrates that retrofitted façades significantly cut energy consumption and CO_2 emissions of a site, confirming that circular façade strategies benefit the environment.
- Limitations include dependence on secondary data, assumed construction details, and the exclusion of economic or social viability. However, the structured approach provides a consistent method for evaluating circular retrofits.
- The overall contribution that can be made in the dissertation is the creation of the framework-decision, which is a combination of the circles design, energy simulator, and life-cycle of the material.
- Future research should focus on bio-based alternatives, on-site material reutilisation, and digital material passports to expand circularity beyond aluminium-based systems and enhance overall building adaptability.

5.4 Contribution to Knowledge

The research will be enormous input towards the construct of academic literature on the subject of high-rise buildings retrofits, the integration of the circular economy, and the ecological friendly design of the facade. Firstly, it proposes a comprehensive methodological framework that combines the simulation of building performance (DesignBuilder/EnergyPlus) with the embodiment of carbon analysis (carbon as a design) and the assessment using the DfD concept regarding circularity. Throughout the paper, the use of operational energy and embodied carbon presents how the two have to be intertwined in regards to the retrofit measures in facilitating the achievement of the net-zero goals.

The research has input in the already existing body of knowledge on the circular economy of the built environment by offering a systems perspective to high-rise residential renovation. The study highlights the dangers of using energy-efficient technology implementation in the absence. considering end-of-life waste and material flows, which can perpetuate high carbon burdens (Densley

Tingley, 2022). It provides empirical evidence of how structural, regulatory and heritage limitations impact the feasibility of the the idea of the circular retrofit strategy in various settings by studying simultaneously the retrofit of Sleaford House and Trellick Tower.

These new aluminium rainscreen systems have mechanical, reversible fixings coupled with mineral wool insulation offering a retrofit solution that would meet the UK fire safety legislation (since Grenfell) and adhere to principles of circular material. The given design proposal helps fill in the existing literature gap when aluminium is usually neglected because of its high embodied carbon, but it is rarely considered in-depth in terms of recyclability, modularity, and DfD. The dissertation reinvents the definition of aluminium as a possible circular material to use in retrofitting high-rise buildings in that recycled-content aluminium and mechanical disassembly can influence embodied impacts along more than one lifecycle loop.

The comparative analysis of Sleaford House and Trellick Tower can enhance the knowledge of the diversity of retrofit in accordance with the building type. It is established that there is no universal retrofit approach and that each approach must be adapted to the local constraints such as the heritage status, structural capacity, risk-taking by the client and available funding (SHDF, ECO4, Historic England guidance). This background is of significance as significant amounts of retrofit research presuppose ideal situations or middle-rise, not complicated and limited high-rise estates.

Furthermore, the research improves practice by offering a clear decision-making matrix for stakeholders such as designers, housing associations, and policymakers. It integrates carbon performance with DfD metrics, adheres to rules, and considers the challenges of relocating components within a high-rise building. This approach aligns with the recent trend in literature towards whole-life decision frameworks (for example, combining total value of ownership approaches, Azcarate-Aguerre et al., 2022) instead of focusing on retrofit plans that only address energy.

In summary, the dissertation offers theoretical and practical contributions, including a replicable mixed-methods methodology, enhanced understanding of circular retrofit in high-rise environments, and a justifiable design solution featuring an aluminium rainscreen that balances performance, safety, and circularity.

5.5 Research Limitations

Even though this research has some good points, it's important to know its limits so that the results aren't overstated or misinterpreted. A principal limitation is the sole dependence on secondary data—published case studies, EPDs, the ICE database, and policy documents. These sources allow for breadth and comparability, but they don't show site-specific anomalies, variations in occupant behavior, or retrofit quirks that aren't reported. There is always some uncertainty when you move published performance data (like from other UK retrofit projects) to the case studies.

Simulation modeling at DesignBuilder was based on several assumptions because designbuilder could not access proprietary drawings or in-situ measurements. These have assumptions of how quickly the water will creep in, amount of heat that will be collected indoors, when human beings will be present and the circumstances at the edges. Although standard benchmarks, and calibrations were assumed, these assumptions might create dissimilarity in the results of simulation and the real-world performance, particularly in older stock, where airtightness is not recorded properly. Thermal bridging and facade-edge effects are also simpler to comprehend in the model. The effects are huge potential contributors to energy performance in tall buildings, but they are difficult to model in software.

The research employed average embodied carbon parameters of ICE and EPDs in the analysis of embodied carbon. These aspects do not necessarily indicate the distance of shipping a product or its manufacturing. Since sensitivity/uncertainties analysis is not carried out, the results of embodied carbon should be treated as approximate and not precise. Such a drawback is common to retrofit studies, although it limits the degree of confidence in the evaluation of specific material selections.

The case study methodology precludes generalization. The two buildings - Sleaford House and Trellick Tower, are quite contrasting and yet they do not represent the entire high-rise building in the UK. Structural systems, maintenance history, tenant dynamics and climatic changes have big differences and may influence the outcomes of retrofitting.

Markedly, cost and financial viability were not taken into consideration. The analysis focuses on carbon and circularity indicators, but it does not involve the life cycle cost modelling and the net present value calculation which is extremely critical to enable the stakeholders to make a decision. Otherwise, suggested retrofit variants may seem good in technical terms, but they may not be affordable.

Likewise, there was no empirical investigation of stakeholder engagement and social variables resident acceptability, disruption during retrofit, and long-term maintenance commitments. Such less concrete features tend to influence the effectiveness of the results of a retrofit in practice and may indicate shortcomings or opportunities which are outside the technological or policy scope.

Finally, the paper will concentrate on the UK with references to British standards, policies, and climate. The applicability of lessons to a wider context might exist; but there is a limited ability to transfer lessons to other countries with different regulation structures or energy systems.

The study has been found to have its limitations, but it has its value as an exploratory and methodologically valid contribution but not a conclusive frame work.

5.6 Future Research

The results and limitations indicate various promising directions for future research to enhance and build upon this study.

Empirical Validation C Post-Occupancy Evaluation (POE): The next step would be to apply measured operational data of retrofitted high-rise buildings, preferably after several seasons. Comparing the outcomes of the simulations to the actual performance would assist in order to refine the assumptions of the models, improve the confidence, and indicate the discrepancies between the actual and expected performance of the stock particularly when it is old. Incorporating indoor environmental quality (IEQ) indicators such as occupants thermal comfort, humidity and addition of occupant satisfaction to this would render the retrofit assessment more helpful than merely observing energy and carbon.

Lifecycle Costing C Financial Models: Full life cycle costing (LCC) would entail incorporating capital costs, maintenance, replacement, and deconstructed salvage values would be in the form of making decision-making easier in terms of making retrofitting decisions. The combination of the Life Cycle Costing (LCC) and Total Value of Ownership (TVO) frameworks such as that suggested by Azcarate-Aguerre et al. (2022) would simplify making more practical trade-offs between the carbon emissions, the circularity, and the cost-effectiveness.

Enhance Material Innovation Research: Future research has to focus on hybrid bio-based facade systems (sandwich panels made of recycled aluminum alloy), and new materials (e.g., recycled aluminum alloys, better metal coating) because this study focused on mechanical connections in aluminum rainscreen systems. These research works should include sensitivity analysis in terms of embodied carbon and recyclability possibility.

Future Advanced DfD and Component Grading Shells: In the future, probabilistic models of structural performance classifications with circularity selection options can be combined with probabilistic gradient grading approaches to reusable components (e.g., Meng et al., 2025). Similarly, expanding the range of deconstruction design taxonomy (Pristerà et al., 2024) into the context of high-rise retrofit would make the strategies of DfD customized to real buildings.

Broader Comparative Studies The approach to wider samples of towers (in other areas and structural types and heritage status) would demonstrate the strength and generality of the method. A comparison of retrofit results in climates with varying climates (e.g., Scotland and southern England) can bring out localized optimization patterns.

Stakeholder and Behavioral Research: Face to face engagements amid residents, housing associations and local attorneys and contractors using interviews or survey would clarify operational constraints perceived risk, and perceived maintenance anticipations are determinants of retrofit uptake. These kinds of socio technical insights may be embedded on decision- making models.

Digital Tools C Material Passports: More work and testing of BIM-enabled material passports, circular twins, and circular tracking of supply-chain could make it a reality to make projects circular in retrofit projects. On-site assembly to end-of-life traceability is particularly an opportunity to develop a circular governance of buildings.

Policy and Regulatory Analysis: The UK retrofit policy is undergoing rapid transformation, thus, future research ought to explore the role of ongoing redefinitions of the EPC requirements, post-Grenfell facade regulation and net-zero policy facilitation in influencing the feasibility of retrofitting. This involves creating models of funding schemes such as SHDF, and analyzing how relaxations or incentives regarding heritage level can benefit with circular retrofit.

In conclusion, the dissertation is a preliminary move in the direction of unifying objectives in a carbon management, retrofit performance, and the circular economy in high-rise residential towers. The subsequent stage of research must validate, develop and expand these concepts across the levels of empirical, financial and material as well as socio-political dimensions. By doing this, the bigger retrofit collective will be able to pursue solutions that are not only low-carbon, but also robust, adaptive and aligned with the circular future.

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7. Appendix

Flat 10
Sleaford House
Fern Street
LONDON
E3 3PY

Energy rating

C

Valid until	Certificate number
31 August 2035	**3909-2695-7002-0078-0102**

Property type	Mid-floor maisonette
Total floor area	70 square metres

Rules on letting this property

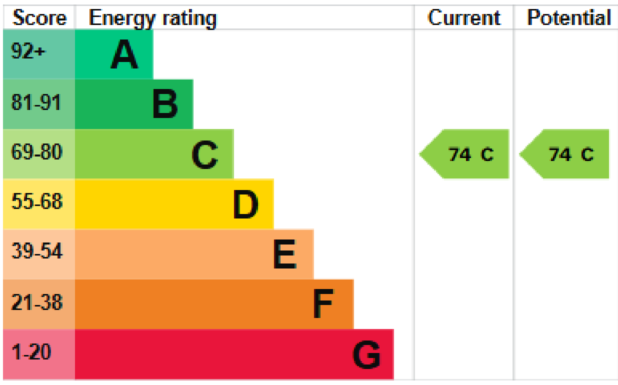
Properties can be let if they have an energy rating from A to E.

You can read guidance for landlords on the regulations and exemptions.

Energy rating and score

This property's energy rating is C. It has the potential to be C.

See how to improve this property's energy efficiency.



The graph shows this property's current and potential energy rating.

Properties get a rating from A (best) to G (worst) and a score. The better the rating and score, the lower your energy bills are likely to be.

Figure 17: EPC Certificate for Sleaford House from GOV.UK Website

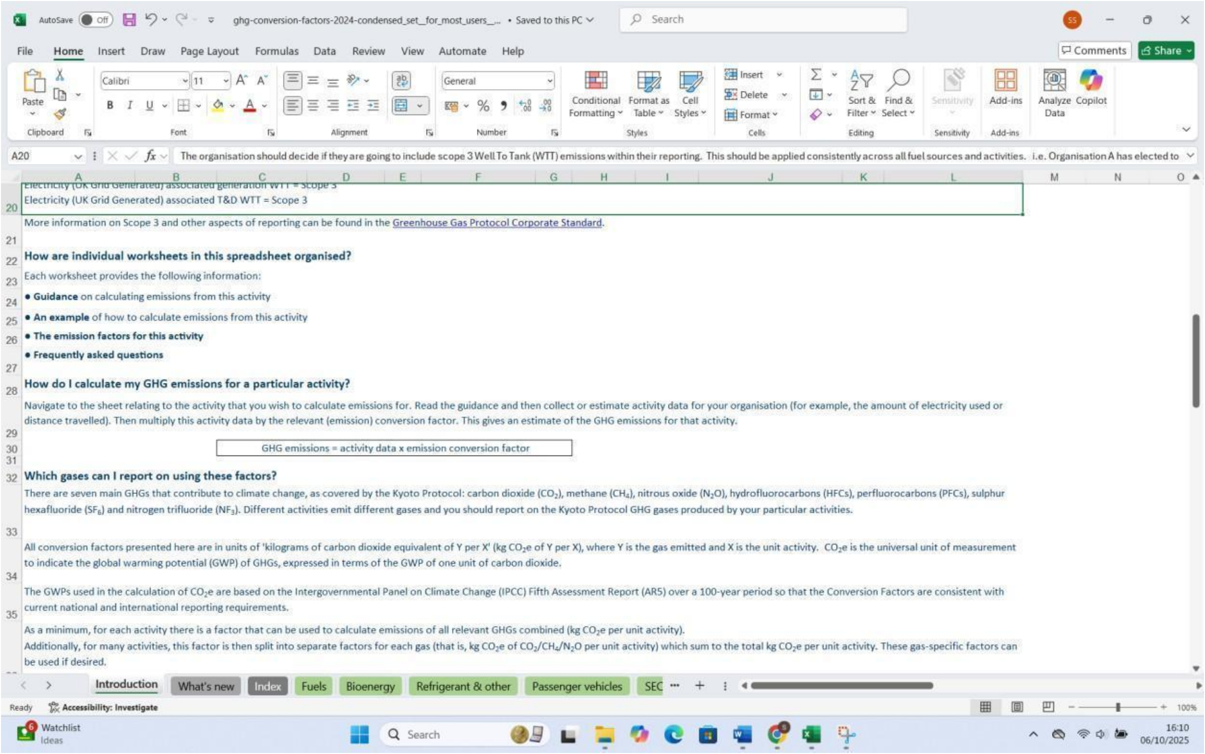


Figure 18: GHG Conversion Factors 2024 for GOV.UK

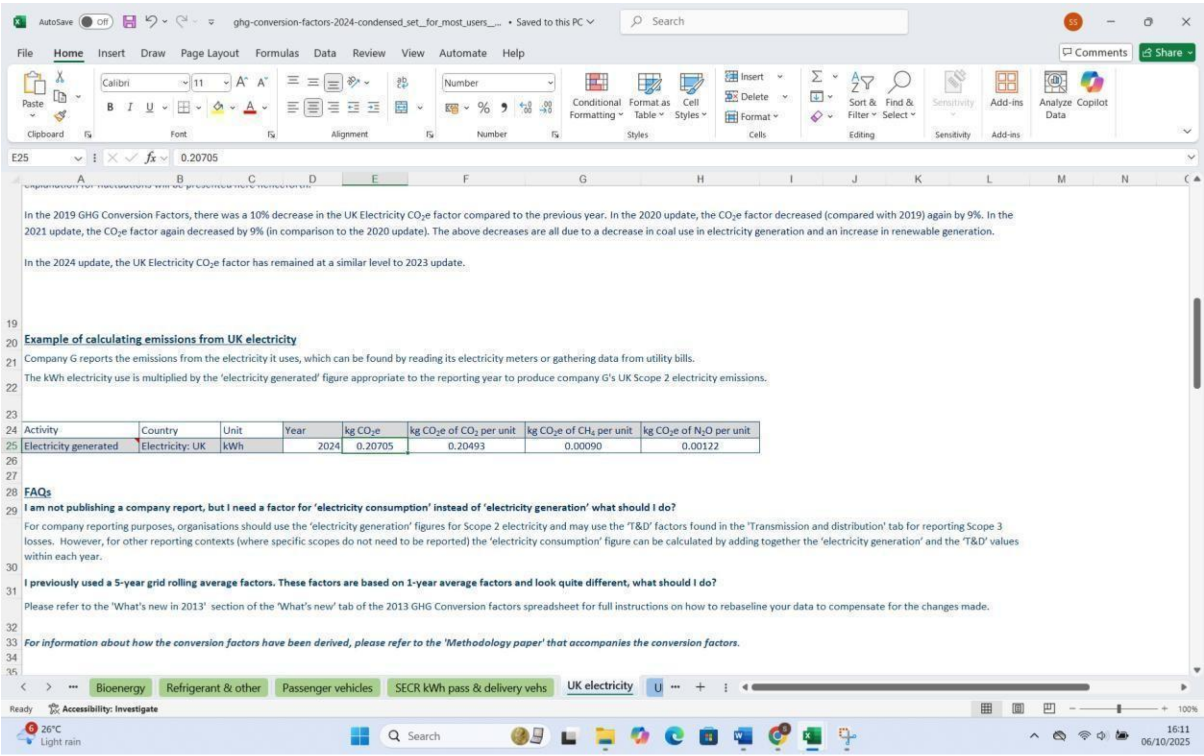
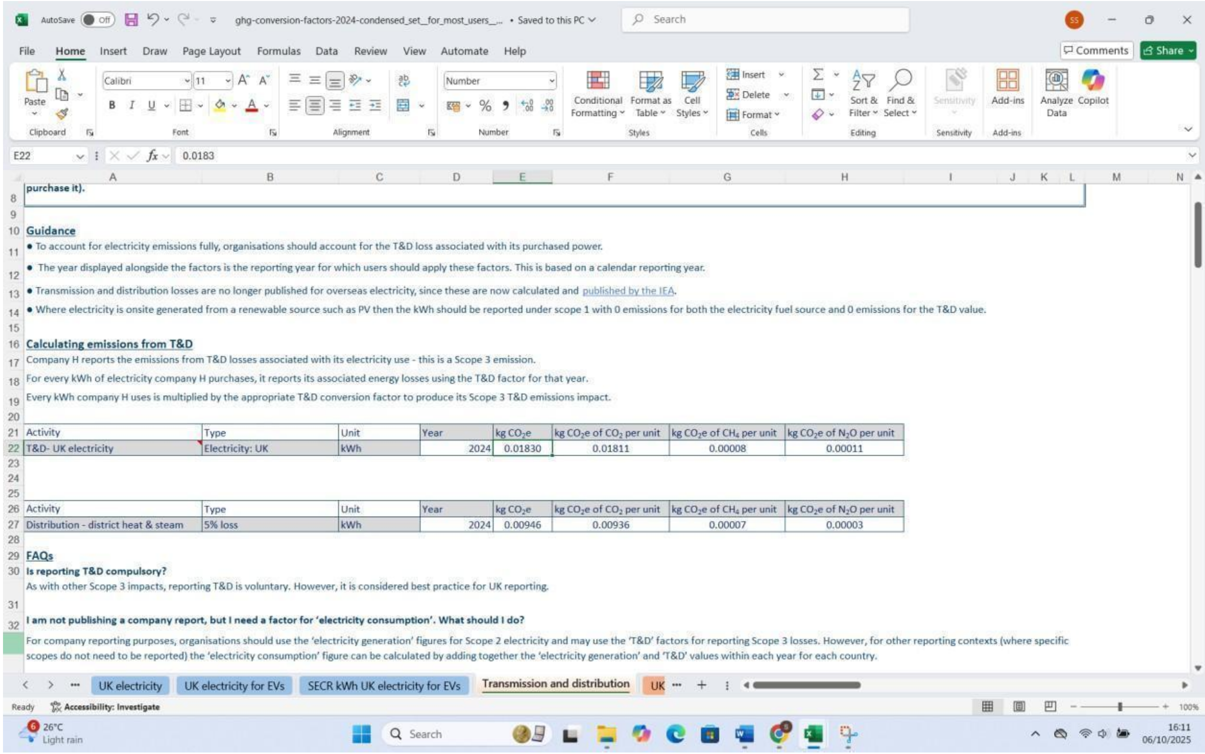


Figure 1S: GHG Conversion Factors 2024 for electricity



purchase it).

Guidance

- To account for electricity emissions fully, organisations should account for the T&D loss associated with its purchased power.
- The year displayed alongside the factors is the reporting year for which users should apply these factors. This is based on a calendar reporting year.
- Transmission and distribution losses are no longer published for overseas electricity, since these are now calculated and published by the IEA.
- Where electricity is onsite generated from a renewable source such as PV then the kWh should be reported under scope 1 with 0 emissions for both the electricity fuel source and 0 emissions for the T&D value.

Calculating emissions from T&D

Company H reports the emissions from T&D losses associated with its electricity use - this is a Scope 3 emission.

For every kWh of electricity company H purchases, it reports its associated energy losses using the T&D factor for that year.

Every kWh company H uses is multiplied by the appropriate T&D conversion factor to produce its Scope 3 T&D emissions impact.

Activity	Type	Unit	Year	kg CO_2e	kg CO_2e of CO_2 per unit	kg CO_2e of CH_4 per unit	kg CO_2e of N_2O per unit
T&D- UK electricity	Electricity: UK	kWh	2024	0.01830	0.01811	0.00008	0.00011

Activity	Type	Unit	Year	kg CO_2e	kg CO_2e of CO_2 per unit	kg CO_2e of CH_4 per unit	kg CO_2e of N_2O per unit
Distribution - district heat & steam	5% loss	kWh	2024	0.00946	0.00936	0.00007	0.00003

FAQs

Is reporting T&D compulsory?

As with other Scope 3 impacts, reporting T&D is voluntary. However, it is considered best practice for UK reporting.

I am not publishing a company report, but I need a factor for 'electricity consumption'. What should I do?

For company reporting purposes, organisations should use the 'electricity generation' figures for Scope 2 electricity and may use the 'T&D' factors for reporting Scope 3 losses. However, for other reporting contexts (where specific scopes do not need to be reported) the 'electricity consumption' figure can be calculated by adding together the 'electricity generation' and 'T&D' values within each year for each country.

Figure 20: GHG Conversion Factors 2024 for electricity

Calculation for Embodied Enegy

Step 1: Material Mass per m²

- Recycled Aluminium (3 mm thick)
  Density = 2700 kg/m³
  Thickness = 0.003 m
  Mass per m² = 2700 × 0.003 = 8.1 kg/m²

- Mineral Wool (120 mm thick, density ~140 kg/m³)
  Thickness = 0.12 m
  Mass per m² = 0.12 × 140 = 16.8 kg/m²

Step 2: Total Mass for 442.4² m (from designbuider)

- Aluminium: 8.1 × 442.4 = 3,580 kg ≈ 3.58 tonnes

- Mineral Wool: 16.8 × 442.4 = 7,430 kg ≈ 7.43 tonnes

Step 3: Embodied Carbon Factors (ICE v3 / EAA, 2020)

- Recycled Aluminium: 4.0 tCO_2e/tonne

- Mineral Wool: 1.2 tCO_2e/tonne

Step 4: Embodied Carbon Totals

- Aluminium: 3.58 × 4.0 = 14.3 tCO_2e
- Mineral Wool: 7.43 × 1.2 = 8.9 tCO_2e

Total embodied carbon = 23.2 tCO_2e (≈23.3 tonnes CO_2e)