Prioritizing deep renovation for housing portfolios

Citation for the original published paper (version of record):
Österbring, M., Camarasa, C., Nägeli, C. et al (2019). Prioritizing deep renovation for housing portfolios. Energy and Buildings, 202. http://dx.doi.org/10.1016/j.enbuild.2019.109361

Energy & Buildings 202 (2019) 109361

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Prioritizing deep renovation for housing portfolios

Magnus Österbring*, Clara Camarasa, Claudio Nägeli, Liane Thuvander, Holger Wallbaum

Chalmers University of Technology, Sven Hultins gata 6, 412 96 Göteborg, Sweden

ARTICLE INFO

Article history:
Received 4 April 2019
Revised 29 July 2019
Accepted 7 August 2019
Available online 7 August 2019

Keywords:
Deep renovation
Building-stock modelling
Portfolio assessment
Energy efficiency
Cost-effectiveness
Property valuation

ABSTRACT

Cost-effectiveness of deep renovation has been assessed thoroughly on a building level. Such studies provide limited guidance when prioritizing renovation measures for a building portfolio. On a stock level, building-stock modelling is commonly used to assess impact of renovation on a national and city level, targeting stakeholders operating at a planning or policy level. However, due to methodological choices and data availability, assessment of property owner portfolios is lacking. The aim of this paper is to calculate and spatially differentiate cost-effectiveness of deep renovation using equivalent annual cost and increase in assessed building value for a portfolio owner as a first step in prioritizing deep renovation within a building portfolio. A bottom-up engineering-based model is applied utilizing building-specific information for a municipal housing company portfolio in the City of Gothenburg, Sweden, consisting of 1803 multi-family buildings. Energy demand for space heating and hot-water is calibrated using measured energy use from energy performance certificates. Deep renovation is assessed by applying a package of measures across all buildings. Results show average energy use reduction across the portfolio of 51% to an average cost of 597 EUR/m^2 living area. While average energy cost savings account for 21% of equivalent annual cost, there are seven buildings where more than half the annual equivalent cost of renovation is covered by energy cost savings. Similarly, the distribution of change in assessed building value is large for individual buildings, ranging from 0–23%. Aggregating results to larger areas tend to average out results while differences between individual buildings within areas persists. As such, the cost-effectiveness of deep renovation should be assessed on a building-by-building basis rather than for an area or neighbourhood. The results are intended as a first step in prioritizing deep renovation within a building portfolio and further detailed assessment is needed.

1. Introduction

Worldwide, buildings account for significant use of energy and for developed countries, a majority of buildings in use by 2050 have already been built [1]. On a European level, the existing building stock is responsible for 40% of total energy use and 36% of CO_2 emissions. Residential buildings account for approximately 75% of the European building stock resulting in 30% of the EUś overall energy demand and emissions [2]. In this light, the European Commission demands all member countries to define long-term renovation strategies, aiming at decarbonising national building stocks by 2050. These plans should be supported by a 'solid financial component' and ideally address other positive side-effects of improving energy efficiency in buildings, such as economic, social and environmental benefits [3].

Building-stock modelling (BSM) is commonly used to explore the potential development of the existing building-stock. Emphasis is typically placed on the energy use of the building-stock, either focusing on the current state [4,5] or evaluating the potential development of the stock [6,7]. Modelling approaches have evolved from using representative buildings with scaling factors to account for the building stock on a national or pan-national level [8,9] to increasing use of geographic information systems to model urban building-stocks [10].

While the spatial resolution has increased, building-stock descriptions used as input for these models have seen little development and are still largely based on using representative buildings and scaling factors to aggregate results. With increased spatial resolution, building descriptions based on representative buildings lose accuracy and commonly results are only presented at aggregate levels for districts, neighbourhoods or entire cities [11]. As a result, stakeholders operating at a planning or policy level are commonly targeted by BSM. A few exceptions can be found

* Corresponding author.
E-mail address: magnus.osterbring@chalmers.se (M. Österbring).

https://doi.org/10.1016/j.enbuild.2019.109361

where other potential stakeholders have been identified. It has been suggested that construction companies can use energy performance certificates (EPCs) to assess the size of the renovation market [12,13] points to the possibility to use results for educational purposes. Subsequently, the intended stakeholders for BSM vary but can generally be divided into three broad categories: urban planners, energy planners and governmental bodies needing policy support. However, the use of BSM to support property owners is missing. There are several reasons why this is the case. First, the use of representative buildings limits results and analysis to higher levels of aggregation while the main concern of property owners is property or building specific. Second, using a building-specific description of the stock requires a granularity in data which may not be available or accessible. In addition, the lack of disaggregated energy consumption data in BSM has been brought up in several papers as an issue [14–16]. Third, fragmented markets with many small property owners limit the need for a portfolio level analysis. As a result, BSM has not been applied for economic assessment of deep renovation from a portfolio owner perspective.

Currently, renovation strategies of property owners are mostly defined by component degradation or obsolescence and not necessarily by market value increase [17]. Moreover, most of the implemented measures are based on 'reinstatement' where existing technologies with limited effect on energy use are being reapplied [18]. In contrast, to fulfil energy and carbon reduction targets on all levels – global, European, national, municipal and organisational - deep renovation is required. The economic impact of energy efficiency measures (EEM) has been a subject of study in the past years [19–21]. In the European research field, most initial analyss focused on requirements and measures for improvements needed to fulfil the Energy Performance Building Directive (EPBD) [22,23]. Over the last decade, there have been several large EU funded projects focusing on EEM in the existing stock such as HERB (Holistic energy-efficient retrofitting of residential buildings)[1], E2ReBuild (Industrialised energy efficient retrofitting of resident buildings in cold climates)[2], NEWBEE (Novel Business model generator for Energy Efficiency in construction and retrofitting)[3], RETROKIT (Toolboxes for systemic retrofitting)[4], EASEE (Envelope Approach to improve Sustainability and Energy efficiency in Existing multi-storey multi-owner residential buildings)[5] and NOVICE (New Buildings Energy Renovation Business Models incorporating dual energy services).[6] In most cases, these projects focused on assessing the viability and effect of EEM on individual buildings. Several research papers with a similar aim exist. For instance, [24] seeks to study the most profitable combination of insulation and glazing while [25] developed an optimization model to define cost-effective intervention measures in an attempt to minimize energy use in the building. Moreover, several studies focused on gathering empirical evidence on the economic impact of EEM in the housing stock [26,27], many of them using EPCs as a reference for their assessments [28–31]. However, the cost-effectiveness of deep renovation including an increase in assessed building value on a housing portfolio level is not addressed.

The aim of this paper is to spatially differentiate cost-effectiveness of deep renovation using equivalent annual cost (EAC) and a simplified method to assess change in building value for a portfolio owner as a first step of prioritizing deep renovation within a building portfolio. A deep renovation is a renovation which reduces both the delivered and the final energy consumption of a building by a significant percentage compared with the pre-renovation levels leading to a very high energy performance [32]. In this paper, the comprehensive renovation package applied is considered to constitute a deep renovation. The municipal housing company in the City of Gothenburg, Sweden, is used as a case study.

2. Materials and methods

The energy performance of the housing portfolio of the municipal property company in the City of Gothenburg is calculated using previously developed methodologies for describing, calculating and calibrating building-stocks using a bottom-up engineering-based approach where every building is treated individually [33,34]. The portfolio consists of 1803 multi-family buildings totalling 6.2 million m^2 heated floor area. The impact of deep renovation is spatially assessed in terms of reduced energy use as well as cost-effectiveness using EAC and assessed change in building value for each building.

2.1. Data

The data used for the BSM has mainly been gathered from national databases. The Swedish Mapping, Cadastral and Land Registration Authority provided relevant parts of the building and property register for the city of Gothenburg. The property register contains information on ownership and rental income while the building register contains information on building type, year of construction, year of renovation and value year. The value year is of particular interest as it has several functions. The value year can be used to assess the extent of previous renovation measures and provide information regarding the remaining life-time of a building [35]. Furthermore, the value year is used for taxation purposes to calculate the change in taxation value. Table 1 describes how the Swedish Tax Agency requires a renovation to be registered as a change in value year depending on the cost of renovation in comparison with new construction cost [36]. In addition, reference values for the cost of new construction are updated yearly by the Swedish Tax Agency. For 2018, the reference value is 1695 EUR/m^2 living area. Buildings with a value year of 2011 or later are exempt from municipal property fee for 15 years. The municipal property fee for multi-family buildings is 0.3% of the taxation value and is capped at 127 EUR/apartment and year for 2018. On average, the municipal housing stock is subject to a municipal property fee of 125 EUR/apartment and year. Additional taxation data was provided by the Swedish Tax Agency regarding value areas used in property taxation. The City of Gothenburg is divided into 55 value areas with different weighting factors used to determine property taxation.

The National Board of Housing, Building and Planning supplied all EPCs for the city of Gothenburg. The Swedish EPCs are unique since they not only contain information on building characteristics such as heating, ventilation and cooling systems, but also measured energy use for space heating (SH), domestic hot-water (DHW), and auxiliary electricity use. 2D shape files were provided from the City planning office and converted to 3D using height information from the EPC. The EPCs are connected to the building registry using the building ID and the property registry is connected to the building registry using the property ID. Midpoint Coordinates in the building registry is then used to spatially match these datasets to each individual footprint in the 2D-map of Gothenburg and each corresponding value area. As not all EPCs contain the correct identifier, 5901 of the 6320 EPCs were spatially linked to a building. In total, 1803 MFB equivalent to 6.15 million m^2 HFA owned by the municipal housing company is used in this study.

[1] https://cordis.europa.eu/project/rcn/105487/factsheet/en.
[2] https://cordis.europa.eu/project/rcn/100470/factsheet/en.
[3] https://cordis.europa.eu/project/rcn/104538/factsheet/en.
[4] https://cordis.europa.eu/project/rcn/104534/factsheet/en.
[5] https://cordis.europa.eu/project/rcn/102518/factsheet/en.
[6] https://cordis.europa.eu/project/rcn/210577/factsheet/en.

Table 1
Change in value year depending on cost of renovation in relation to new construction cost.

Renovation cost	Calculation of value year
< 20% of new building cost	No change in value year
20–70% of new building cost	The value year is changed proportionally based on investment cost over new construction cost
> 70% of new building cost	The value year is set to the year of renovation

2.2. Building characterisation

To further characterise the buildings, the initial U-value of components is based on random sampling of a normal distribution using methods based on previous work [34] where mean values have been selected using an age-type classification based on architecture history [37], historic building regulations and surveys as described in [33]. The buildings are then further characterized based on the building characterization method described in [34]. In addition to U-values, the method defines the initial state regarding g-value of windows, occupancy-related parameters (e.g. number of occupants, daily hot water consumption, etc.) as well as other parameters such as ventilation rate and shading factor by random sampling from input distributions in order to account for variability and heterogeneity in the stock. The method also accounts for previous renovation and replacement measures in two steps. First, by defining the year of the most recent intervention for each component based on a Weibull distribution of the component lifetime, previous reinstatement and replacement cycles are applied to start from the renovation year. The Weibull distributions are fitted per component and construction type using data from [38,39]. Second, the effect of the intervention is defined by updating the U-value (in case of envelope components) or efficiency (in case of heating and ventilation systems). The intervention of envelope components is constrained depending on the extent of the renovation based on the value year (see Table 1). The constraints are applied so that windows are always assumed to have been replaced. The roof is assumed to have been retrofitted if the economic extent of the renovation was larger than 20% of new construction costs while floor and walls are assumed to have been retrofitted if the economic extent of the renovation was larger than 50% of the new construction costs. In addition, the surface areas of each building are calculated based on extrusion of building footprints using the building height and connected to the U-value of the relevant component.

2.3. Energy modelling and calibration

The energy demand of buildings is calculating using a bottom-up engineering model previously applied in [34]. It calculates the monthly energy demand of each building in terms of space heating, hot water, appliance use, lighting and auxiliary electricity use (ventilation, pumps, etc.). The model uses a monthly steady-state method to calculate space heating demand based on the ISO EN 52,016–1 [40].

The initial state of the buildings is calibrated based on measured energy use from the EPCs. By creating 100 versions of each building through sampling values from the input distributions outlined above, the model selects the building version which most closely fits the measured energy demand of the EPC.

2.4. Deep renovation measures

The measures making up the deep renovation package and their costs are shown in Table 2. The renovation packages involve reinstatement and energy efficiency measures for the different building components listed. The package of renovation measures is applied to each building, although the specific measures differ slightly where the measures specified for the heating and ventilation system are dependent on the current state. Cost data for materials, labour and design of the individual measures are taken from [41–43]. All costs are excluding VAT. Cost factors and minimum technical lifetime of the different envelope components depend on the construction type and can vary significantly. In the case of façade retrofit the minimum technical lifetime ranges from 22 years for a wooden façade to 40 years for a brick façade. The technical lifetime is based on [38,39]. Moreover, the cost factors for heating systems depend on the installed heating power, where specific costs decrease with increasing power.

2.5. Economic assessment

The economic impact of the renovation package is assessed both in terms of EAC of the investment needed and the change in building value. The equivalent annual costs are calculated for each component individually and summed up for each building (Eq. (1)). Using EAC enables summing up investment costs taking into account the different lifetimes of the investments. The lifetime of the investment is chosen as the minimum technical lifetime of the different components, which is based on the same lifetime data as is used for the calibration of the status quo (see above). A discount rate of 4% is used based on a previous study of renovation of Swedish multi-family buildings [44].

$$EAC_i = C_i \frac{r}{1-(1+r)^{-t_i}} \tag{1}$$

EAC: Equivalent annual costs for a component in [EUR/y]
C_i: Investment costs of EEM for a component in [EUR]
r: Discount rate
t_i: lifetime of component i [y]

The Swedish Tax Agency's method is used to assess the change in building value. According to real estate appraisal valuation methods, the method used by the Swedish Tax Agency can be classified as simplified, using a combination of comparable and investment/income methods [45]. By using location-based factors derived from the value area in combination with rental income levels and value year, the taxation value, R, is calculated according to Eq. (2) and Table 3. The area factor, N, varies between 0.4–15 although for the City of Gothenburg all area factors are within the span 5.25–9.75. In general, the area factor is high in and around the city centre and lower on the outskirts of the city. This means that the difference in assessed building value between the highest and lowest value areas in Gothenburg is almost a factor two from location alone. H is the yearly rental income in EUR/Year. The capitalisation factor, f, is derived according to Fig. 1 based on the value year and area factor. The capitalisation factor is updated every six years in conjunction with the general national property valuation. Fig. 1 shows the values of the most recent national property valuation which took place in 2013. Note that the relative impact of value year is larger for a lower area factor and that the capitalisation factor has a positive correlation with area factor for older value years while it has a negative correlation for more recent value years. The Swedish Tax Agency states that the taxation value should represent 75% of the market value, which is applied

Table 2
Renovation measures making up the deep renovation package.

Component	Renovation measure	Cost range	Minimum technical lifetime [years]
Wall	Façade retrofit with +200 mm insulation ($\lambda = 0.035$ W/mK)	94–221 EUR/m^2	22–40
Roof	Roof retrofit with + 400 mm insulation ($\lambda = 0.035$ W/mK)	72–151 EUR/m^2	20–41
Window	Window replacement with a triple glazed window with U-Value of 0.8 W/m^2 K	903 EUR/m^2	29
Floor	Floor retrofit with + 100 mm insulation ($\lambda = 0.035$ W/mK)	71 EUR/m^2–85 EUR/m^2	68
Heating system	District heating remains with same system, all other heating systems are replaced with a ground/water heat-pump (Seasonal Coefficient of Performance = 3.3)	District heating: 154 EUR/kW for a 25 kW system	15
		Heat pump: 1122 EUR/kW for a 25 kW system	18
Ventilation system	Central exhaust and supply systems are replaced with a central system with heat recovery (HRR = 75%), exhaust only systems and naturally ventilated buildings are equipped with an exhaust system with an exhaust-air heat-pump (Seasonal Coefficient of Performance = 2.5)	Exhaust and supply ventilation with heat recovery: 533 EUR per dwelling	17
		Exhaust ventilation with heat pump: 1067 EUR per dwelling	24
Water pipes	Reinstatement of pipes	1429 EUR per dwelling	27
Sewage pipes	Reinstatement of pipes	2286 EUR per dwelling	40
Electrical system	Reinstatement of the electrical system	3809 EUR per dwelling	44

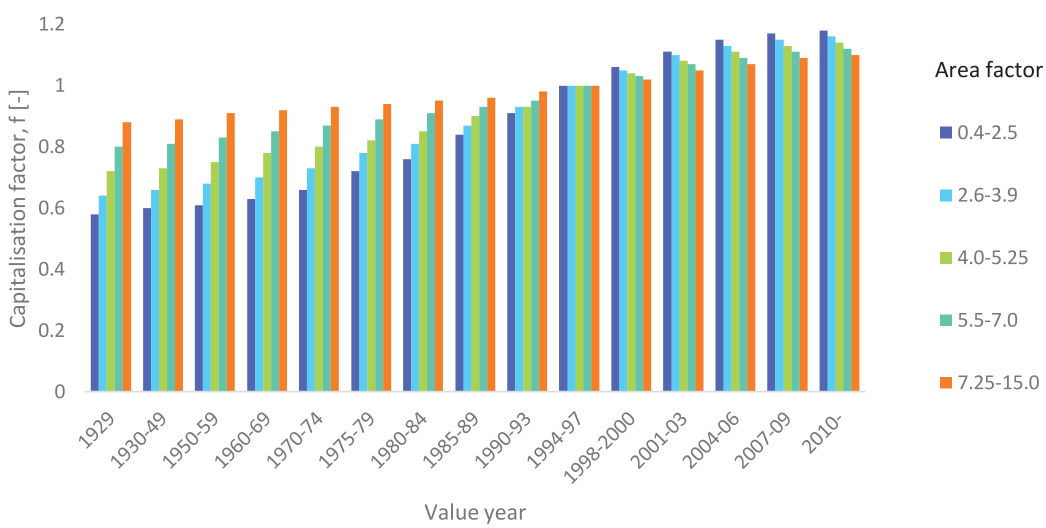

Fig. 1. Capitalisation factor, f, as a function of value year and area factor.

Table 3
Description of variables used to calculate the taxation value.

Variable	Description	Unit
R	Taxation value	[EUR]
N	Area factor	[-]
H	Yearly rental income	[EUR/year]
f	Capitalisation factor, based on value year and area factor according to Fig. 1.	[-]

in the assessed change in building value.

$$R = N\,x\,H\,x\,f \quad (2)$$

3. Results

Results are presented for the municipal property owner for the City of Gothenburg spatially in maps and as figures. First, we present calculated final energy use for SH, DHW and auxiliary electricity use in relation to the characteristics of the stock. Second, we present the impact of deep renovation of the stock with a focus on final energy use and cost-effectiveness of EEM. Third, we highlight the impact of deep renovation on property value in relation to the energy cost savings and investment cost.

3.1. State of the portfolio

For the building portfolio of the Gothenburg municipal housing stock, calculated final energy use (i.e. delivered energy) for SH, DHW and auxiliary electricity use is on average 113 kWh/m^2 year. The results of the calibration can be seen in Fig. 2 where the absolute relative error between measured and calculated final energy use is given as a share of buildings in the portfolio. The results are calibrated to within 6% of measured energy use for SH and DHW on a portfolio level and 90% of the buildings are within a 30% margin of error. Fig. 3 shows calculated final energy use grouped by year of construction to show the energy performance and relative size per age group. The energy use varies somewhat between the age groups, but the general trend is a steadily increasing energy performance from the 1950s and onwards. Buildings from the 50 s, 60 s and 70 s are most prevalent and constitute 71,3% of all HFA.

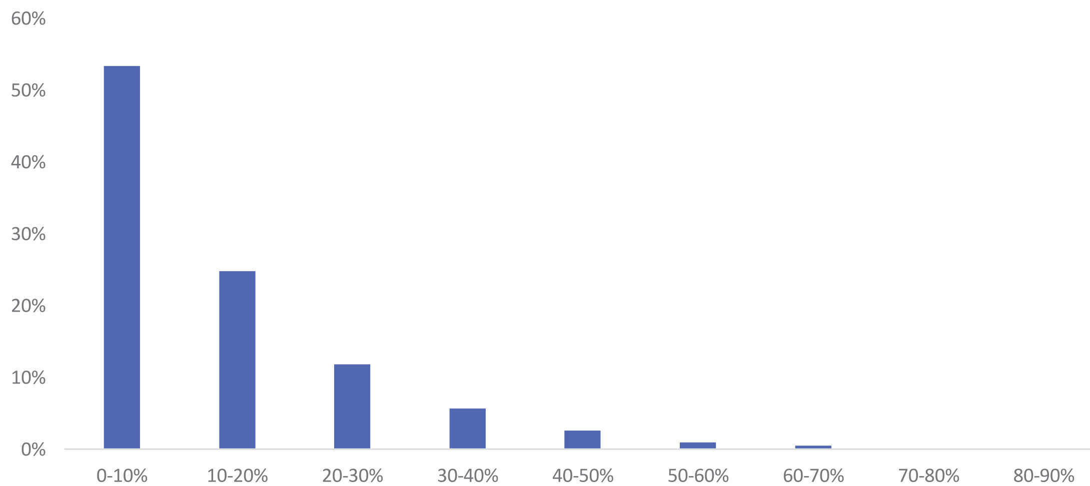

Fig. 2. Absolute relative error between calculated and measured final energy use.

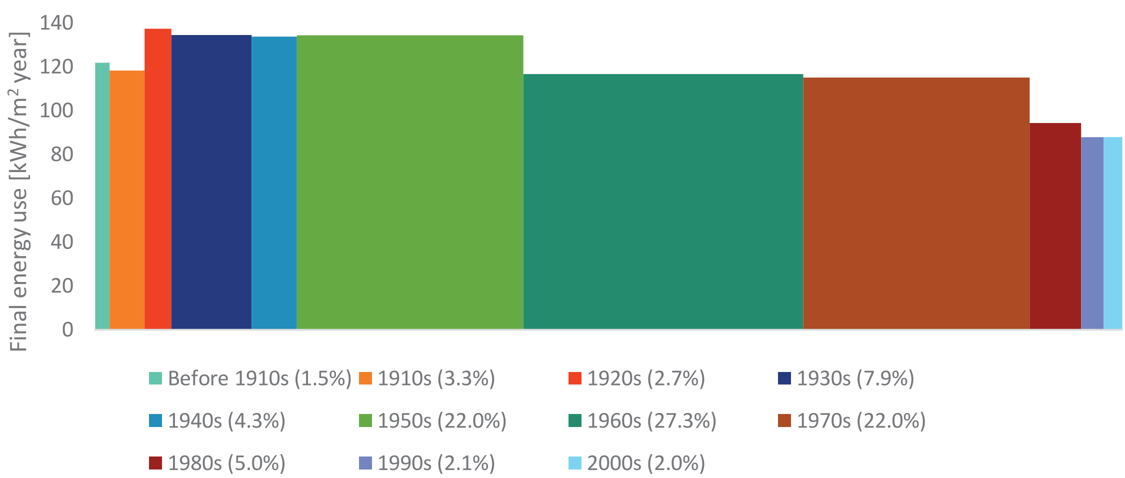

Fig. 3. Overview of the portfolio showing final energy use per age group based on year of construction. The width represents the share of heated floor area of age groups in relation to the entire portfolio [%].

Table 4
Average U-value of components per age group based on year of construction.

Year of construction	U-value wall [W/m^2 K]	U-value roof [W/m^2 K]	U-value window [W/m^2 K]	U-value floor [W/m^2 K]
Before 1910	0.82	0.36	2.46	0.20
1910s	0.63	0.34	2.06	0.19
1920s	0.74	0.33	2.19	0.19
1930s	0.77	0.33	2.18	0.19
1940s	0.79	0.33	2.41	0.20
1950s	0.69	0.30	1.95	0.20
1960s	0.53	0.27	2.10	0.20
1970s	0.54	0.27	2.32	0.20
1980s	0.41	0.23	2.36	0.20
1990s	0.32	0.20	2.13	0.21
2000s	0.15	0.14	1.01	0.15

In Table 4, average U-values of components is shown for the age groups to provide additional context.

In Fig. 4, buildings in the portfolio are instead grouped by area factor to show the relative size and energy performance in relation to the value of the location. Again, the differences in energy performance are small with a slightly higher average energy performance for buildings in areas with an area factor above nine and below five. It should be noted that while 58% of the stock is situated in areas with an area factor below seven, a large share of the stock is also located in areas with an area factor above 8. This furthers the view that the portfolio is highly diverse in terms of location and age groups. In Fig. 5, the spatial distribution of buildings and corresponding value factors are shown. As can be seen, the stock is mostly situated outside of the city centre.

3.2. Cost effectiveness of deep renovation

On a stock level, average final energy use is reduced by 51%, from 113 kWh/m^2 year to 55 kWh/m^2 year by applying the renovation measure to all buildings. Final energy use per age group based

Fig. 4. Final energy use of buildings in the stock aggregated to value factor for the value area corresponding to each building. The width represents the share of heated floor area of buildings per area factor in relation to the entire portfolio [%]. The value factor has been rounded down to the nearest integer.

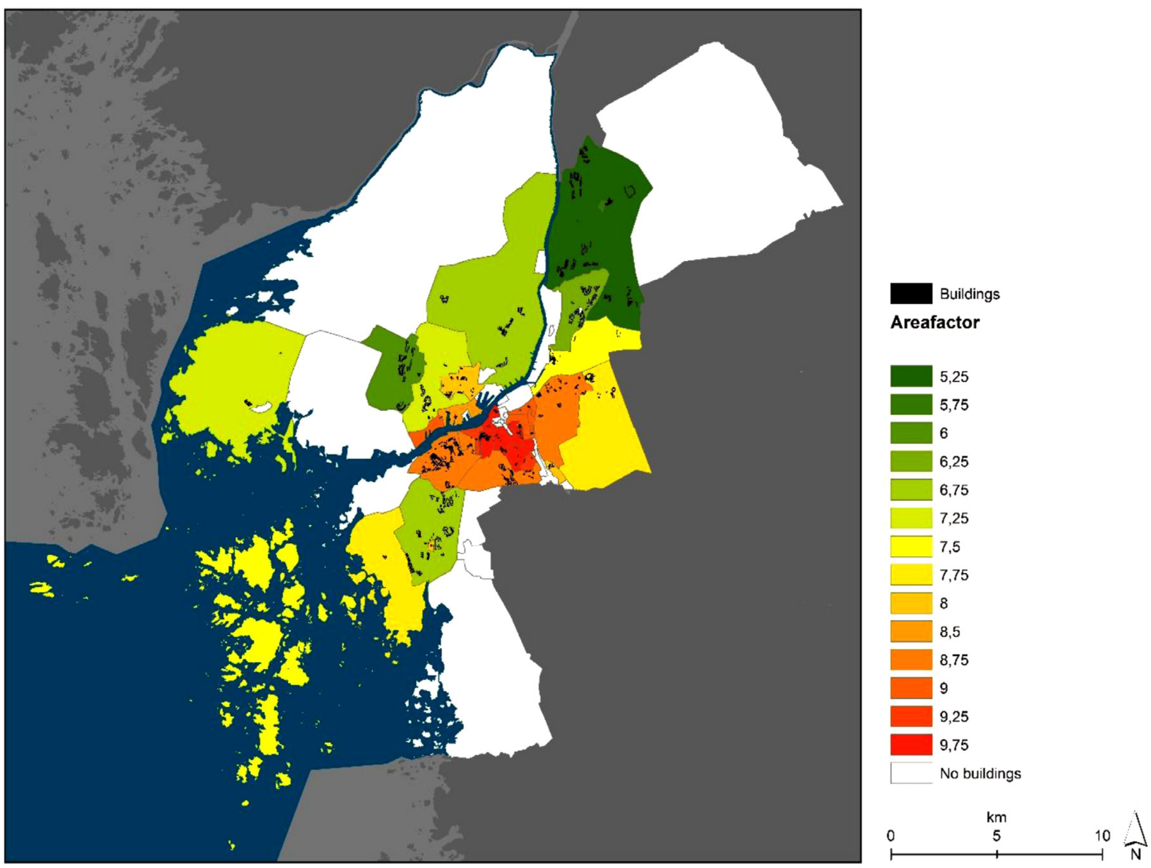

Fig. 5. Spatial distribution of buildings and corresponding value factors for the areas. Value factors have been grouped by rounding down to the nearest integer. Number of buildings in each category is shown in brackets.

on year of construction is shown in Fig. 6. As a first step to assess the cost-effectiveness of deep renovation, final energy cost savings as a share of EAC are shown in Fig. 7. While the applied renovation package is similar for all buildings, due to individual differences between buildings the cost-effectiveness of deep renovation varies greatly. There are several reasons for this. First, deep renovation for buildings with an initially higher energy performance will have a lower impact on energy use while costs remain similar. Second, the compactness (envelope area in relation to floor area) of buildings have a significant impact. Smaller buildings are in general disadvantaged by this as well as older buildings due to having taller ceilings. Third, certain reinstatement costs scale by number of apartments and not by building size. On average, annual cost savings due to reduced energy use covers 21% of the equivalent annual retrofit cost. However, for 7 buildings energy cost savings alone offset more than half the EAC of deep renovation. This indicates a need for additional gains for these measures to be profitable through lower maintenance cost, exemption from property fee or increasing rent levels.

In Fig. 8, the final energy cost savings is shown as a share of EAC aggregated to value areas. As can be expected, aggregated results show smaller differences and the majority of areas show energy cost savings accounting for 21–25% of EAC. This indicates that targeting certain areas for deep renovation may not be the most cost-effective option but rather a building-specific approach should be used. This point is further enhanced in Fig. 9, where the energy

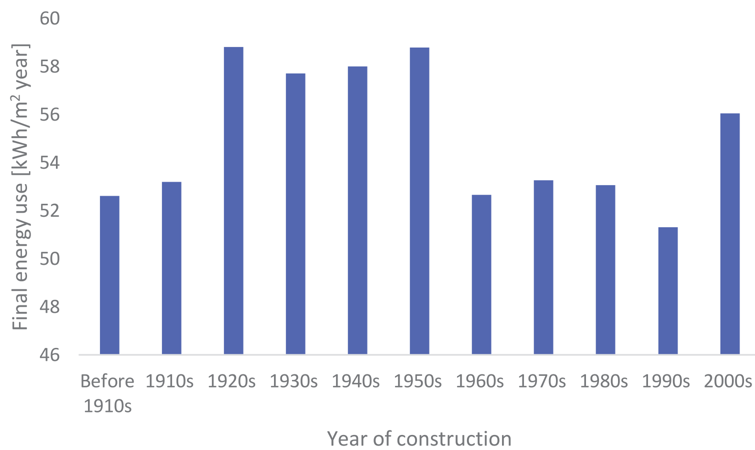

Fig. 6. Final energy use for SH, DHW and auxiliary electricity use after applying the renovation package to the entire portfolio. Buildings are grouped based on year of construction.

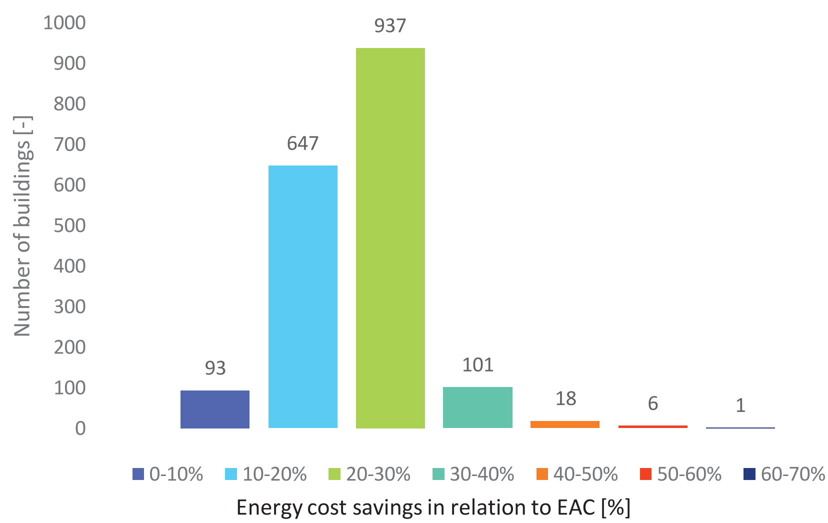

Fig. 7. Number of buildings grouped by yearly energy cost savings in relation to equivalent annual cost [%].

cost savings is shown as a share of EAC for a specific value area. As can be seen, the cost-effectiveness of deep renovation of individual buildings within the area varies greatly.

In Fig. 10, the final energy saved is shown in relation to the change in assessed building value. The largest energy use reductions are typically found in buildings with a lower change in assessed building value. As the change in assessed building value is calculated based on a new value year, it would suggest that buildings in central locations where the location factor and rent levels are higher have a lower potential to reduce energy use. In addition, as reinstatement costs scale non-linearly with size, larger buildings with a sizable potential for reducing energy use will also have a lower change in assessed building value.

In Fig. 11, assessed change in building value is shown in relation to investment costs. Buildings with investment costs lower than 20% of new construction costs (339 EUR/m^2) do not get a change in value year and subsequently no change in assessed building value. Again, while there in general is a positive correlation between investment cost and change in assessed building value, the individual differences are large. In addition, the change in assessed building value is small in comparison with investment cost, on average 9%. Only 3 buildings have a change in value year which allows for exemption from property fee. For those three buildings, being exempt from property fee would save them on average 2.1 EUR/m^2 year. For buildings that do not get exempt from property fee due to renovation, the average fee increases with 0.11 EUR/m^2 year. As such, the change in property fee due to renovation is limited compared to investment costs. While deep renovation only impacts part of the assessed building value directly through a change in value year, secondary effects such as an increase in area factor and rent levels may provide additional value.

4. Discussion

In this paper, we have developed a novel approach for assessing and differentiating cost-effectiveness of deep renovation within a building portfolio using EAC and change in assessed building value. Deep renovation is certainly not suitable for all buildings in the portfolio, neither from an energy nor cost-effectiveness point of view. Rather, the results serve as a first step to prioritize buildings and areas or neighbourhoods to differentiate where deep renovation is suitable within a large building portfolio. Further detailed assessment of buildings suitable for deep renovation is needed as well as tailoring of the renovation measures to each building. For

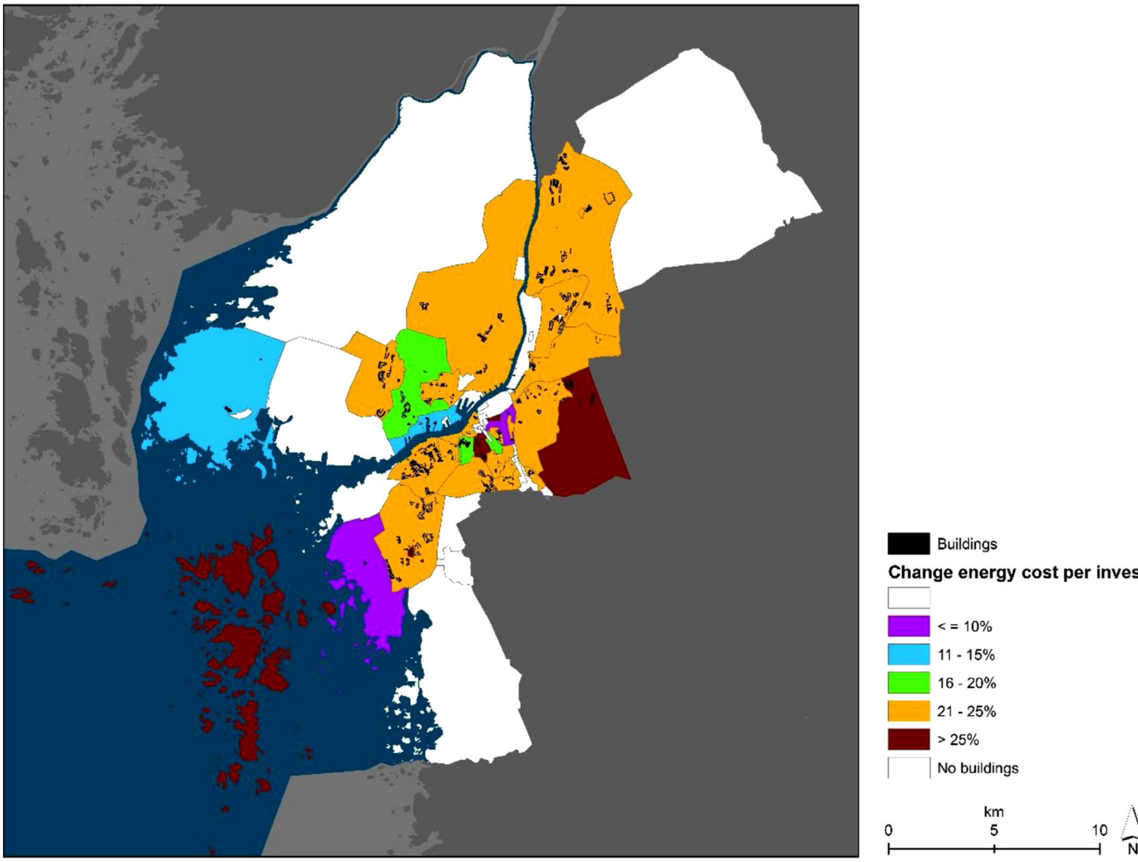

Fig. 8. Yearly energy cost savings in relation to equivalent annual cost aggregated to value areas.

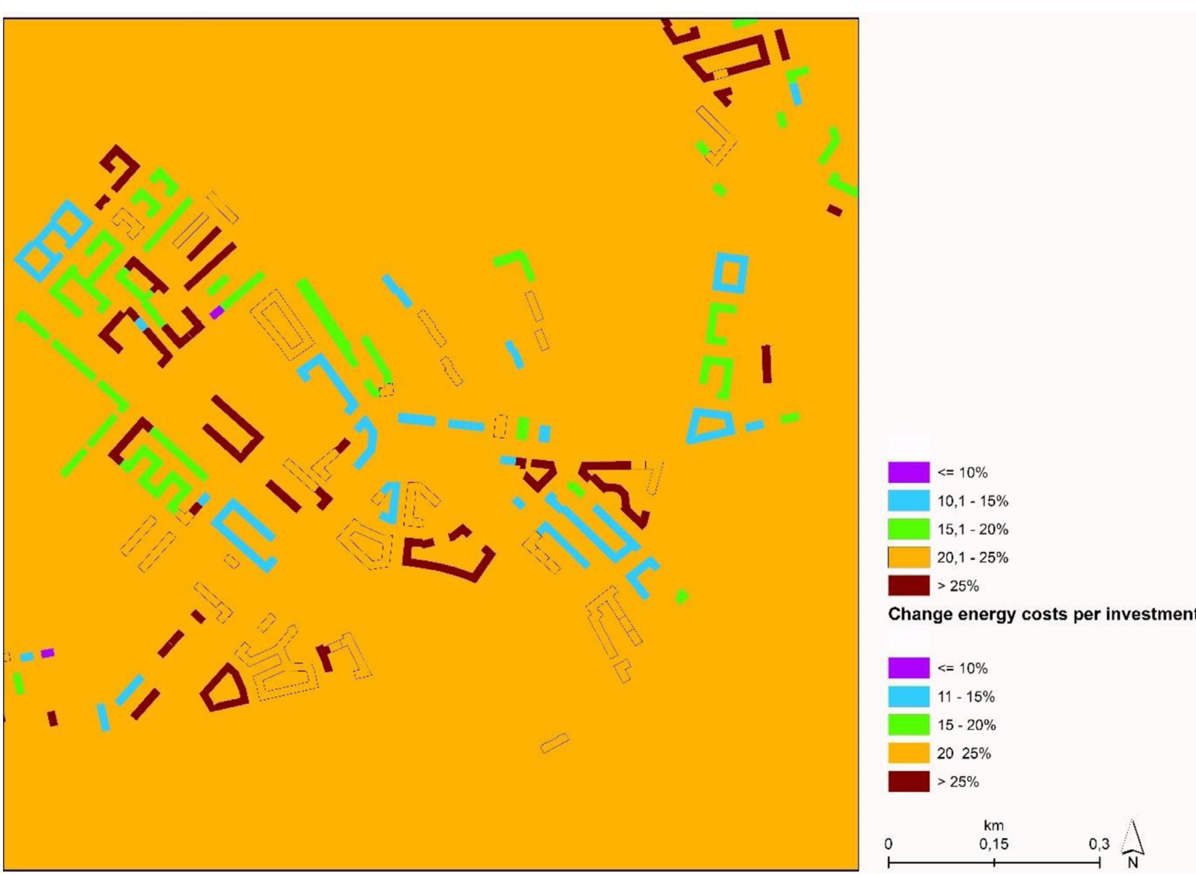

Fig. 9. Yearly energy cost savings in relation to equivalent annual cost. Background colour shows average yearly energy cost savings in relation to equivalent annual cost for the value area.

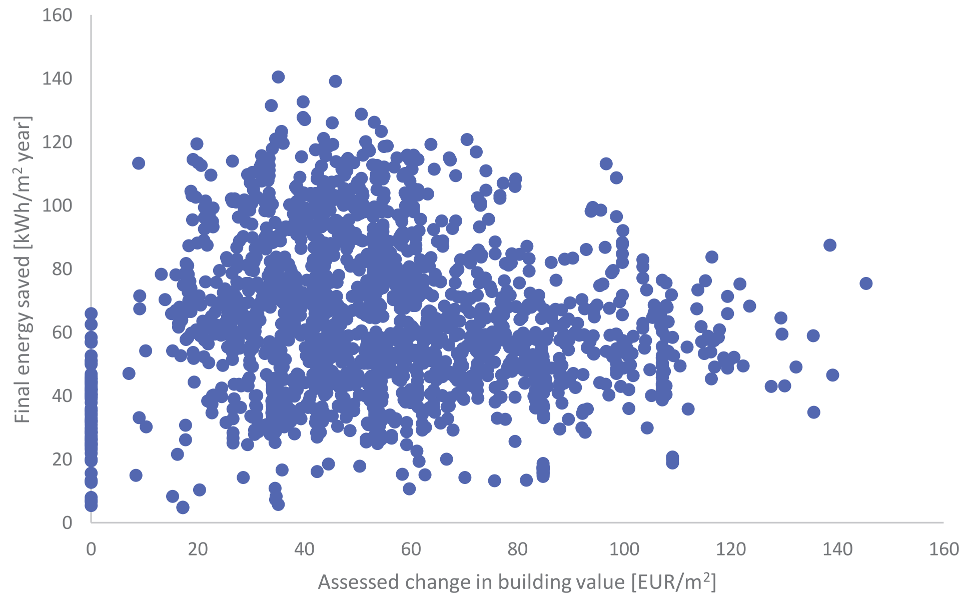

Fig. 10. Final energy saved in relation to assessed change in building value.

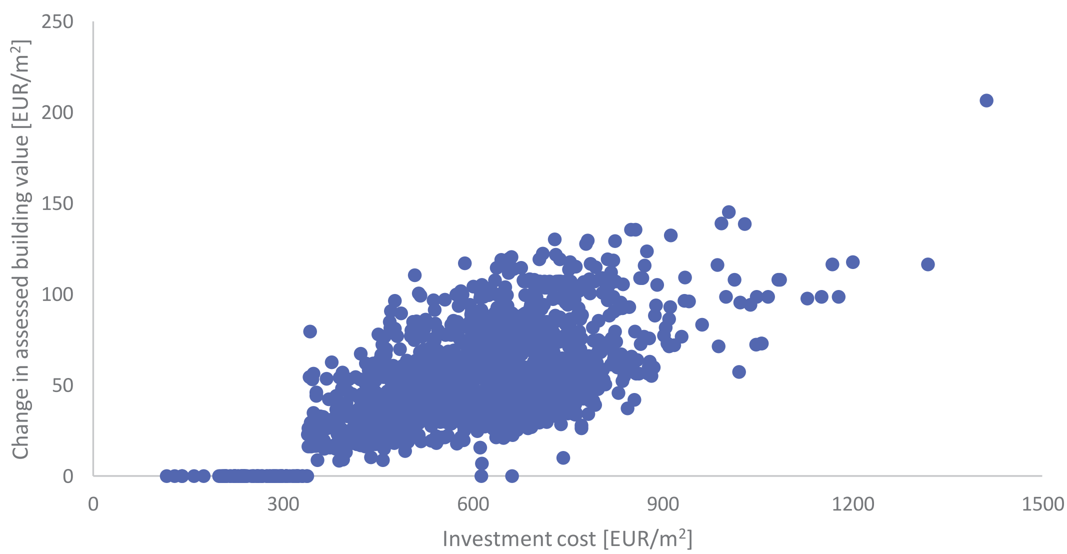

Fig. 11. Change in assessed building value in relation to investment cost.

a detailed economic assessment the framework proposed in EN 15,459–1:2017 [46] could be used and additional uncertainty analysis could be performed [47]. While the deep renovation package on average provides a 50% energy use reduction across the portfolio, there is no single building where energy cost savings completely offset investment costs. However, while energy cost savings on average covers 21% of investment costs, there are several buildings where it covers a substantial part. If change in assessed building value is accounted for, the gap is further diminished. The effect of change in property fee is limited when assessing cost-effectiveness but may prove to be the differentiating factor when assessing profitability in marginal cases. To overcome the remaining gap, there is a need to reduce cost of renovation, increase rental income and/or lower maintenance costs. The broad application of similar renovation packages used in this paper should be tailored to each individual building to optimize cost-effectiveness. Furthermore, the timing of interventions could be optimised to coincide with end-of-life of components by adding information from maintenance plans [18]. This would allow for assessing additional EEM from a marginal cost perspective, discounting for reinstatement costs [48]. Similarly, by identifying buildings suitable for extension, the cost-effectiveness of deep renovation could be improved as part of new construction. Another option to reduce the cost of deep renovation would be to target areas with a concentration of buildings suitable for deep renovation, where repetition factors and economies of scale could improve the cost-effectiveness of deep renovation. As such, map-based visualizations can be an effective tool in identifying and communicating areas to prioritize which are suitable for deep renovation. However, as cost-effectiveness of deep renovation can vary substantially within areas, aggregated results should be used with care. Regarding potential to increase rental income to offset investment costs, the possibilities are limited in the Swedish case due to regulation, as only measures affecting the living standard are accounted for. If substantial changes in rent levels are needed to cover the cost of renovation, socio-economic implications may be accounted for [35].

In general, the change in assessed building value using to the Swedish taxation agency model is small compared to investment costs but similarly to other results there is a large distribution where the assessed building value increases with up to 23% of investment costs. The method used to assess change in building value is simplified. Although a previous study [49] has shown good agreement between assessed value and sale prices for income properties, further work could compare results to those given by hedonic models [19,50]. Furthermore, in this paper only direct effects of deep renovation are considered through a change in value year describing the state of the building. Additional effects of deep renovation, such as increase in value of an area or neighbourhood due to renovation activities could be accounted for [51]. In addition, deep renovation is likely to result in an increase in rent levels which would further impact the assessed building value. As such, the assessed change in building value presented in this paper is likely a low estimate.

It is clear from the distribution in results that any generalization regarding cost-effectiveness of deep renovation is troublesome at best. As such, to adequately assess the technical or economical potential of deep renovation of the existing building-stock, a building-specific approach should be used. In addition to providing a more nuanced view of the current stock and its potential development, a differentiated building-stock description allow for aggregation of results arbitrarily, enabling assessment untethered from geographical or economical boundaries to suit individual stakeholders. While data may be lacking to enable building-specific modelling on a national or European scale, synthetic building-stocks can be used to provide similarly nuanced results [34].

The lack of measured energy consumption data on a building level is commonly cited as a barrier to reduce uncertainty in BSM. In this paper, energy demand is calibrated on a building level using measured energy consumption from EPCs resulting in 80% of buildings being within 30% of measured energy use values. While it is certainly possible to further improve upon, data quality issues regarding the measured consumption values in the EPCs is problematic. For instance, a building from the mid 1960s lacking heat recovery and with no indication of previous renovation activities is listed as having an energy performance around 50 kWh/m^2 year while calculated results indicate the energy demand should be tripled. As such, forcing the calibration to adjust for an unreasonable measured result is deemed unnecessary. To further reduce uncertainty, calibration would ideally be done based on updated consumption values provided by the property owner. In addition, information regarding the current state of the buildings and remaining service life of components is limited and could be further improved upon by integrating maintenance plans. Finally, an up to date 3D model of the building-stock would be beneficial in reducing uncertainty and enable more accurate estimations of surface areas.

Future work should assess other property owners to showcase different stock conditions and subsequent implications. As location has a significant impact, stocks with a larger geographic spread could be investigated. In addition, the modelling framework could be expanded to non-residential buildings although a different approach would be needed for energy modelling as well as property valuation.

5. Conclusions

By using a bottom-up engineering-based model utilizing building-specific information for the municipal housing company portfolio in the City of Gothenburg, deep renovation is assessed by applying a package of energy efficiency measures across all buildings. Deep renovation is assessed in terms of equivalent annual cost, assessed changed in building value using a simplified method as well as energy use reduction and subsequent energy cost saved. Results show average energy use reductions across the portfolio of 51% to an average cost of 597 EUR/m^2 living area. On average, energy cost savings alone account for 21% of equivalent annual cost. However, the difference within the portfolio is large and there are cases where more than half of the EAC is covered by energy cost savings. Similarly, the average change in assessed building value due to renovation is 9% of investment cost while the range for individual buildings is 0–23%. As such, the cost-effectiveness of deep renovation varies greatly which should be accounted for when prioritizing deep renovation within a portfolio. The results are intended as a first step in prioritizing deep renovation within a building portfolio and further detailed assessment of buildings suitable for deep renovation is needed as well as tailoring of the renovation measures to each building.

As nationally available data is used, the method can be applied to any building-stock in Sweden. However, to increase the accuracy of the results, maintenance plans and surveys of the specific stock in question could be integrated to better estimate the current state of the buildings in the stock. While similar data may not be nationally available in other countries, data from specific property owners could be used to the same effect. Future work could expand on the assessed change in building value using advanced methods and a similar modelling approach could be used for non-residential buildings.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property. We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author.

Acknowledgment

The authors would like to thank EIT Climate-KIC, AoA Energy, SIRen, NCC AB, The Swedish Energy Agency and EC H2020 DREEAM for funding the project.

References

[1] U. Sbci, in: Buildings and Climate change: Summary For Decision-Makers', United Nations Environment Programme Sustainable Buildings Climate Initiative, Paris, 2009, pp. 1–62.
[2] B. Atanasiu, C. Despret, M. Economidou, J. Maio, I. Nolte, O. Rapf, Europe's buildings under the Microscope: a Country-by-Country review of the energy performance of Buildings, Build. Perform. Inst. Eur. (2011).
[3] E. Recast, Directive 2010/31/EU of the European parliament and of the council of 19 may 2010 on the energy performance of buildings (recast), Off. J. Eur. Union 18 (06) (2010) 2010.
[4] F. Ascione, R.F. De Masi, F. de Rossi, R. Fistola, M. Sasso, G.P. Vanoli, Analysis and diagnosis of the energy performance of buildings and districts: methodology, validation and development of urban energy maps, Cities 35 (2013) 270–283.
[5] K. Fabbri, M. Zuppiroli, K. Ambrogio, Heritage buildings and energy performance: mapping with GIS tools, Energy Build 48 (2012) 137–145.

[6] N.H. Sandberg, I. Sartori, H. Brattebø, Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock, Energy Build 82 (2014) 287–295.
[7] F. Vásquez, A.N. Løvik, N.H. Sandberg, D.B. Müller, Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock, Energy Build 111 (2016) 37–55.
[8] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: a review of modeling techniques, Renew. Sust. Energy Rev. 13 (8) (2009) 1819–1835.
[9] M. Kavgic, A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, M. Djurovic-Petrovic, A review of bottom-up building stock models for energy consumption in the residential sector, Build. Environ. 45 (7) (2010) 1683–1697.
[10] C.F. Reinhart, C. Cerezo Davila, Urban building energy modeling – a review of a nascent field, Build. Environ. 97 (2016) 196–202.
[11] M. Österbring, L. Thuvander, É. Mata, H. Wallbaum, Stakeholder specific multi-scale spatial representation of urban building-stocks, ISPRS Int. J. GeoInf. 7 (5) (2018) 173.
[12] M. Gangolells, M. Casals, N. Forcada, M. MacArulla, E. Cuerva, Energy mapping of existing building stock in Spain, J. Clean. Prod. 112 (June 2013) (2016) 3895–3904.
[13] J.A. Fonseca, A. Schlueter, Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts, Appl. Energy 142 (2015) 247–265.
[14] A. Mastrucci, O. Baume, F. Stazi, U. Leopold, Estimating energy savings for the residential building stock of an entire city: a GIS-based statistical downscaling approach applied to Rotterdam, Energy Build 75 (2014) 358–367.
[15] M. Aksoezen, M. Daniel, U. Hassler, N. Kohler, Building age as an indicator for energy consumption, Energy Build 87 (2015) 74–86.
[16] A.T. Booth, R. Choudhary, D.J. Spiegelhalter, Handling uncertainty in housing stock models, Build. Environ. 48 (1) (2012) 35–47.
[17] E. Kazimieras Zavadskas, A.R. Kaklauskas, S. Raslanas, International journal of strategic property management evaluation of investments into housing renovation evaluation of investments into housing renovation, Int. J. Strateg. Prop. Manag. 83 (8) (2004) 177–190.
[18] A. Farahani, H. Wallbaum, J.-O. Dalenbäck, Optimized maintenance and renovation scheduling in multifamily buildings–a systematic approach based on condition state and life cycle cost of building components, Constr. Manag. Econ. 0 (0) (2018) 1–17.
[19] J.J. Mcarthur, C.G.H. Jofeh, Portfolio retrofit evaluation: a methodology for optimizing a large number of building retrofits to achieve triple-bottom-line objectives, Sustain. Cities Soc. 27 (2016) 263–274.
[20] D.P. Lorenz, S. Trück, T. Lützkendorf, Exploring the relationship between the sustainability of construction and market value: Theoretical basics and initial empirical results from the residential property sector, Prop. Manag. 25 (2) (2007) 119–149.
[21] N. Miller, J. Spivey, A. Florance, Does green pay off? J. Real Estate Portf. Manag. 14 (4) (2008) 385–400.
[22] A. Uihlein, P. Eder. Policy options towards an energy efficient residential building stock in the EU-27 §, Energy Build, vol. 42, pp. 791–798.
[23] S. Caird, R. Roy, H. Herring, Improving the energy performance of UK households: Results from surveys of consumer adoption and use of low-and zero–carbon technologies, Energy Efficiency 1 (2) (2008) 149.
[24] A. Audenaert, L. De Boeck, K. Roelants, Economic analysis of the profitability of energy-saving architectural measures for the achievement of the EPB-standard, Energy 35 (2010) 2965–2971.
[25] E. Asadi, M. Gameiro Da Silva, C.H. Antunes, L. Dias, Multi-objective optimization for building retrofit strategies: a model and an application, Energy Build 44 (2011) 81–87.
[26] E. Kazimieras Zavadskas, A.R. Kaklauskas, S. Raslanas, Evaluation of investments into housing renovation, Int. J. Strateg. Prop. Manag. 83 (8) (2004) 177–190.
[27] E. Pikas, J. Kurnitski, R. Liias, M. Thalfeldt, Quantification of economic benefits of renovation of apartment buildings as a basis for cost optimal 2030 energy efficiency strategies, Energy Build 86 (2015) 151–160.
[28] S. Stanley, R.C. Lyons, S. Lyons, The price effect of building energy ratings in the Dublin residential market, Energy Effic. 2053 (2016).
[29] M. Hyland, R.C. Lyons, S. Lyons, The value of domestic building energy efficiency — evidence from Ireland, Energy Econ 40 (2013) 943–952.
[30] F. Fuerst, P. McAllister, A. Nanda, P. Wyatt, Energy performance ratings and house prices in Wales: An empirical study, Energy Policy 92 (2016) 20–33.
[31] R.P. Pascuas, G. Paoletti, R. Lollini, Impact and reliability of EPCs in the real estate market, Energy Proced. 140 (Dec. 2017) 102–114.
[32] E.E. Directive, Directive 2012/27/EU of the European parliament and of the Council of 25 October 2012 on energy efficiency, amending directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32, Off. J. L 315 (2012) 1–56.
[33] M. Österbring, É. Mata, L. Thuvander, M. Mangold, F. Johnsson, H. Wallbaum, A differentiated description of building-stocks for a Georeferenced urban bottom-up building-stock model, Energy Build 120 (2016) 78–84.
[34] C. Nägeli, C. Camarasa, M. Jakob, G. Catenazzi, Y. Ostermeyer, Synthetic building stocks as a way to assess the energy demand and greenhouse gas emissions of national building stocks, Energy Build 173 (2018) 443–460.
[35] M. Mangold, M. Österbring, H. Wallbaum, L. Thuvander, P. Femenias, Socio-economic impact of renovation and energy retrofitting of the Gothenburg building stock, Energy Build 123 (2016) 41–49.
[36] Swedish tax agency, 'SKV A 2015:14', 2015.
[37] C. Björk, P. Kallstenius, L. Reppen, Så Byggdes Husen 1880-2000: arkitektur, Konstruktion Och Material i Våra Flerbostadshus Under 120 år, Svensk Byggtjänst, 2013.
[38] U. Agethen, K. Frahm, K. Renz, E.P. Thees, Lebensdauer Von Bauteilen, Zeitwerte [Lifetime of Building Components, Time Values], Bund Technischer Experten eV, Essen, 2010.
[39] IP BAU, Alterungsverhalten Von Bauteilen Und Unterhaltskosten - Grundlagendaten Für Den Unterhalt und Die Erneuerung Von Wohnbauten [Ageing Behaviour of Building Components and Maintenance Costs - Background Data For the Maintenance and Refurbishment of Residenti, IP BAU, Bern, Switzerland, 1994.
[40] ISO, 'ISO 52016-1:2017: Energy performance of buildings–Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads–Part 1: calculation procedures'. 2017.
[41] INCIT, UNDERHÅLLSKOSTNADER - REPAB FAKTA, INCIT, Mölndal, 2017.
[42] Wikells, Sektionsfakta-ROT 17/18 Teknisk-ekonomisk sammanställning Av ROT-byggdelar (Technical and Financial Compilation of Building Parts), Wikells Byggberäkningar AB, Växjö, Sweden, 2017.
[43] Wikells, Sektionsfakta-VSS 17/18 Teknisk-ekonomisk sammanställning Av VVS-byggdelar (Technical and Financial Compilation of HVAC Parts), Wikells Byggberäkningar AB, Växjö, Sweden, 2017.
[44] G. Blomé, » Ekonomisk värdering av ägarstrategier i ett Miljonprogramsområde i Malmö: Hyresfastigheter på Lindängen «, Rapport', Malmö högskola, 2014.
[45] E. Pagourtzi, V. Assimakopoulos, T. Hatzichristos, N. French, Real estate appraisal: a review of valuation methods, J. Prop. Invest. Financ. 21 (4) (2003) 383–401.
[46] European Committee for Standardization, 'EN 15459-1:2017 energy performance of buildings - Economic evaluation procedure for energy systems in buildings - Part 1: calculation procedures.', 2017.
[47] E. Di Giuseppe, M. Iannaccone, M. Telloni, M. D'Orazio, C. Di Perna, Probabilistic life cycle costing of existing buildings retrofit interventions towards nZE target: methodology and application example, Energy Build 144 (2017) 416–432.
[48] A. Farahani, H. Wallbaum, J.-O. Dalenbäck, The importance of life-cycle based planning in maintenance and energy renovation of multifamily buildings, Sustain. Cities Soc. 44 (2019) 715–725.
[49] C. Janssen, B. Söderberg, Estimating market prices and assessed values for income properties, Urban Stud 36 (2) (1999) 359–376.
[50] M. Cajias, D. Piazolo, Green performs better: energy efficiency and financial return on buildings, J. Corp. Real Estate 15 (1) (2013) 53–72.
[51] C. Ding, R. Simons, E. Baku, The effect of residential investment on nearby property values: evidence from Cleveland, Ohio, J. Real Estate Res. 19 (1) (2000) 23–48.