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Net zero retrofit of older tenement housing – The contribution of cost benefit analysis to wider evaluation of a demonstration project☆

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ABSTRACT

The United Kingdom is legally committed to net zero by 2050; Scotland by 2045. How much will retrofitting older homes contribute to meeting net zero? What lessons can we learn from demonstrator projects? We present results from a social cost-benefit analysis of a demonstrator retrofit carried out on a Victorian tenement building in Scotland. The paper discusses the process and implications of this analysis, while also providing lessons learned from the wider evaluation. The cost-benefit analysis indicates that retrofitting provides better social value than demolition and new building in this project. However, the optimal amount of investment in retrofitting is sensitive to the assumptions made. Furthermore, the wider evaluation findings suggest it may be difficult to transport findings from any one setting to another. Local context matters.

1. Introduction

The United Kingdom has committed to ambitious net zero targets (2050 for the UK; 2045 for Scotland). Around one fifth of carbon emissions come from the built environment. In Scotland, 80–85% of the total housing stock that will exist in 2045 is already built, even with high volumes of new build housing over the next 20 years (Scottish Government, 2021), Therefore, we must find ways to retrofit our existing housing, much of it older and sometimes in poor condition, to meet net zero.

How much will retrofitting older homes contribute to meeting net zero? What lessons can we learn from demonstrator projects? In this paper, we present findings and lessons learned from the cost-benefit analysis of a retrofit demonstration project. The project was a green retrofit of a Victorian tenement block in Glasgow, Scotland. It sought to meet the EnerPHit standard. The EnerPHit standard is a set of high efficiency 'fabric first' criteria for retrofitting existing housing and was developed by the PassivHaus institute. To meet the standard, retrofitted homes must show substantial reductions in energy demand for heating and cooling, as well as airtightness and insulation improvement. This means the project was a "deep" retrofit in that it installed multiple improvements at the same time and took a systems approach to reduce energy use (see BEIS, 2021a). This demonstrator project was a partnership between the city council and a local housing association, working closely with a firm of conservation architects and an innovative construction contractor. Renewable energy sources were funded by the Scottish Government. The partners worked with an academic team that led a holistic evaluation of the project, financed by the Scottish Funding Council.

Modelling of deep retrofits gives potential energy use reductions of up to 90% (Mohammadpourkarbasi et al., 2023; Sierra-Pérez et al., 2018). Actual measured performance also shows substantial gains: Jones et al. (2013) showed 60–74% CO_2 emission reductions for houses in Wales; a meta-analysis of 116 deep retrofits in the U.S. found average energy savings of 47% (Less and Walker, 2014); Gupta and Gregg (2016) found CO_2 reductions of 57–75% in south England; and a UK government review of the literature found reductions of 35–56% (BEIS, 2021a). There is disagreement in the literature on how financially viable they are for homeowners. Some studies find relatively quick pay-back periods for retrofits (Massimo et al., 2021; Yu et al., 2011; Kok et al., 2012), while others find pay-back periods may be much longer, and some retrofits may never pay-off (Jones et al., 2013; Liu et al., 2018). These studies show the pay-back period can depend on local context, climate, and the assumptions in the analysis. Crucially, however, the pay-back in these studies does not include the social value of abated greenhouse gas emissions, or other non-market values such as health benefits. Only one

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deep retrofit study we are aware of includes the value of greenhouse gas abatement: Colclough (2021) finds a Benefit-Cost Ratio (BCR) of 1.9 for a social housing deep retrofit in Wexford when these values are included. An additional problem is the behavioural response of housing occupants, who may decide to use the energy savings to consumer more energy. This is known as the “rebound effect” (see Sorrell et al., 2009). This may be one reason why forecast energy savings from deep retrofits tend to be lower than realised savings (BEIS, 2021a).

Our study provides evidence on the value of retrofitting older housing stock while including non-market values and the potential behavioural response occupants. We carry out an orthodox cost-benefit analysis (CBA) which follows the UK government Treasury’s guidelines. We include the value of abating greenhouse gas emissions, and other non-market values. We model the behavioural response of households via the rebound effect and show how this affects our findings. Finally, we go beyond the results of the cost-benefit analysis and present findings and lessons learned from the full, holistic evaluation of this green retrofit project. We provide background to the study, set the project in the context of contemporary policy debates and the many challenges in developing a tenement strategy for retrofit. We explain how the project took shape and how the holistic evaluation of it was conceptualised and structured. The paper then sets out the cost benefit analysis methods used, the model’s key results against two counterfactuals and also presents the results of sensitivity analysis. The paper’s conclusions discuss the implications of this analysis but also reflects more widely on lessons emerging from the integration of the CBA with the wider evaluation process.

The CBA findings indicate that deep retrofitting provides better social value than demolition and new building in this project. However, the optimal amount of investment in retrofitting this building is sensitive to the assumptions made in our analysis. Our discussion of the CBA process suggests that similar projects should work closely with architects, builders and local context experts, such as social housing associations, to ensure accurate estimates of costs and benefits. The wider evaluation findings we present suggest that it may be difficult to transport findings from any one setting to another. The local legal and economic context matter. Heterogeneity in housing type and quality matters. The logistics of retrofitting a block of flats all at once, compared to a single household, also matter. We end the paper with a discussion of possible directions for future research.

The paper presents new knowledge, supports aspects of retrofit policy and practice thinking, and also takes a strong and consistent methodological approach to the social cost benefit analysis (SCBA) undertaken. This is the first such SCBA of a field retrofit in Scotland. It presents findings for a typical Victorian urban tenement, of which there are more than 70,000 such properties in Glasgow alone. It demonstrates the value of retrofit versus demolition and new build but also the sensitivity of retrofit options to the assumptions applied – we make these assumptions explicit. This new knowledge has fed directly into tenement housing strategy in the city where the council had been working in the dark regarding the relative magnitudes of costs and benefits. The project was also expensive in upfront capital costs, but this has to be traded off against the long-term net benefits of the project. Furthermore, the wider holistic evaluation suggested that the deep retrofit had generated large scale savings on energy costs for residents but also that near equivalent net benefits could be generated with less arduous standards than EnerPHit (Gibb, et al., 2023).

The paper follows a robust orthodox approach to SCBA, drawing on official government analytical good practice and official measures of, for example, carbon emission valuations (and their sensitivity); also, adopting standard norms for key parameters such as the ‘rebound’ effect and optimism bias, drawing on the UK Treasury Green Book, the (then) BEIS and DLUC departmental guides to analysis.[1] Allied to the rich data available for costs on the retrofit project and the two counterfactuals used (see below for details), the resulting analysis has the key merits of avoiding questionable assumptions or other non-typical parameters or variables. It starts from a stronger perspective from an analysis review point of view and is internally consistent and defensible. We see this robustness as an essential pragmatic way to deliver credibility in the eyes of third parties such as funders, investors and policymakers. It also strengthens the holistic multi-level evaluation of the project, in terms of learning lessons and transferability.

2. Background

2.1. Policy background

Successful housing retrofit to achieve decarbonisation is a complex policy problem (Gibb, 2022). First, the existing housing stock varies considerably in terms of its alignment with different interventions, and also may require more basic physical repairs and improvements. Second, the ownership of specific property types, such as tenement flats, will often be varied with mixed tenure present within many tenement blocks. This creates difficulties gathering group contributions to common works and retrofitting of all units in a block. Private owners have quite different incentives from non-market social landlords and commercial landlords. Third, there is no definitive position on technical solutions to achieve decarbonisation and this lack of clarity sits alongside a range of funding or subsidy mechanisms and assumed co-financing by property owners (Green Finance Institute, 2020). In a devolved setting like in the UK, subsidised funding and delivery measures can come from local government, the Scottish Government or from the UK government (Grant Thornton, 2021). This is not always well-organised in terms of choices that owners can make. Fourth, there are a series of important transactions costs that inhibit retrofit: large upfront costs, searching for information and funding help, reliable tradesmen and contractors, the inconvenience of carrying out the work, and collaborating with a wider local group of residents where larger scale projects are required. Fifth, many are inhibited by problems of the overall expense of interventions, as well as concerns about the effectiveness of unknown heating systems.

All of this is combined with considerable uncertainty about the policy and technical landscape. There are several levels of uncertainty. First, Scottish tenement law, supposed to ascribe a comprehensive basis for collective action among owners, is inadequate. Currently, the Scottish Law Commission is considering introduction of condominium type arrangements as standards for dealing with common repairs alongside mandatory regular inspections and a repairs sinking fund. This will take considerable time to be legislated for and implemented, but it is essential if retrofit work is to be consistently advanced in the tenement sector.

Second, there is no consensus underlying the relative importance of fabric first retrofit versus the choice and significance of zero emission domestic energy systems. Fabric first designs focus on the design of the building and materials used, such as the insulation and windows, rather than a focus on additional items such as the type of heating system, or adding solar panels to housing. There is also debate over the necessity of adopting high level fabric first insulation, airtightness, etc., prior to choosing the forms of heating in buildings (NESTA, 2021).

Third, there is considerable disagreement among built environment professionals and the policy community about the appropriate measures

[1] BEIS was the Department for Business, Energy and Industrial Strategy, now the Department for Energy Security and Net Zero (DESNZ)’ DLUHC is the Department for Levelling-up, Housing and Communities.

and standards to use when articulating the minimum achievable form of retrofit intervention. Below, we focus on the EnerPHit standard,[2] but this is far from the only choice to achieve deeper forms of green retrofit for older properties like pre-1919 tenements. Social housing has actively contributed to debates within government about setting standards that they will have to apply across the social housing sector in Scotland.

Finally, there has been a reluctance to apply robust methodologies to provide cost-benefit or cost-effective measures of intervention value for money. Estimated costs of retrofit to society are huge and in the billions of £s for Scotland alone (the Scottish Government, 2021; assumed a total cost of **£33 billion**), as well as for the Glasgow City Region (Grant Thornton, 2021, estimated a central forecast cost of between **£4–20 billion**)). This study is a formal cost-benefit analysis based on conventional UK Treasury Green Book methods, applying government good practice on the valuation of carbon and other sustainability dimensions of such appraisals such as the treatment of counterfactuals and other known challenges with environmental interventions e.g. behaviour change by recipients.

2.2. The Niddrie road project

The demonstration project consisted of a sandstone tenement block of eight one bed flats with a single walk-up close in the inner south side of Glasgow, in a high-density tenement-dominated part of the city (for full evaluation see Gibb et al., 2023). The property was built in the 1890s and had been in the private rented sector with one landlord owing seven of the eight properties. Fig. 1 shows the property after completion of the retrofit (the retrofitted block is to the right with the red close door).

The project emerged out of a city council policy to reduce the dominance of private renting in certain neighbourhoods by enabling, through financial support, social landlords (housing associations) to purchase empty blocks to improve them, converting them into social housing. In 2019, the city council asked Southside housing association, who had already been involved in these acquisition programmes, if they would like to take on the properties in Niddrie road, offering support to purchase and improve the properties. The housing association had engaged a conservation architect, John Gilbert Architects, to provide options for the level and type of property improvement and the initial likely solution was to provide a high level of energy efficiency standards across the eight units.

Fig. 1. Photo of Niddrie road, post construction, 2023

However, in the autumn of 2019, another option arose. The housing association noted that the Scottish Funding Council (SFC) had launched a Climate Emergency Competition for research projects that could make a significant impact on climate change. Having secured the agreement of housing researchers at the UK Collaborative Centre for Housing Evidence (researchers for the project were based at the Universities of Glasgow and Strathclyde) to lead the evaluation, a partnership involving the academics, the council, the housing association, the architects and a construction firm was rapidly assembled. Critically, they decided to opt for a fourth retrofit solution which was an EnerPHit (PassivHaus equivalent) standard for the retrofit, something made possible because the housing association had control of the entire tenement block. This was a more ambitious and potentially expensive standard, but one that would make the project a learning and scaling environment for the city's emerging tenement strategy as well as being important to the many local housing associations with tenement stock in their portfolio.

A holistic evaluation, involving measurement of domestic energy consumption, post-occupancy survey, process evaluation of key decision making through the life of the project, as well as a formal cost-benefit analysis, was approved. The evaluation and build project were launched in 2020 just three weeks before the UK's first lockdown as a result of the Covid-19 pandemic.

After the design stage was complete, the project involved external wall insulation to the rear and gable end of the property with internal wall insulation for the front of the building. There was internal remodelling of the property, e.g. increasing the size of rear windows, as well as installation of mechanical ventilation and wastewater heat recovery, as well as external works to repair the sandstone frontage and aspects of the roof. Critical to the retrofit was airtight plastering of the properties with lime mortar. Further details are summarised in Fig. 2.

Due to Covid-19 and other delays associated with planning permission, the construction phase did not end till the summer of 2022, and after extensive testing, the properties were let to social tenants in the autumn of that year.

The project faced and overcame a number of challenges that are germane to the cost-benefit analysis discussed below. First, the project had to overcome city council planning policy for older tenements which initially did not allow external wall insulation, nor did it allow photo voltaic panels on the roof or heat pump units attached to the back of the building. In the end, the lower two floors of the building used heat pumps connected to units in a shed in the back, with modern gas boilers on the top two floors. External wall insulation was in fact eventually permitted. Second, funding was secured from the city council and the Scottish Government, but the largest share came from the housing association's private finance (and ultimately, tenant rental income). Costs were high but after one subtracts the acquisition costs and the basic improvements to make the property lettable to contemporary standards, the actual deep retrofit cost around £35–40,000 per unit. This is still a very significant cost and one closely related to the detail and extent of the work required.

How might one summarise the outcomes at Niddrie road? What follows is the results so far from the full, holistic evaluation (Gibb et al., 2023). There are now eight social tenants living in modern, warm, energy-efficient (and low-cost energy) traditional tenement flats. In terms of technical performance, interim monitoring results indicate that

[2] In the UK the most widely used standard of energy performance is the Standard Assessment Procedure (SAP), which is needed for granting buildings mandated Energy Performance Certificates. For reasons we outline in the methodology section we do not use this.

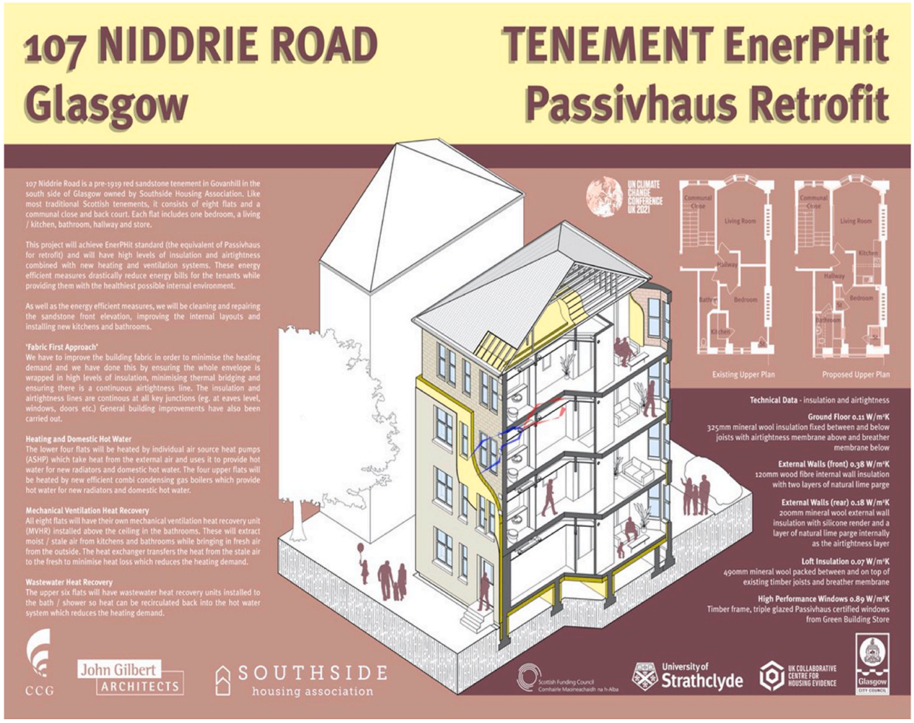

Fig. 2. Diagram of the project works.

the retrofit has successfully reduced energy consumption to the targeted level. This reduced energy usage is not at the expense of occupant comfort. Indoor temperature readings show good levels of heat throughout the homes, and occupants report themselves better satisfied with thermal comfort than in their previous homes.

However, while performance measurement is still underway, the team expects the properties to not quite make the EnerPHit standard, as a result of a small number of cold spots that prevent 100% airtightness. Nonetheless, the team still expects that fuel bills will be radically reduced by an order of 75–80%.

In the rest of the paper, we focus on our cost-benefit analysis, which generates positive conclusions about the social net benefit of the Niddrie Road project. This may provide information and guidance to spending departments across Government in the UK, and it also sets the high-cost levels in context with both a deep retrofit and the comparative costs of counterfactuals, stressing the importance of embodied carbon costs. At the same time, this is, we believe, a robust empirical analysis following current good practice in a way rarely observed in this broad policy space. Together, it helps to provide a more balanced account of a radical demonstrator of a deep green retrofit.

3. Methodology and data

The primary goal of the cost-benefit part of the evaluation was to adhere to a strict, orthodox social cost-benefit analysis while incorporating "non-market" values, such as the cost of greenhouse gases, and including potential behavioural responses from tenants (i.e. rebound effects). By social cost-benefit analysis, we mean one which considers all costs and benefits that can be expressed in monetary form which are borne by the people of the UK. By non-market values we mean monetary values of factors which are not bought or sold in a market, and which therefore are assigned monetary values through alternative means. By orthodox we mean adhering to UK government Treasury "Green Book" guidance. The Green Book is used across all central and local government departments in economic appraisal and evaluation. The Green Book has been supplemented with guidance from Department for Communities and Local Government (DCLG) and the Department for Energy Security and Net Zero (DESNZ, formerly the Department for Business, Energy and Industrial Strategy) for economic appraisal on valuing housing and greenhouse gas emissions, respectively. By adhering to the widely used, orthodox approach we hoped our results would be recognised as consistent with and comparable to government cost-benefit analysis of investments, avoid any sense of 'special pleading' in the model construction, and therefore more policy relevant.

Social cost-benefit analysis provides final figures as Net Present Values (NPV). A NPV is *net* in the sense that it is benefits minus costs. It is *present* because costs and benefits in the future are discounted compared to the present, and so future values are converted into the value they are worth today. There are several reasons for discounting future values. Firstly, it accounts for inflation. Secondly, it allows comparison of projects which have different cost and benefit profiles over several years. Thirdly, it incorporates the fact that individuals typically value the real (as in after inflation) value of cash more in the present than that same real value in the future (e.g. see Warner and Pleeter, 2001). Fourthly, it accounts for economic growth, i.e. that over the long-run per-capita income has grown in real terms, which means a society is materially richer in market goods and services in the future compared to the past. Fifthly, it accounts for the *social* choice in time preferences, which may be different from any simple aggregation of individual time preferences. Finally, it accounts for the opportunity cost of capital. To retrofit the tenement, we must use resources that we could have simply invested for a relatively "risk-free" rate of return. In all our calculations, we used the standard UK government social discount rate of 3.5% a year. This is the rate the UK government recommends future costs/benefits are discounted due to all the above factors. This is applied after discounting for inflation. In summary, first we estimate the nominal costs and benefits for each year. Then we take the estimated deflator from the Office for National Statistics (ONS) GDP deflator forecasts, we multiply the nominal amounts by 100 × the deflator to remove the effects of inflation and obtain real values. Finally we discount each year's real values using the 3.5% rate. So values one year ahead of 2022 were worth only 96.5% of the real values estimated, i.e. X is worth X × (1–0.035) if it comes next year. Values two years ahead are discounted twice, so are worth 93% — X × (1–0.035) × (1–0.035).[3]

We took the inflation discount from the Office for National Statistics (ONS) GDP deflator forecasts, as standard in government appraisal. NPVs were presented in cash terms, but as a secondary outcome we also used benefit-cost ratios (BCR). BCRs are used extensively in government to compare different projects. They give insight into the marginal value of using resources on one project compared to another, whereas the NPV gives insight of the total value. If a BCR is greater for one project compared to another, it means the last pound spent on it gives more value than the last pound spent on the comparison project.

Fig. 3 shows how a CBA appraisal works, with the NPV of some investment option calculated, as well as the NPV of some counter-factual option, before finally comparing two NPVs against one another.

3.1. Assembling the counter-factual

In standard cost-benefit analysis, the retrofit option would be compared to a "business-as-usual" scenario to see whether it gave more value that the status-quo. However, in conversations with the housing association, it became clear there were several possible choices that could be made. In some cases when they have purchased a property, they will knock down the old building and construct a new one to lease to tenants. In other cases, they will perform a refurbishment as well as the retrofitting that is expected to be required by law in the future from landlords. For the purposes of this project, we took the required future standard to be the Energy Efficiency Standard for Social Housing post 2020 (EESSH2).[4] Therefore, we settled on two counter-factuals to compare to the EnerPHit retrofit. These were called "New Build" and "EESSH2" respectively. The main scenario we called "EnerPHit".

Data were assembled from a variety of sources. The main sources were from the housing association, the construction firm, and the architects. An additional resource for non-market values was the guidance given by DESNZ on pollutants and the social value of greenhouse gas abatement. Finally, we also used good-practice estimates derived from the literature on embodied greenhouse gas emissions used in construction, typical rebound effects, optimism bias and the social value of a tenancy. These are further explained in section 4.

3.2. Cost data

Cost data for the retrofit and both counterfactuals was constructed with the help of the housing association, the construction firm, and the architects. The retrofit project costs were £1.295 million in 2022 pounds. The cost of acquisition was £60,000 per unit. The combined cost per unit of the EnerPHit retrofit and refurbishment was initially £88,000 consisting of £44,000 for the basic refurbishment of the vacant properties plus £32,000 for the initial cost of the EnerPHit retrofit and £12,000 for contingencies. Once on site, the costs per unit rose because of further costs incurred arising from unanticipated problems with the condition of the property e.g. requiring to strip the building back to the bare bricks because of the condition of the plasterwork (note that these realised increases over the two years apply both to the EnerPHit retrofit and the costs of the originally proposed basic refurbishment of the tenement compared to the original costs).

The cost data for the counterfactuals was initially constructed only from historical data from previous housing association projects. There included both new buildings and retrofits/refurbishments. However, the plausibility of this data matching the counterfactual costs for the Niddrie Road project was challenged by the architects, who argued that the Niddrie Road property, due to location, age and its dilapidated state, needed additional modelling to be comparable. It was also the case that we were relying on the relatively sparse data available to the housing association, who only had a few recent projects they could share cost data from. Therefore, the authors worked with the architects to remove the costs associated with initial refurbishment, which was needed to make the Niddrie Road legally habitable, and to model the costs of the counterfactuals based on the historical data, but with Niddrie Road property characteristics taken into account (such as location). The net result of this was the cost profiles for the main project and the counterfactuals were around 50% less once these factors were considered. The relative difference in costs was largely unchanged between the project and the counterfactuals, but it did mean that each option was more likely to have a positive NPV than before the change.

The largest element of the cost data was the initial capital costs of building, demolition, and installation of materials. The second largest cost was the maintenance over the 30-year period and the factor management fees. Unique to the "New Build" counterfactual was the additional costs of embodied carbon. This is the greenhouse gas emissions created by the demolition and construction of the new flats (including transport of materials and use of building supplies and machinery specific to demolition and new build). More details on the values used for greenhouse gas emissions are below. The exact amount of embodied carbon for the counterfactual new build can only be estimated. Initially, we planned to produce a fully modelled estimate using modelling software for embodied carbon usage. However, given the many unknowns in the counterfactual new building and the time and expense in building the embodied carbon estimates, we decided this was beyond the scope of the project. Therefore, we instead use as a guide the concrete frame flat estimates for the embodied carbon from Spear et al. (2019).

The final costs to note were unique to the EnerPHIT option and involved the staff and tenant training on the EnerPHIT components. These were small in comparison to all other costs, but the time taken was estimated and each house was costed at the area median wage.

3.3. Benefits data

The largest benefit of the properties in every scenario was the consumption of housing services, but these were valued the same across all properties so did not affect the ranking of the options (although they do affect the NPV figures and the benefit-cost ratios). These were valued at average social rents for the area and market.

The next largest benefit by value was the energy saved. This was calculated separately for both the gas saved and the electricity saved. To calculate these values we first need modelled estimates of the energy saving compared to the unimproved building. We discuss these estimates below. The second piece of information we need is estimates of the long-run value of energy. These are supplied by DESNZ and split into low, central, and high scenarios. These scenarios are based around the uncertainty in the value of energy prices in the future. Both gas and electricity have separate long-run estimated values supplied by the UK government, so we used these throughout the analysis. We multiplied the modelled energy saving in that year by the UK government estimated value of the energy in that year. This is the standard approach in UK government cost-benefit analysis. The difficulty is in obtaining reasonable estimates of change in energy consumption.

The changes in energy consumption were initially obtained through the Standard Assessment Procedure (SAP). SAP modelling is a government mandated methodology for assessing the energy and

[3] A worked example: in two years the benefits minus costs are £500. The forecast deflator is 102. We calculate £500 × $\frac{100}{102}$ = £490.20. This gives us the real value. We then discount it by the discount rate 3.5%. This is by the calculation £490.20 × (1 − 0.035) × (1 − 0.035) = £456.50. So £500 in two years is equivalent to £456.50 today.

[4] The EESSH2 standard, as was intended in broad terms at the beginning of this study in 2019. However, subsequently, the Government working with the social housing sector, is undertaking a fundamental review of the standard and measurement for this new social housing energy efficiency standard. The outcome of this review is expected in the Autumn of 2023.

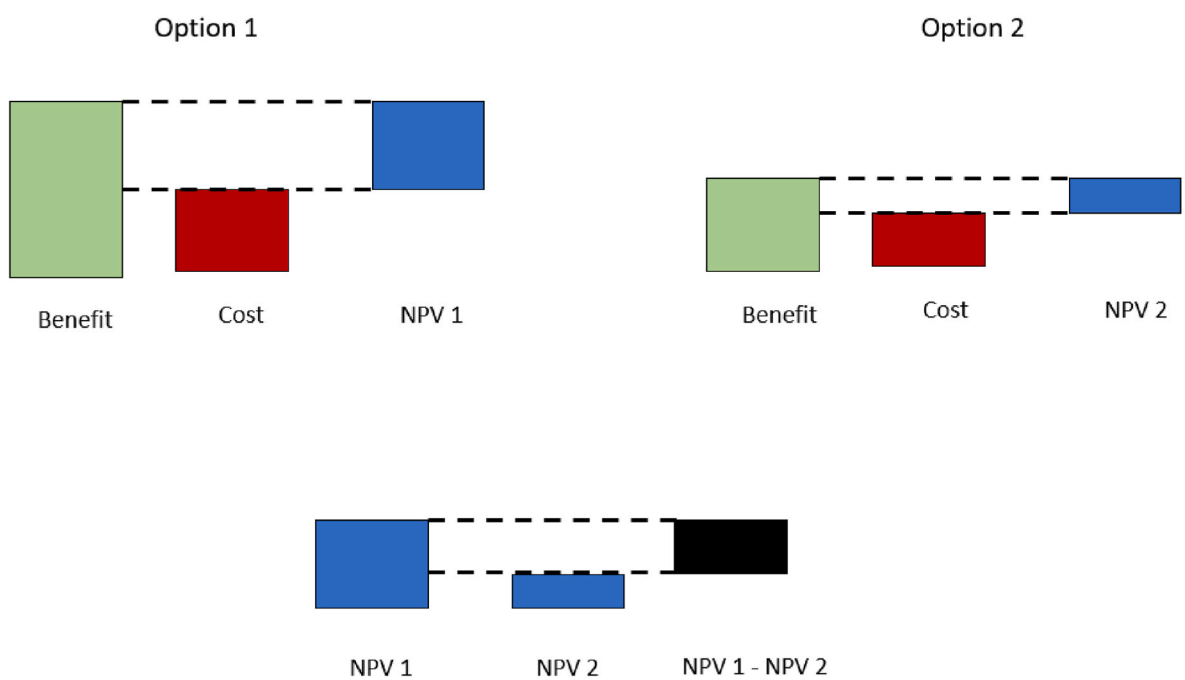

Fig. 3. The goal of cost-benefit analysis.

environmental performance of dwellings (DESNZ, 2022). It is used when an energy performance certificate (EPC) is generated for a household. Despite the widespread usage of SAP in the UK, it has come under a degree of criticism for being inaccurate. Criticism includes: treating every house as if it had the climate and altitude of central UK (the Pennines), not considering the cumulative impact of improvements, and estimating the number of occupants based on floor space. See Kelly et al. (2012) for a more detailed criticism of the SAP model. Some studies have shown SAP to be less accurate in forecasting energy usage compared to the alternative Passive House Planning Package (PHPP) (see Palmer, 2020; Moran et al., 2014; Moutzouri, 2011). PHPP is a model developed by the Passive House Institute specifically for modelling houses that use PassivHaus components, as the EnerPHit retrofit does. Although SAP performs well for the most part, its performance is significantly worse for houses that diverge significantly from "standard" housing (Palmer, 2020), and houses with PassivHaus components fit this model. Therefore, after some discussion with the architects we decided to model the energy change, and therefore greenhouse gas abatement, with PHPP modelling software. The net effect of this was to increase the energy saving of all options. The biggest increase was for the EnerPHit option, as would be expected given it uses PassivHaus components. It also changed the share of energy consumption for the EnerPHit option. Comparatively less electricity was saved and far more gas, reflecting the use of air source heat pumps in some of those properties.

The decrease in energy usage has the further benefit of decreasing greenhouse gas emissions. The value of these saved emissions was also taken from the UK government social value of CO2 equivalent emissions. As several greenhouse gases are emitted in the use of gas and electricity generation and have different greenhouse effects, the total emissions are converted to Carbon Dioxide equivalent amounts. Although some emissions are traded, the value of these decreased emissions is mostly non-market. The literature has estimated the value of a decrease in emissions in several ways, but we use the UK government values, which are mandated for use in government cost-benefit analysis. To calculate the value from decreased emissions we take the amount of energy that is saved from the modelling described above, minus a behavioural rebound effect. This is an income effect, where households saving energy are therefore also saving money, and may decide to use some of that money to consume more energy (usually in the form of additional heating). Energy savings that are lost to rebound effects are valued at the cost of the energy (because this is what it is worth to the household). The net of rebound effect energy saving is then split between electricity and gas saving. This is because the UK government official estimates we use project that the electricity grid will become less polluting as time goes on, and therefore saving electricity decreases less greenhouse gas emissions in later years. The same is not true for gas savings. The final step is to take the electricity or gas saving, and calculate the emissions abated, and multiply this by the social value of CO2 equivalent emissions for that year.

A similar process was carried out for other pollutants, such a nitrous oxide. These pollutant gases are detrimental to health and are a byproduct of gas and electricity usage. We use the UK government calculations of the emissions abated, given the modelled energy changes, and multiply this by the DESNZ suggested values.

We also include health benefits resulting from air quality improvements in EnerPHit houses. Literature reviews find that EnerPHit standard housing have better air-quality than conventional housing (Moreno-Rangel et al., 2020). This is due to the mechanical ventilation and strict standards required to meet the EnerPHit standard. Hamilton et al. (2015) show that more energy efficient homes without this improved ventilation may even lead to worse health outcomes. We use the estimates in Hamilton et al. (2015) health benefits. We assume health benefits of 0.033–0.038 QALYs in total each year. This is multiplied by the estimated value of a QALY from the UK Department of Health.

The final benefit is the social value of a tenancy. We do not include this in the main estimates but do in the sensitivity analysis. Organizations such as the UK Collaborative Centre for Housing Evidence (CaCHE) and the Housing Associations' Charitable Trust (HACT) have worked on providing evidence and monetary values for the positive externalities a social tenancy generates (Gibb, et al., 2020). HACT provide a social value bank and calculator to help generate these values. However, precise values require detailed data and surveys from the surrounding area which was felt to be beyond the scope of the CBA. We therefore used as a guide the estimate of the social value of a tenancy in Barnes et al. (2018). This does not affect the relative rankings of the options but does affect the NPV and BCRs in the sensitivity analysis.

We show the full cost and benefits considered in Table 1.

Table 1
Costs and benefits framework.

Type of Cost/Benefit	Group Cost/Benefit falls to	Included in Cost-Benefit Analysis?
Costs		
Initial installation/capital costs	Housing Association	Included
Maintenance costs	Housing Association	Included
Administrative costs	Housing Association	Included
Familiarisation with equipment costs	Tenants	Included
Embodied carbon of Construction	Society	Included
Benefits		
Property value uplift	Housing Association	Not included
Lower energy costs	Tenants	Included
Increased "comfort taking" energy use	Tenants	Included
Improved health outcomes from better ventilation	Tenants	Included
Lower energy use	Tenants	Included
Lower greenhouse gas emissions	Society	Included
Improvements in air quality	Society	Included
Housing Services	Tenants	Included

4. Results and discussion

4.1. Main results

All results were presented either in NPV (Table 2) of 2021 pounds sterling or in BCRs (Table 3). All results were also presented according to the low, medium and high scenarios that use the DESNZ provided estimates of the costs of energy and social value of pollution abatement, as explained previously.

The main results show, under all three scenarios, that the New Build has the lowest NPV and BCR. The biggest difference between the New Build and the other options is the larger costs of demolition and building compared to retrofitting flats that, under our assumptions, would last for the 30 year timescale under consideration. However, even with similar costs to the EnerPHit option, the New Build would still be the worst option due to the embodied carbon emissions in the demolition and construction.

A second finding is that the highly efficient EnerPHit and the less efficient but less costly EESSH2 option have similar NPVs and BCRs under all three scenarios. In the higher scenarios the benefits of carbon abatement are larger, and the benefits from energy saving are also larger, therefore the NPV of the EnerPHit option eventually overtakes the EESSH2 option as it is far more energy efficient. However, in the lower scenarios the reduced costs of the EESSH2 option mean that it has a higher NPV and BCR than the EnerPHit option, despite being less efficient.

In Fig. 4 we see the cumulative NPV each year in the central scenario to show the time until each option reaches a positive NPV. The initial capital costs are clear at the outset, while the benefits are more gradual. The EESSH2 option reaches a positive NPV by year 18 and the EnerPHit by year 20. The New Build option does not reach a positive NPV in the 30-year period under consideration.

Alternatively, in Fig. 5, if we look purely from an emissions rather than NPV perspective, the EnerPHit option saves the most greenhouse gas emissions. The New Build saves the least despite being more efficient that the EESSH2 option. This is because of the embodied emissions of the construction and demolition. The EnerPHit option saves the most tonnes of greenhouse gas emissions, with a final saving after 30 years of 429 tonnes. This is followed by the EESSH2 at 257 tonnes. The New Build starts with a significant emissions deficit because of the embodied carbon in the demolition and building. We use as a guide the concrete frame flat estimates for the embodied carbon from Spear et al. (2019). We estimate the embodied carbon of demolition and construction as 20 tonnes of Carbon Dioxide equivalents. This means that the final abatement for the New Build after 30 years is 205 tonnes.

Table 2
Net present value of options (£, 2021).

Option	Low Scenario	Central Scenario	High Scenario
New Build	-£479,425	-£455,271	-£424,510
EESSH2	£248,159	£277,571	£315,390
EnerPHit	£210,311	£266,506	£331,140

Table 3
Benefit-Cost ratio of Options.

Option	Low Scenario	Central Scenario	High Scenario
New Build	0.70	0.72	0.74
EESSH2	1.28	1.32	1.36
EnerPHit	1.21	1.27	1.34

Finally, we also considered alternative NPVs and BCRs where the values are weighted based on the income level of who benefits and who bears the cost. These weights are called distributional weights. We use the standard method of calculating them as given by the UK Treasury Green Book.[5] We assumed half the tenants in the social housing flats would be from the bottom quintile of income, and half from the second quintile. This tenant mix is assumed to be the same for every option. Therefore, benefits and costs to these tenants are weighted at 3.28 and 1.56 respectively for the bottom and second quintile tenants. Costs and benefits to the housing association or society in general are weighted at 1.

In Table 4 we see that with distributional weights all the options have higher NPV, and the NPV of New Build is now positive. We can also see much higher BCRs in Table 5. This is because the value of the energy savings and housing services are benefits to the tenants and therefore receive a higher weight due to the tenants' low household incomes. However, the New Build is still always worse than the other options. The EnerPHit has a higher NPV than EESSH2 in all scenarios now, due to the increased energy savings enjoyed by the tenants, but the BCRs remain higher for the EESSH2 option, meaning that the last pound spent on EESSH2 has a higher marginal net benefit than in EnerPHit.

In Fig. 6 we see the profile of cumulative NPV under the central scenario with distributional weights. The New Build achieves a positive NPV in year 17, EESSH2 in year 7, and EnerPHit in year 8.

In summary, the choice between the ESSH2 and EnerPHit retrofit options is sensitive to what assumptions we impose, and on how large the future value of greenhouse gas emission abatement and reduced energy consumption is. We further explore the sensitivity of the results in the sensitivity analysis below. In contrast, the New Build is generally always the worst choice for both NPVs or BCRs. We now explain in more detail how the results change depending on the assumptions used. In CBA this is called sensitivity analysis.

4.2. Sensitivity analysis

Sensitivity analysis in CBA is carried out to test how sensitive results are to changes in assumptions. We have included all the results of the

[5] The UK Treasury uses an elasticity of marginal utility of income figure of 1.3. That is, the higher your income the less each additional pound is worth to you. For example, for a billionaire an extra £100 does not matter as much as it would do for someone in poverty. Given this suggested 1.3 figure, we divide the median income of the affected group by the median income in the UK and raise the result to the power 1.3. This is the distributional weight that benefits and costs to that group are multiplied by. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/938046/The_Green_Book_2020.pdf.

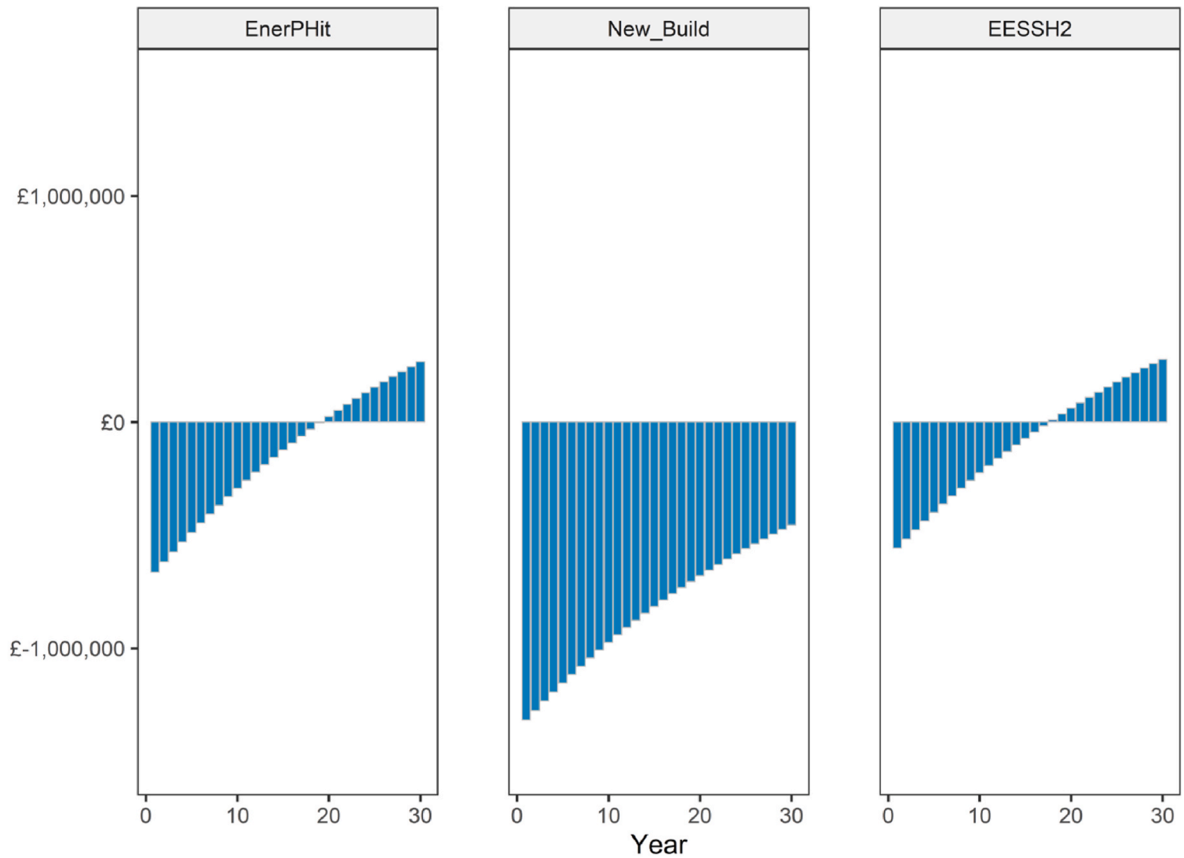

Fig. 4. Cumulative net present value of options, central scenario (£, 2021).

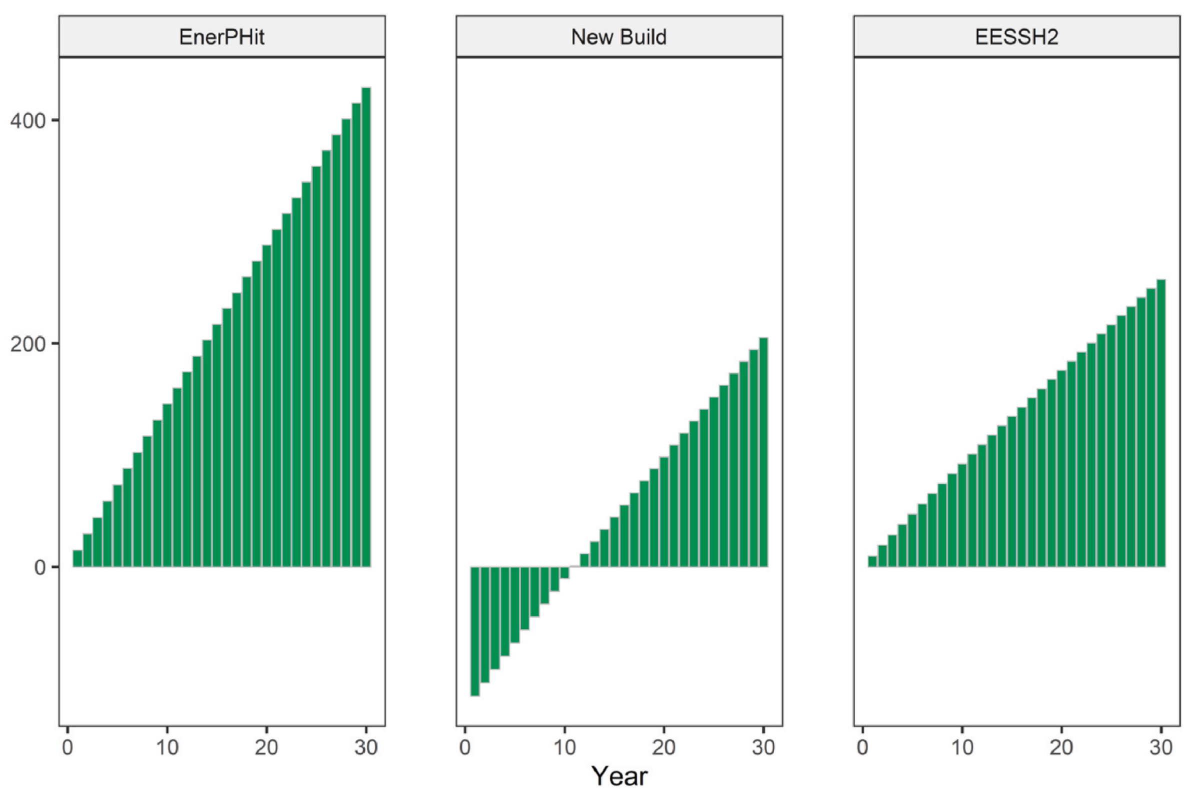

Fig. 5. Cumulative Carbon Dioxide Equivalent Emissions Abated, tonnes.

Table 4
Net present value of options, distribution weighted (£, 2021).

Option	Low Scenario	Central Scenario	High Scenario
New Build	£645,748	£681,389	£726,304
EESSH2	£1,367,728	£1,400,886	£1,448,048
EnerPHit	£1,387,080	£1,456,999	£1,538,791

Table 5
Benefit-Cost ratio of Options, Distribution Weighted.

Option	Low Scenario	Central Scenario	High Scenario
New Build	1.40	1.42	1.44
EESSH2	2.56	2.60	2.66
EnerPHit	2.41	2.48	2.56

sensitivity analysis in the appendix, but summarise here for convenience,. We examined adding or dropping three different elements: health benefits from better ventilation in the retrofit, the social value of a tenancy, and optimism bias (Optimism bias is the empirical observation that realised benefits of preferred options are often less than estimated, and realised costs are often higher – see Flyvbjerg and Bester, 2021). We also examined changing the strength of the rebound effect and the costs of maintenance. The rebound effect is a behavioural effect where some of the money saved by efficiency improvements is used by households to consume more energy. This is called "comfort taking" and represents a welfare improvement to the household as they realize the gains from efficiency by consuming the energy. For example, some gains from heating efficiency are used by the household to live at a higher indoor temperature than they would have without the efficiency gains. Our main analysis uses a rebound effect of 20%, in line with Greenbook methodology, but our sensitivity analysis varies this by between 0% and 30% using the plausible bounds for home heating rebound effects in Sorrell et al. (2009).

In all cases the New Build option was still the worst of the three. Similarly, although there were slight differences in the NPV and BCRs with the changes, the EESSH2 and EnerPHit options remained similar in social value. Therefore, the sensitivity checks do not change the rankings of the options very much, but they do change the NPVs. See appendix for full results of the sensitivity analysis.

4.3. Discussion of results

The main finding in our results is that retrofitting this tenement provides better value for money compared to demolition and new building. This finding was generally robust to various sensitivity checks. The implication is that, where similar buildings have at least a 30-year lifespan remaining, it may be a better option to retrofit rather than demolish. This can even be the case when the new building is more efficient than the old one, just as our New Build option was more efficient than the EESSH2 option, because of the increased costs of building and the embodied emissions this entails as well. This was true for our case both in NPV terms and in total greenhouse gas emissions.

The second implication of our results is that the optimal level of investment in retrofitting a building, in terms of NPV, is sensitive to many different factors. If the extent of realised efficiency gains is far less than predicted for a maximal retrofit, then it will give far lower gains in NPV than a less cost-intensive improvement. This could happen because the retrofit components do not operate as well in some building set-ups, or are not used correctly, or the tenants use the efficiency gains to consume more energy as "comfort-taking". For example, Peñasco and Anadón (2023) found 100% rebound effects for loft and wall insulation in the UK after four years. However, if the gains are realised, then it is optimal to invest far more in retrofitting. This is in NPVs, but for

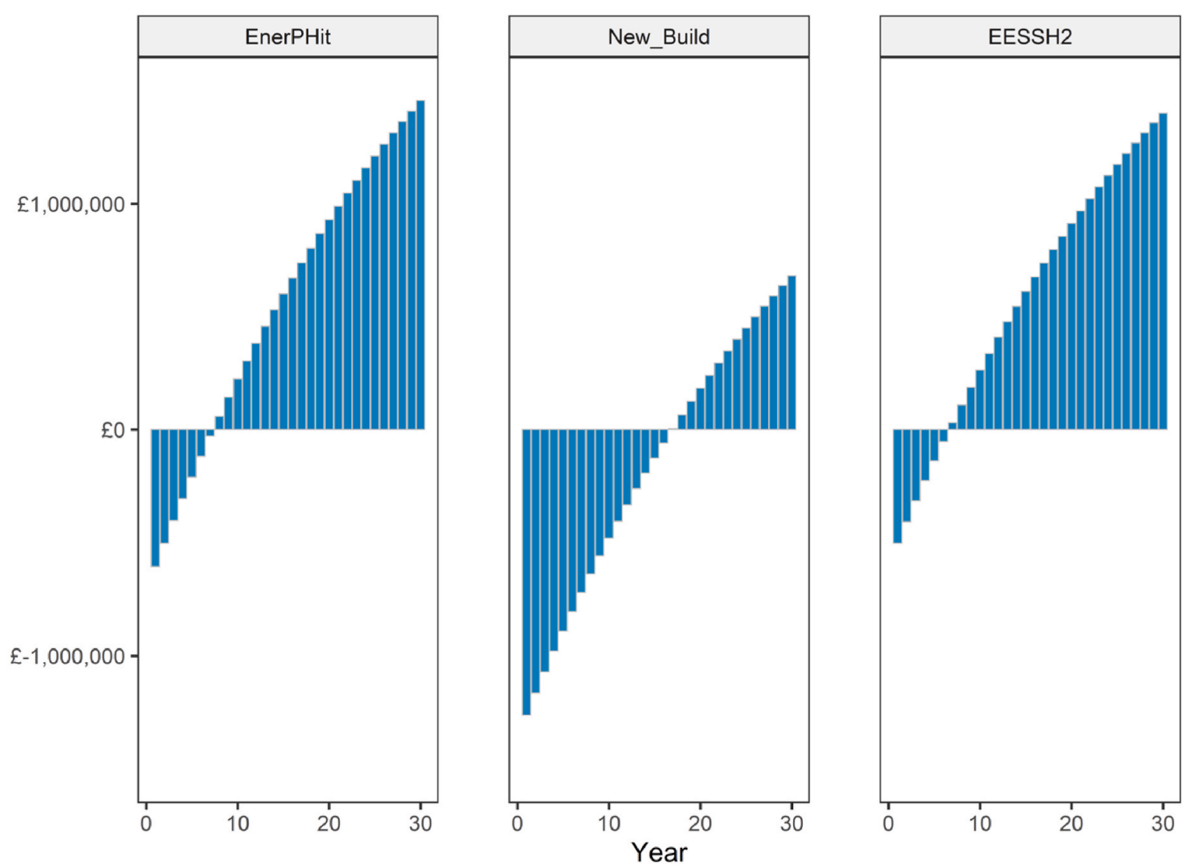

Fig. 6. Cumulative net present value of options with distributional weights, central scenario (£, 2021).

minimizing greenhouse gas emissions, more efficient retrofits are always better in our analysis. This points to another important influence on our results: the social value of greenhouse gas emissions abatement. We use the UK government's three different levels for the social value of emissions abatement, as well as the value for energy saved (low, central and high scenarios). Which retrofit option was better depended a great deal on these values. Furthermore, the social value of emissions abatement is disputed within the literature (e.g., see Watkiss and Downing, 2008, or Stern et al., 2022), indeed the UK government used far lower values for its cost-benefit analyses until only 2021 (BEIS, 2021b).

In summary, our cost-benefit analysis results imply retrofitting is a good investment compared to demolition and new building, but that the optimal level of retrofitting depends on a variety of factors, may depend on local context and on the relative weighting of greenhouse gas emissions abatement compared to other investments.

5. Conclusions and policy implications

This paper presents findings that were part of a wider evaluation of the deep retrofit of a traditional tenement block in Glasgow. Because of the scale of such housing in the city and across Scotland, decarbonising these tenements is important. However, retrofit of these buildings faces considerable technical, economic, legal and logistical challenges. This project endeavoured to learn lessons for scalability and insights for a citywide tenement strategy. The evaluation of the project supported these ends but also tried to understand its impact in terms of energy consumption, tenant wellbeing, and the costs and benefits of such an investment, the latter being the main focus of this paper.

The main findings of our orthodox cost benefit analysis indicate that retrofitting is generally superior to the demolition and replacement of such tenements. We find that the difference for the base case between a retrofit at a level close to current policy requirements (EESSH2) and the EnerPHit approach is less clear cut (the EnerPHit model produces greater decarbonising benefits but at a higher cost) and is sensitive to the assumptions deployed. However, only the EnerPHit model has the potential to approach net zero.

We stressed in the main part of the paper that we deliberately tried to follow orthodox Green Book practice to strengthen third party and government confidence in these results. We also found that higher valuations of carbon emissions also strengthened the case for deeper retrofit. At the same time, we contend that the assumptions made regarding things like optimism bias, rebound effects and other decisions on assumptions are warranted.

However, emerging lessons from the wider evaluation contain important caveats. If we look at these from the point of view of our above categorisation of challenges, we can highlight specific points, all of which suggest further research opportunities.

- *Technically*, the fundamental heterogeneity of the tenement form and its variable condition, undeniably limits the scalability of specific lessons (although components of the process are certainly transferable). It also suggests that it will be difficult to achieve EnerPHit in practice without adjusting to a room by room testing of airtightness. However, the evaluation concludes that larger blocks of multiple tenements may be a minimum efficient scale for the work. It also indicates that fabric first approaches to insulation and draught-proofing as well as to the common parts of the building are essential. The evaluation also suggests that slightly lower non-EnerPHit standards, may take the decarbonisation outcomes substantially towards the levels required but at lower cost. This latter point is an important subject for further research.
- *Economically*, the relatively high cost per unit will deter investment, particularly in a context where social landlords are being asked to increase rents to deliver on multiple policy goals while keeping them affordable. At the same time, tenements are almost always mixed tenure and mixed income, raising economic incentive challenges to encourage homeowners and private landlords to retrofit, as well as solving common repairs problems, and addressing just transition problems. Currently, access to public funds for private owners may be too weighted towards renewable energy systems and not co-ordinated enough with necessary fabric first physical property improvements. Integrated financing innovations are also critical to scaling up tenement retrofit by individuals, as is the proper accounting for embodied carbon in ranking public policy decisions around retrofit. There is also sense in impartial one stop shops for advice, subsidy/delivery choices and supplier/contractor recommendation, perhaps kitemarked and supported by local government.
- *Legally*, progress needs to be accelerated around Scottish tenement law reform in order to support block-level owner occupier and private rented retrofit outcomes. However, the proposals need to be carefully understood and tested in terms of wider system consequences and fairness. At the same time, planning policy rules operating in a city need to be updated to be retrofit-ready.
- *Logistically*, policymakers need to think hard about the transaction cost economics of how best to organise a tenement retrofit strategy in neighbourhoods and districts of cities. In particular, there is the issue of *decanting* residents while work is underway, as compared to the hassles and problems of living in and through during the retrofit building works. Again, this is in part a direct function of the mixed nature of a specific tenement contrasting individual owners and social landlords. The Niddrie road tenement block had the huge advantage of being empty when it was acquired and thereafter when the works were carried out. In practice, the built professionals we worked with suggested a range of options – working on individual properties when they are vacant or in between tenancies, carrying out external works with the residents in situ, and only moving people out into temporary alternative accommodation when internal works makes this necessary. Clearly, this assumes a ready supply of such decanting alternatives, which may be challenged in tight markets where there are already alternative housing uses for such property.

There are limitations to this sort of case study research which should be identified. First, the data is never perfect for a task like SCBA and compromises and trade-offs have to be made. We have tried to be explicit and transparent about such decisions throughout. Second, there is much criticism in the UK regarding the assumptions and orthodoxy of the Green Book approach to economic appraisal (Gibb and Christie, 2024) and this includes from environmental economists, regarding the discount rate chosen, time periods for analysis and the appropriateness of different assumptions. Our reasoning for adoption of the mainstream is simply to provide a defensible argument to government analysts in a context where housing investments fare poorly in appraisal scoring regimes. This pragmatism, when it yields a positive outcome like in this case, can only help the argument for green retrofit. Furthermore, we contend that the sensitivity analysis around assumptions can help the more Green Book-sceptical reader have a sense of the range of possible outcomes. A third inevitable limitation is that this project is only one case study of eight properties. We of course acknowledge and would welcome further modelling of different retrofit standards across the pre-1919 tenement stock in comparable neighbourhoods. Nonetheless, this is important proof of concept research containing important information to help the city, housing associations and others make retrofit investment decisions.

Future research could explore Scotland's forthcoming Passivhaus equivalent design standard for new buildings. One potential avenue would be to conduct a Social Cost-Benefit of pilot projects compared to standard new builds as counterfactuals. Additionally, there is a need to evaluate the various subsidy instruments available for retrofitting older housing. Furthermore, the development of practical, simple tools, based on social cost benefit analysis principles, could help practitioners carry out economic appraisals in a transparent, cost-effective and comparable way.

CRediT authorship contribution statement

Anthony Higney: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kenneth Gibb:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Anthony Higney reports financial support was provided by Scottish Funding Council. Ken Gibb reports financial support was provided by Scottish Funding Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2024.114181.

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