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Evaluation of cost-effective measures for the renovation of existing dwellings in the framework of the energy certification system: A case study in Norway

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ABSTRACT

The Energy Performance Certificate (EPC) for existing dwellings has not been able to promote the renovation rate. The main reasons are associated with the low quality of the assessment and renovation recommendations provided. These are not able to provide the information or confidence needed to undertake a renovation project. So far, neither reports for the EPBD nor studies by researchers have proposed modifications to the model used to assess existing buildings under the EPBD. The present research proposes a procedure to evaluate, design improvements, store and share data on the renovation process of each building. Specifically, the procedure is based on three steps, the first one is to apply simplified measurements on the dwelling, laser scanning and envelope testing. The second stage, using the electricity consumption data, was to calibrate and calculate the thermal properties of the building. Finally, tailor-made recommendations for the whole life cycle of the house are proposed and stored in a database. After an optimisation and life cycle analysis of different measurement packages. The results show that by incorporating currently available tools, such as scanners, smart meters and BIM, a complete building condition profile can be obtained, stored and shared, and renovation measures with their benefits and costs can be realistically proposed. This study is in line with what has been proposed by previous studies, the need to digitise the certification system, to use new technologies and to capture the trust of the users.

1. Introduction

The renovation of the existing building stock is one of the main challenges worldwide, and at the same time one of the main opportunities to achieve high energy efficiency and environmental objectives. Table 1.

Eurostat data in 2019 indicates that the building sector consumes around 40% of total energy used in Europe, of which the residential sector alone accounts for >50%. According to the Building Performance Institute of Europe (BPIE) [1], 97% of today's buildings need to be renovated. Existing building stock is not considered energy-efficient today, supported by the fact that at least 40% were built before the 1960s when most building codes did not include energy efficiency requirements [2]. This indicates that there is an easily-identified group of buildings that have the potential to significantly reduce energy consumption levels in the building sector. However, the development of a renovation plan to increase renovation rates towards "deep renovations" is not an easy task [3]. This is in addition to the lack in the European construction sector of a comprehensive approach to deep renovation at acceptable cost and quality [4]. Consequently, the renovation process has been slow, with an annual renovation rate of about 1%, whereas the European Commission defines an annual renovation rate of 3% to achieve the proposed environmental targets [5].

Abbreviations: ASHRAE, American Society of Heating, Refrigerating and Air-conditioning Engineers; BIM, Building Information Modelling; BRP, Building Renovation Passport; CV(RMSE), Coefficient of Variation of the Root Mean Square Error; EPBD, Energy Performance of the Building Directive; EPC, Energy Performance Certificate; FEMP, Federal Energy Management Program; IFC, Industry Foundation Classes; IPVMP, International Performance Measurements and Verification Protocol; IRR, Internal Rate of Return; IRT, Infrared Thermography; LCC, Life Cycle Cost; NMBE, Normalised Mean Bias Error; T_o, Outside Temperature; T_R, Reference Temperature.

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Table 1
Literature review of recent studies on measures to improve the certification system.

Improvement	building	Stakeholder	Country	Year	Reference
Assessment of energy reduction before and after renovation according to EPCs	Multifamily building	Policymakers	Sweden	2019	[16]
Enhancement of the analysis of EPC data	Building stock	Policymakers	Spain	2018	[17]
Prediction of energy consumption	Dwellings	Building owners and policymakers	Luxemburg	2019	[18]
Proposal of a methodology to estimate the energy demand rating of uncertified buildings through machine learning and existing EPCs	Residential buildings	Authorities, policymakers, and urban planners	Ireland	2019	[19]
Proposal of EPC data quality assurance at six levels of validation to refine the understanding of known and unexpected data quality problems	Dwellings	Policymakers	Sweden	2019	[20]
Linking of data between the EPC database and energy consumption at district level, improvement of the accuracy of the energy assessment and provision of a GIS mapping tool	Residential buildings at district level	Policymakers	Italy	2021	[21]
Proposal of a methodology related to the EPC to evaluate renovation measures.	Residential apartment building	Policymakers	Norway	2020	[22]
Linking of building users' expectations with retrofitting technologies to improve EPC recommendations	Residential buildings	Building owners	Romania	2020	[23]
Proposal of a method to reduce the energy gap between simulation and energy measurements by calibrating reference models	Residential buildings	Policymakers and Building owners	Ireland	2020	[24]
Proposal of an indoor air pollution modelling tool for spatially distributed housing stock, developed using EPC data and a neural network metamodel	Dwellings	Policymakers and occupants	England and Wales	2019	[25]
Proposal of new indicators to identify and prioritise housing in need of renovation	Dwellings	Policymaker and authorities	Spain	2018	[26]

One of the main tools for improving the energy performance of buildings and increasing their renovation rate is the Energy Performance Certificate (EPC). The EPC is a mechanism designed to raise awareness of energy efficiency and promote the improvement of building performance by providing prospective owners and tenants with information on energy consumption [11]. The EPC not only energy labels existing buildings, but also provides recommendations for their renovation to improve their energy performance. Despite the importance of the EPC, this tool has not reached expectations regarding energy efficiency and renovation rate. Two factors contribute to this: First energy labelling tools are tailored for new buildings, focussing predominantly on building design [6], which have been subsequently slightly adapted to evaluate existing buildings. Second, the strict technical requirements designed for energy labelling are inadequate on their own to improve energy efficiency [7]. This is because most of the information required to analyse existing buildings is difficult to find: most of the time the necessary input data to assess the building must be guessed or based on standardised values. This leads to great uncertainty about a building's energy performance and, consequently, potential for improvement. These shortcomings also have an impact on the recommendations included to renovate the building. Both the energy savings and the return on investment may not be realistic, since they are not calculated based on the actual conditions of the building such as thermal properties and energy consumption.

1.1. Studies carried out to improve the EPC

Although there are numerous aspects of the certification system that can be improved, there are several issues that must be considered, such as the actors involved, the development of tools or platforms, the research and training required, the balance between costs and quality etc. Studies aimed at improving the certification system can be divided into two lines of research. The first emphasises the incorporation or improvement of existing components of the certification system. Such is the case of the quality control of data collected in the EPC [8], assessment methods [9], lack of measurements [10], and certifiers' training [11]. The second line of research suggests that improvements in the certificate itself are necessary. Such is the case of the energy rating [12,13], indicators [14] and recommendations included in the certificate [15]. A summary of recent studies addressing improvements in the certification system can be found in the Table 1. This shows the trends in the academic field regarding the aspects of the certification system that receive attention.

The EPC is the main source of information on the efficiency levels of the building stock, providing insight on how to plan future energy policies [25]. While the above table reveals interesting and relevant proposals for updating the certification system, according to our findings, there are no studies that focus on building inspection from the certifier's point of view, as the instructions, tools, method or calculations are often unknown.

1.2. Relevance of this study

The contribution of this study focuses on proposing a method for assessing existing buildings under the energy certification system. As mentioned above, there are no studies that incorporate the difficulties that certifiers must overcome. This is one of the most important aspects of the quality of the results and has the greatest potential to increase the renewal rate in the EU [13 15]. According to a recent study on the different methods for assessing buildings under the EPBD, there is no study that focuses on reducing the energy gap by improving the inspection of buildings. The study concludes that it is necessary to incorporate into the EPBD the new technologies available and that the upcoming changes need to be prepared for the future and the challenges in the coming decades [65]. Aspects that this proposal incorporates, taking a step forward in the modernisation of certification, using BIM, real energy consumption data and the use of measurements instead of standardised inputs. With this, the certification system takes on a robust character, both for policy makers and users.

In concrete, this research proposes a model for building assessment in the framework of the certification scheme. It allows a large amount of data to be collected efficiently and accurately, enabling long-term monitoring and in-depth analysis to develop a renovation plan throughout the building's life cycle. At the same time, It allows energy efficiency to be improved through various levels of intervention. Such as identification of urgent actions, replacement of weakened or underperforming components. This is achieved by strengthening inspection tasks and incorporating emerging technologies such as BIM and smart meters. These are already being used in the construction sector and in energy efficiency benchmarking [27].

The article is structured as follows: In the next section attention is given to the principles and challenges of building assessments, through a comprehensive literature review on building inspection and calibration. This background was put to use in the design of the assessment of the case study. Next, the methodology used is detailed, identifying materials and methods for inspecting the building and data collection. This includes the development of the geometric model, calibration, and cost-effective renovation measures. In the next section, the results are presented and contextualised in a case study. This is followed by discussions on the results and relevance of the study. Finally, the main conclusions are drawn and directions for future research are highlighted.

2. Background on building inspection and calibration

Field inspection and calibration are tasks directly related to the quality of the results. However, these are usually performed in a simplified manner. The challenges posed by these activities and their implications within the framework of the certification system are discussed below.

2.1. Field inspection

Field inspections are required under the certification systems in order to collect technical data about the building. Material that is necessary in the preparation of the certificate [28] include building geometry, envelope thermal properties and characteristics of the HVAC. Besides dwelling geometry, no measurement will be performed [29], most of the collected data will be based on assumptions and standard values. The depth of inspection varies from country to country, depending on their minimum requirements. For instance, in some countries certifiers are not obliged to perform a field inspection, this being the case for Austria, Czech Republic, Estonia, Poland and Germany [8]. While in other countries, the certificate can be issued without need of a certifier [30]. Therefore, inspection tasks can be omitted or simplified. This implies lower quality EPC but at a much lower cost than a thorough inspection [31–348]. Best practices include visual inspection, standardised testing (thermography/thermal imaging, blower door test) and interviews with homeowners. Two critical tasks in the field inspection are presented below, obtaining the geometry and properties of the buildings.of the building envelope.

Assessing the geometry of the buildings: Many existing buildings have outdated or non-existent floor plan drawings [35]. In order to evaluate the performance of a building through simulation tools, the geometry of the building has to be obtained. No specialised tool or knowledge is required to establish the geometry and the dimensions of the building in a traditional way [35]. However, this task will take time, especially in the case of single-family houses. Which are both the most energy inefficient and the most geometrically complex. Nowadays, more sophisticated techniques are available, such as data collected with terrestrial laser scanners, a single point laser range finder [36] and photogrammetry [35]. However, there are some disadvantages, a study [37] estimated that on-site scanning could take up to six hours, three hours in computer work to process the data, and three to five hours to prepare the 3D model. Most of the tasks require manual intervention, especially between BIM and BPS [37,38]. In addition to the above, 3D scanning often requires expensive equipment, trained operators to generate useful information from large point cloud datasets [39]. These problems can lead to simplifications that prevent the full potential of the information captured from being realised. For example, the development of a robust database with applications across different stakeholders and tools.

Assessing the building properties: In cases where the buildings have a history of several occupants during their use, there may be a significant number of modifications with respect to the original condition of the property. The assessment of building properties is likely to be based on visual inspection, which cannot provide the same quality data as measurements. For example, U-values will be calculated according to nominal values per layer, which in many cases are unknown. The most appropriate solution would be to perform in-situ measurements. However, these tasks require a considerable amount of time and knowledge as well as high costs and several pieces of equipment. This is the reason why this task is not mandatory under the certification scheme for residential buildings. If measurements have to be made, the total assessment would take days or weeks, as can be seen in Table 2. However, this may face some challenges in the certification system as it stands at present, given the cost involved and the unpopularity of on-site visits, which are seen as intrusive and of no apparent benefit. [40]. It is important to note that the certification system does not include the inspection of heating systems and boilers. This task is contemplated in the EPBD, but under its own scheme. This could be because heating and boilers require more frequent inspections, which should be carried out by a specialist with technical knowledge in this area.

2.2. Calibration

Through visual inspection, the materials are identified, standardised parameters are used to evaluate the building. Although the building will be evaluated through simulations, this practice presents several complications, as the accuracy of the assessment depends on whether the original conditions of the building have been correctly reflected in the simulation [41]. Many of the input data are unknown or uncertain, forcing the use of estimates [42].

Table 2
Detail of some field measurement requirements.

Inspection task	Type of test	Equipment installation	Measurement
Detecting U-values	*In-situ* heat flux in façade (BS ISO 9869–1:2014)	30 min	3 days
Indoor environment parameter	Indoor air temperature, relative humidity, CO2 concentration	20 min	2 weeks
Airtightness	Blower door test (UNE-EN13829)	–	[*]2–4 h
Thermal imaging survey	Performance of buildings — Detection of heat, air and moisture irregularities in buildings by infrared methods (ISO-6781)	2 h (Pre-heating)	[*]1 Hour
Ventilation rate	Velocity traversal method (EN-16211:2015)	–	[*]1 h
Occupancy behaviour	Survey	–	[*]30 min
Inspection of the heating system	EN 15378–1:2017	–	[**]1–2 h

[*] Estimated values, the time for this task will depend on the size of the dwelling and the experience of the specialist.
[**] The estimated time varies depending on the number of the heating system components.

Examples of these are the thermal properties of the envelope [43], modelling of occupant behaviour [34], climate [44,45], and configuration and efficiency of building system [46,47]. As a result, large discrepancies will occur between the energy performance of the building and the actual consumption [43,48,49].

Although building energy simulation is an effective tool to evaluate building performance, the scarcity of real data has been one of the main difficulties in developing renovation proposals. From this perspective, a calibrated hourly energy model plays a key role in validating simulation models in renovation projects to ensure their reliability [48–50]. Building model calibration refers to the estimation or adjustments of unknown parameters of the simulation model to reduce the gap between simulation and actual performance [48,50]. Moreover, it can provide insight on the thermal or electrical load of a building and better predict the performance of selected energy conservation measures [51]. This is normally done by using the available data and iteratively adjusting the unknown model parameters until the estimated energy performance matches (within the required tolerance) the actual measurements [44,52].

Calibration can be performed in various ways and according to the literature, there is no consolidated method [51,53]. This will depend on the objectives, the type of project, the data available and the skills of the modeller [51,54]. The most commonly used techniques are manual and automatic.[46]. Both have advantages and disadvantages depending on the type of task in which they are used.

Manual Calibration: This method relies heavily on the experience and professional judgment of the modellers since a well-thought-out selection of parameters must be selected and adjusted manually [55]. Normally it requires energy usage data, such as energy bills, smart meters and short-term monitoring [48]. These are used as a reference to test the calibration and to have a thorough knowledge of the physical and operational characteristics of the building. Additionally, manual calibration can be combined with the use of graphical and statistical analysis to guide the calibration process [45]. Manual calibration can quickly identify deviating parameters to fit the model, but finding the optimal solution is time-consuming [51].

Automatic calibration: Automatic calibration is a non-user-driven process, it takes building thermal performance model calibration as a mathematical optimisation operation, where an objective function or penalty function is defined for matching simulation results with measured data [48,55]. The automated method tends to reduce the physical model to a purely mathematical problem, neglecting some physical attributes of the actual buildings. This could result in a mathematically accurate model but a physically inaccurate match. Due to this, some researchers criticise automatic calibration [48]. Another consideration is that the automatic method implies a heavy computational burden, since it is required to iterate constantly until specified tolerances are reached or it must be stopped at a given time. While the power to compute such processes is more affordable nowadays, such an investment must be contemplated. Despite all these drawbacks, it is considered a faster and more effective method than manual calibration [55].

3. Material and methods

The methodology was designed with its application under the certification system in mind. Therefore, restrictions were that the procedure had be simple and capable of being performed by certifiers. In addition, the tools to be used, such as software or measuring equipment, had to be flexible. As can be seen in Fig. 1, the methodology is described in three main steps, building inspection, calibration, and cost-effective measures.

3.1. Building inspection

This first step consists of measurement campaigns aiming to collect accurate data on a broad scale to be used during post-analysis. The inspection process is crucial, as this task will determine the robustness of the results, as well as the potential and relevance of improvements over time. Two primary approaches are used: the scanning campaign and the energy audit.

3.1.1. Scanning campaign

The 3D laser scanning campaign was completed in four hours. The GLS-2000 scanner was used in most of the building. However, HoloLens was used to save time for quick measurements, such as in small storage rooms. A total of 16 scanning measurements were carried out from inside and outside the dwelling. Point cloud processing was done through Autodesk Recap. The main editing process was the alignment of the measurements and the removal of data points that were erroneous due to transparent or reflective surfaces. The resulting point cloud was exported into Autodesk Revit where it was used to model the building. Both procedures were performed in 7 h of work.

3.1.2. Energy audit

The experimental results of the energy audit have two objectives. The first is to provide data for calibration, especially airtightness, mechanical ventilation, and user behaviour. The second relates to the condition of the building, where the state of maintenance and the service life of some components is determined. Such as the condition of the thermal insulation, seals, HVAC, envelope cladding, etc. Although the inspection of the heating and boiler system is not part of the EPC, this item was considered a part of the audit in a simplified form. A check was made of the maintenance of the components and their proper insulation. A checklist containing a list of activities to be completed, including data from the building's users and descriptions of the structure, was prepared before the field inspection. The checklist for inspections can be seen in detail in the appendix. The energy audit considered in-situ measurements, such as the Blower Door Test, Infrared Thermography (IRT) and the airflow rate of mechanical ventilation. The measurement campaign was conducted on one day in winter, under overcast conditions, with the temperature difference between the building and the exterior maintained at around 20 °C. While the blower door test was being performed, a walk-through inspection took place along with the IRT. Thermal bridges and airgaps were detected during the examination, identifying where to prioritise the renovation measures.

The IRT camera used was a FLIR E4 and the TSI 7575 Q-trak was used to measure airflow rate. Thermal images were taken from the building's interior, covering facades and ceilings. The airflow rate on each of the exhaust vents was measured, except on the kitchen hood where the measurements were made in the duct.

3.2. Calibration

The calibration process considers a regression model, a sensitivity analysis, and a sequence of simulations to match the electrical data measured.

3.2.1. Outliers

The data was filtered to reduce noise and extreme values. The outliers were treated based on a monthly analysis to detect unusual (very high) electrical consumption. To reduce their influence on linear regression, those values were weighed. As shown in Figs. 2

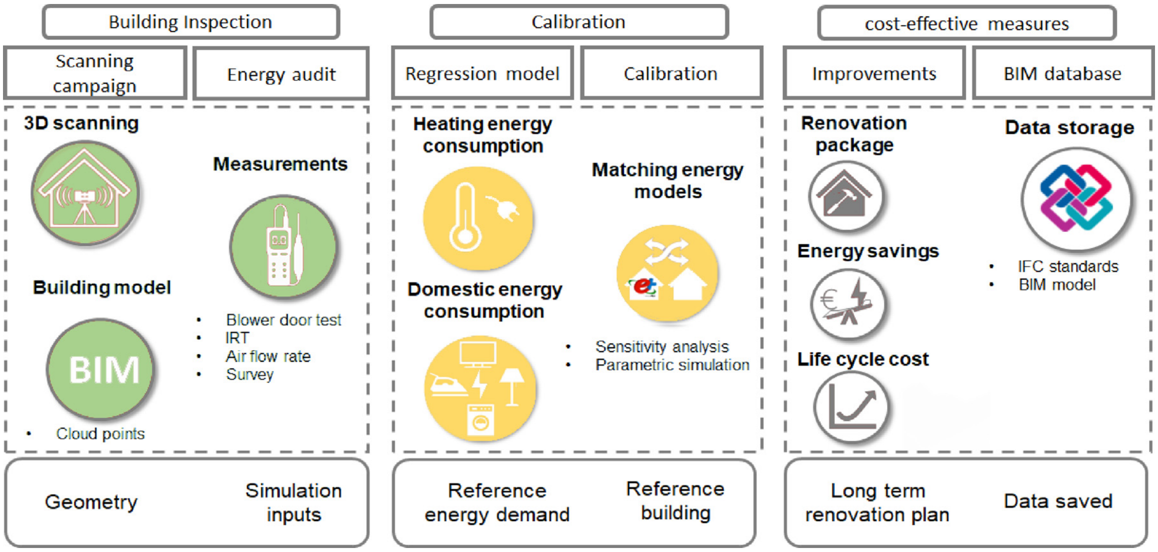


Fig. 1. Scheme of the methodology used in the research.

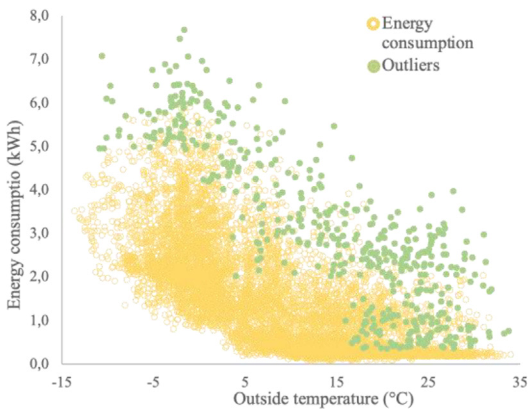


Fig. 2. Smart meter data that have been identified as outliers.

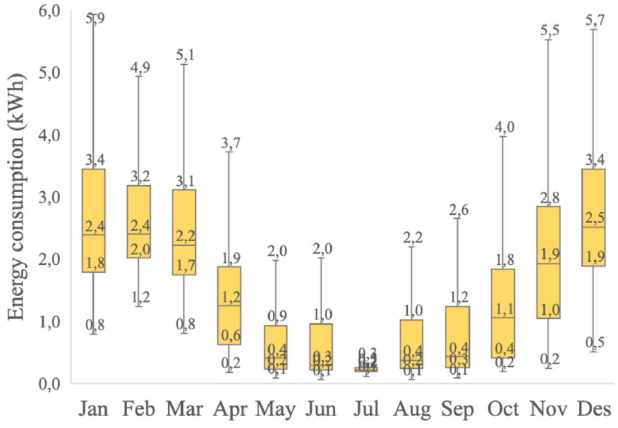


Fig. 3. Boxplot of the annual energy use.

and 3, a total of 433 data points were detected as outliers, representing 5.3% of the total data set.

3.2.2. Regression model

Hourly electricity data from a Norwegian household obtained from a smart meter over a one-year period were used. The data collected contains the total household energy use, including heating and domestic use such as lighting and appliances. To reduce the noise in the data produced by domestic consumption and minimise computational costs during the calibration process, it was implemented a regression model to differentiate the energy used between heating and domestic use. This allows the simulation model to be calibrated with data only derived from heating electricity consumption. Two heating settings are used in the dwelling. One set is designed for when the occupants are active in the building, with the thermostat set to 22°. The other setting is designed for when the occupants are away or sleeping, in which case the temperature is set to 18°. The behaviour of energy consumption for domestic use has a similar profile, as it can be seen in Figs. 4 and 5, which shows the average energy consumption in winter and summer. In the latter season, only energy consumption for domestic use is reflected, as the heating is switched off.

3.2.3. Domestic energy use

To calculate domestic energy use, the months of the summer period were used to determine electricity consumption for one month. The calculated representative month was assumed to be the minimum amount of domestic energy per month. This is because electricity consumption in summer is lower, as there are more hours of natural lighting during this period and indoor activities are less frequent. Therefore, it is reasonable to assume that each month of the year consumes at least the same amount of elec-

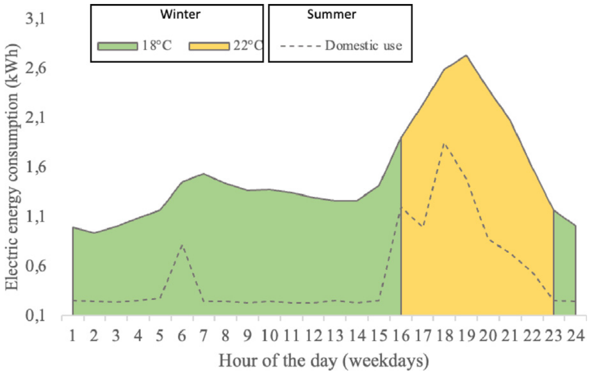


Fig. 4. Average annual energy consumption on weekdays.

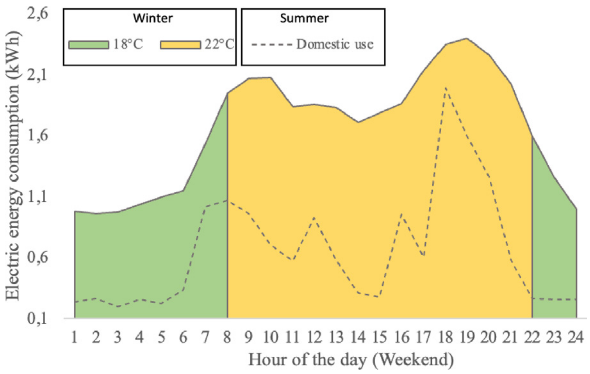


Fig. 5. Average annual energy consumption over the weekend.

tricity in domestic use as calculated in the representative month. The calculated consumption corresponds to 500 kWh, which was then subtracted from each month to estimate the proportion of energy used for heating and domestic use. This estimate will later be used to compare the regression model's energy distribution on a monthly basis. As can be seen in Table 3, from December to March the average domestic energy consumption is 25% of the total energy used, while in April and October it is 50% and in September it is 80%. The remaining months represent the summer period when, due to high outdoor temperatures, domestic energy use is assumed to be 100% of energy consumption.

3.2.4. Heating requirements as a function of outdoor temperature

It was noted that the electricity measured had three distinct patterns, two of which are linked to the changes in the heating points. The third corresponds to the periods of transition between heating setpoints. When the setpoint temperature is 22 °C and changes to 18 °C, for a period of time the indoor temperature is higher than the setpoint temperature, dropping the energy consumption. The opposite situation occurs when the setpoint changes from 18 °C to 22 °C where it requires a large amount of energy to reach the higher setpoint. To address these indoor temperature variations on the regression, it was necessary to use three reference temperatures, which were determined using the outdoor temperature and the schedule of each heating setpoint. Fig. 6 shows the reference heating temperatures and the energy baseline as well.

3.2.5. Domestic consumption patterns

One way to check the quality of the regression model is to recreate the data measured by the smart meter. This is accomplished by adding the domestic electricity consumption to the regression model. To do so, a pattern of domestic electrical consumption was created for weekdays and weekends. The pattern was calculated using the summer energy consumption for June and August (July was excluded since the building was unoccupied). For both, weekdays and weekends, the median energy used was calculated for each hour. The domestic energy consumption patterns obtained can be seen in Figs. 7 and 8. The resulting calculation can be compared to the total energy measured by the smart meter verifying that both behave similarly. The comparison between regression and measurement can be seen in Fig. 9.

The parameters used to explain the heating energy used in the linear regression are shown in Equations (1) and (2),

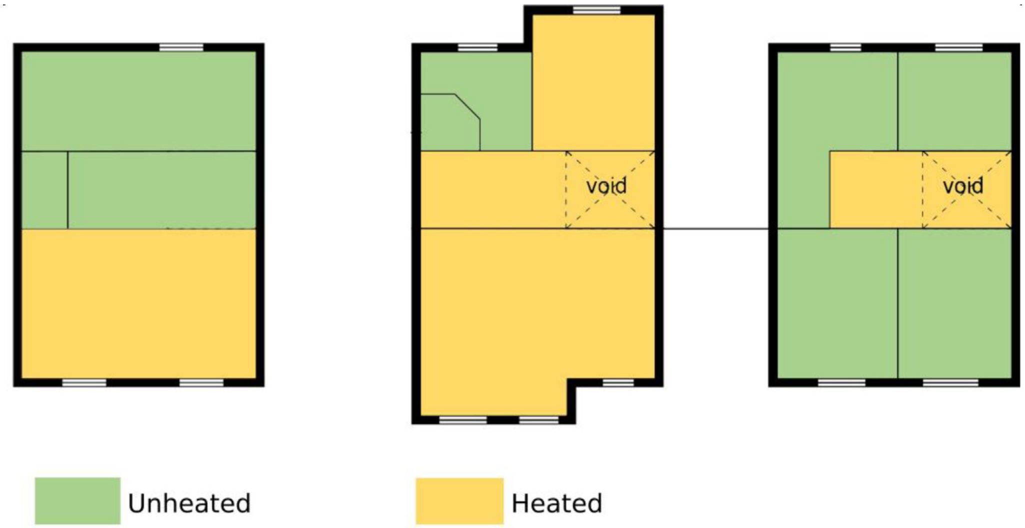
$$\begin{aligned} \textit{Total electricity consummption} &= \textit{Heating consumption} \\ &\quad + \textit{Domesumption} \\ &\quad + \textit{Domestic consumption} \end{aligned} \tag{1}$$

$$\textit{Heating consumption} = \beta_1 + \beta_2 * (T_R - T_o) \tag{2}$$

where β_1 is the baseline of the energy consumption, i.e., the electric energy used when the building is in operation without any disturbance, such as heating or any domestic activity, but with only the equipment that is constantly operating such as refrigerators or everything that is constantly plugged in.

The β_1 parameter can be found during the summer season at night. The β_2 parameter is the slope of the regression model, the

Table 3
Distribution of energy consumption between heating and domestic use during the year.



Consumption source	Jan	Feb	mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Des
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
Heating	1513	1319	1380	532	18	0	0	0	132	488	984	1523
Domestic	500	500	500	500	500	500	500	500	500	500	500	500

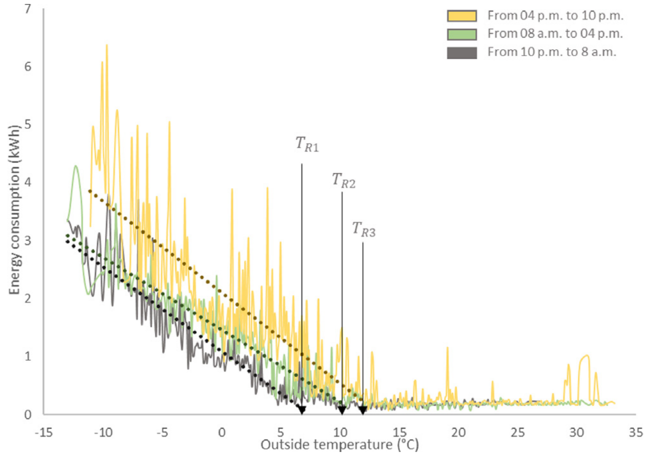


Fig. 6. Reference heating temperatures used in the regression model.

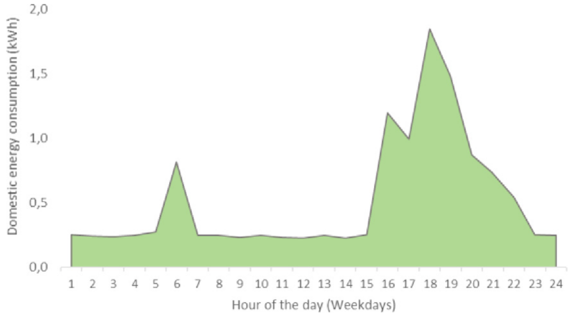


Fig. 7. Domestic energy use pattern on weekdays.

T_R is the reference temperature for each heating period and the T_o is the outside temperature.

3.2.6. Sensitivity analysis

Sensitivity analysis is used to identify the parameters with the greatest influence on the final energy use of a building. In this way, the number of simulations and the time spent in the calibration process can be minimised [41,56]. This allows discriminating factors that have a low influence on the simulation [42]. At the same time, it allows the ranking of the parameters with the highest impact, making it possible to organise the order in which each parameter is tested. The local sensitivity analysis method was used in this study. This approach is based on one factor at a time, while all other factors are held constant. For this task, the heating energy demand was simulated for each selected parameter, ventilation, U-values, air tightness and heating temperature settings. Four variations of each parameter were selected. Each range of values is within the expected performance for the building conditions. The impact on energy demand of each simulated value and average change of each parameter can be seen in Fig. 10. As it can be seen that the most influential parameters for the calibration process are the heating setpoints, windows and wall U-values.

3.2.7. Goodness of fit

The second round of simulations focuses on the evaluation of the goodness of fit of the model with the curve resulting from the regression, taking only into account the heating consumption. The simulations were carried out in Design Builder. The purpose was to verify the accuracy of the calibration, meaning to compare the predicted output of the model to the actual measured data for the same set of conditions. An uncertainty analysis was performed, which according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14-2014, is the process of determining the degree of confidence in the true value when using measurement procedures and/or calculations [57]. The main uncertainty indices suggested by the most relevant references such as ASHRAE, Federal Energy Management Program (FEMP) and International Performance Measurements and Verification Protocol (IPVMP) are Normalised Mean Bias Error (NMBE), Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) and coefficient of determination (R2) [58], which were used for the uncertainty analysis. Hourly weather data for 2018 such as temperature, relative humidity, the direction of the wind, and speed were obtained from the building's nearest weather station.

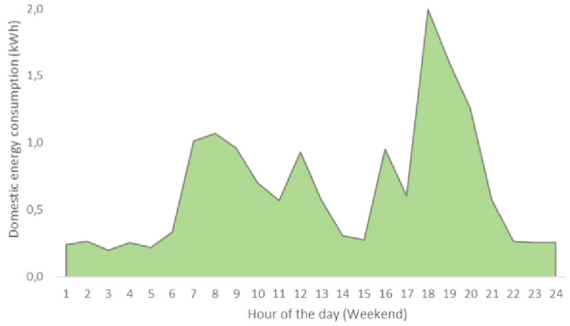


Fig. 8. Domestic energy use pattern on the weekend.

3.2.8. Cost-effective measures

The renovation measures proposed for the building were based on the field inspection and the calibration process results. Three renovation levels were given: urgent, necessary and suggested. Urgent measures refer to the building aspect that should be repaired as soon as possible because its lifetime has already expired or is about to expire, which could cause heavy expenses or cause damage. Under necessary measures, renovation options were given in connection with the lifespan of the original component. These measures can be implemented along with other elements which may need to be replaced later, but it would be more cost-effective by doing them together. Suggested renovation measures are also linked to the building's life cycle. These measures are however not cost-effective. Because of their energy saving power these measures are included, but they are highly expensive. If the recommendations are implemented, these should be done at the end of the renovation process.

3.3. Energy savings and LCC analysis

A constrained multi-objective optimisation was carried out using DesignBuilder simulation software through the built-in Genetic Algorithms (GA). The optimisation objective functions used were to minimise energy and minimise implementation costs. The input parameters used during the optimisation are listed in Table 4. This iterative process seeks to find the best combination of parameters in building cost-effective packages while satisfying at the same time the minimum requirements of the Norwegian building code. The tested options were divided into three renovation levels, with the first two based on the Norwegian building codes TEK10 and TEK17, and the third on the Norwegian passive house standard NS3700.

To avoid energy-saving measures being impractical given their cost, a life-cycle cost analysis was performed to define the suitability of each package of savings and investment measures. The reduction rate for the calculation was 7%, the electricity price was 2.02 NOK/kWh and the scaling rate was 1%. Table 5 shows details of the cost and lifetime for the LCC assessment.

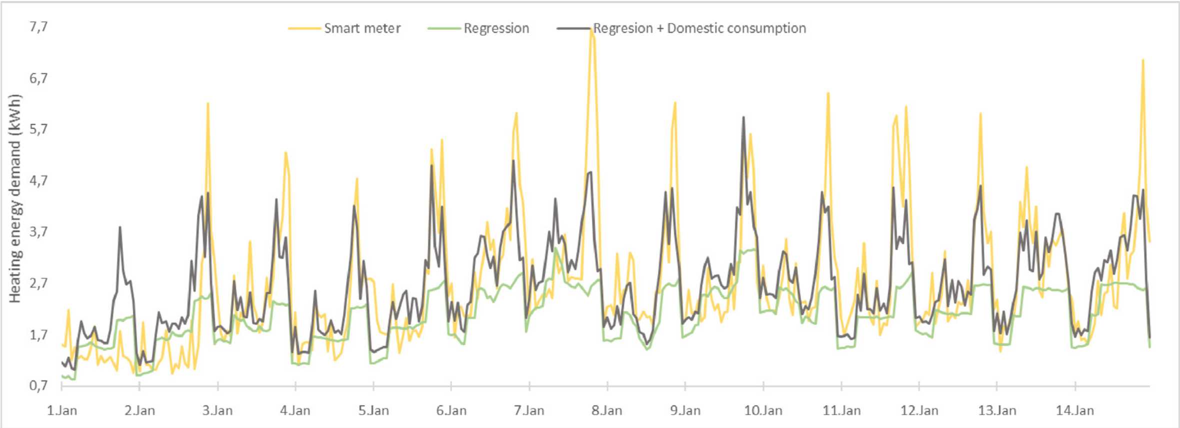


Fig. 9. Comparison between Smart Meter measurement, regression and regression including calculated domestic consumption.

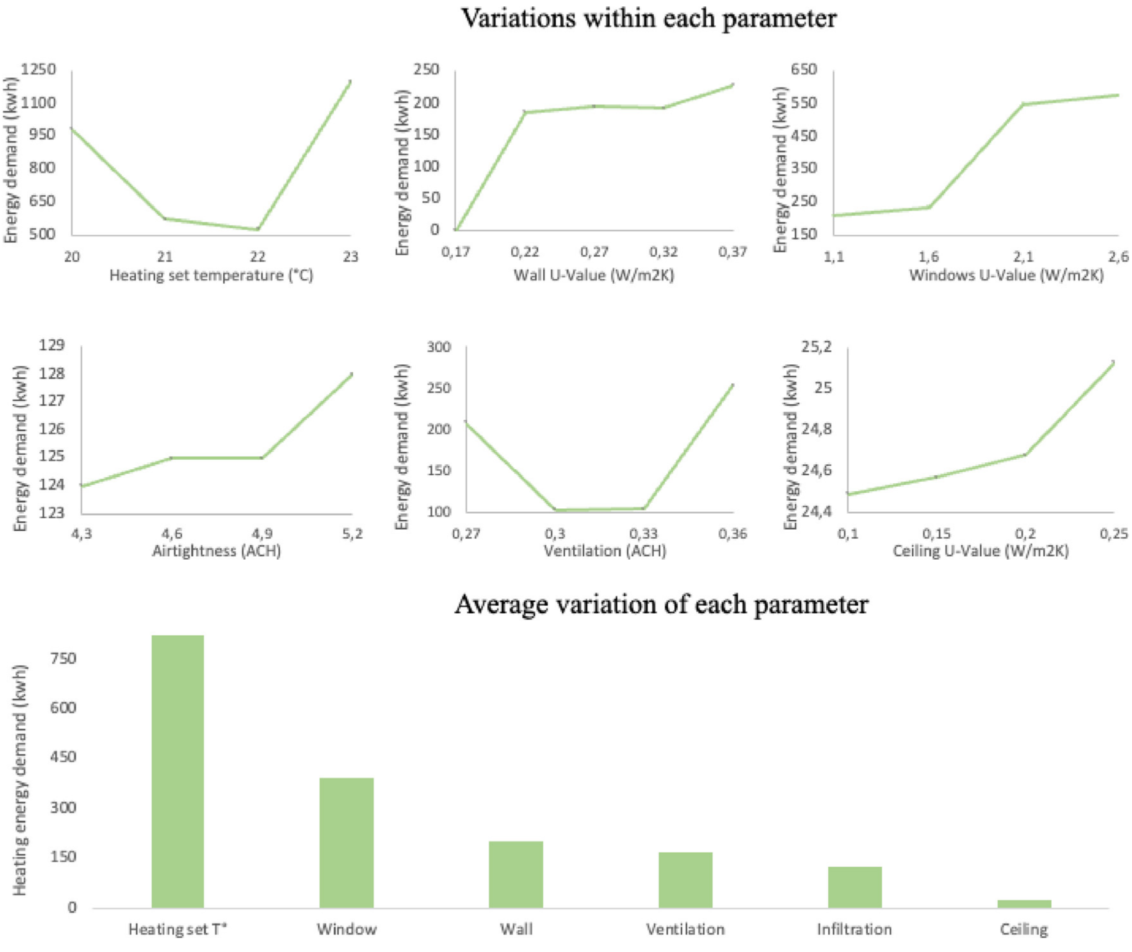


Fig. 10. It illustrates the simulated scenarios for each parameter, and their impact on energy demand. The bar chart summarises all combinations used, showing in decreasing order the average variation of each parameter.

3.4. BIM database

A database was used to save the results of the various tasks performed, which were capable not only of being stored, but also of being transferred and shared between different actors and updated over time. This was done through the use of BIM using a standardised method based on ISO 16739–1:2018 [61].

3.5. Building case

A dwelling was used to establish the baseline for the energy demands. The building corresponds to a wooden terraced house in Oslo which is Norway's second most popular type of residential building . Constructed in 1997, the building consists of three floors: a basement and two upper floors. The basement is reinforced con-

Table 4
Parameters used to identify cost-effective packages.

Renovation level	Improvements						
	Wall	Ground floor	Internal floor	Ceiling	Windows	Door	Airtightness
	W/(m2*K)	W/(m2*K)	W/(m2*K)	W/(m2*K)	W/(m2*K)	W/(m2*K)	ACH
Conservative	0.22	0.18	0.18	0.18	1.20	1.20	4.00*
Medium	0.18	0.13	0.18	0.10	0.80	1.20	2.50
Ambitious	0.10	0.10	0.18	0.08	0.80	0.80	2.50**

* Value proposed by the authors as more realistic to achieve than that used by the building code for new buildings.
** Value proposed by the authors as more realistic to achieve than the one used by the passive house standard.

Table 5
Cost and lifetime used for each improvement. Costs taken from Norsk Prisbok [59] and lifetime from TotalConcept [60].

Element	Level	Investment	Lifetime
		NOK/M2	Years
Wall (**adding mineral wool insulation**, **variable thickness)**	Conservative	382	60
	Medium	443	
	Ambitious	665	
Ground floor (Demolition of the concrete floor and installation of Expanded Polystyrene (EPS) Insulation, variable thickness, followed by the installation of a new concrete floor.)	Conservative	1470	60
	Medium	1527	
	Ambitious	1773	
Internal floor (adding mineral wool insulation)	all	394	60
Ceiling (adding EPS, variable thickness)	Conservative	394	40
	Medium	511	
	Ambitious	590	
Windows (Thermopane window with plastic/PVC frame)	Conservative	5392	30
	Ambitious	6474	
Door (airtight wooden door with sealing strips and interior insulation.)	Conservative	4130	30
	Ambitious	4308	

crete while the upper floors are made of a wood frame. Although the dwelling was built in the late 90′s, the insulation levels are quite high because the Nordic countries, particularly Norway, have one of the EU's most stringent regulations. Housing insulation levels were put into effect in the 1940 s. The dwelling has not been retrofitted, so it is assumed to have its original insulation (about 20 cm).

Oslo's climate corresponds to a cold climate with no dry season and a warm summer (Dfb) according to the Köppen-Geiger climate classification. In this case, the cold season is the main concern for the building design, but the summer outside air temperature and solar irradiation, especially if combined with a relatively high internal gain (typical for office buildings), may require cooling [66].It is important to note that climate change will in many cases change the performance of buildings and the needs they must meet [67]. The Table 6 summarises the characteristics of the case study.

4. Results

4.1. Scanning campaign

The time spent on these tasks was divided as follows: 4 h to scan, 5 h to prepare the BIM model and 3 h to prepare the IFC file. It should be noted that if the implementer is familiar with these tasks, they can be performed more quickly. The processed results can be seen in Fig. 11. The BIM model will be used as a database to store the results and information about the building collected during the inspection.

4.2. Energy audit

The supporting material for the design of the renovation packages is the information collected through the inspection and the checklist.

4.2.1. Survey

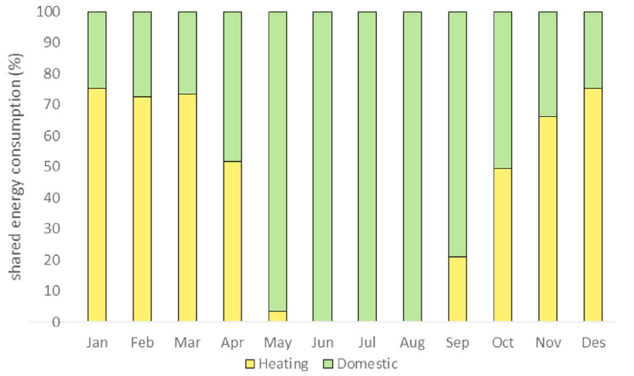
The results show that there is no significant damage to the building, but the airtightness requires attention, as well as the lifespan of certain elements such as wall cladding and roof shingles. It is also noted that the floor between the main level and the basement is not insulated, and it is recommended that this element be added as part of the renovation parameter for the simulation campaign. Windows are the only element that has been renovated since the construction of the building. The heating system and its settings are already efficient, keeping the indoor temperature at 19 most of the day and only heating the common areas.

4.2.2. Measurements

The result of the blower door test shows that the airtightness of the building is similar to that of a similar house built at around the same time, given the airtightness of 6.1 ACH [62]. As regards the air flow rate, it was found that the total ventilation rate was 98 m3/h. A comparison between the measurements and the Norwegian standard recommended for new buildings can be seen in Table 7.

4.2.2.1. IRT imaging. The IRT imaging shows no damage in the building, some geometric thermal bridges have been noticed. However, these did not show any visual problems with condensation, nor did they suggest significant energy losses. The insulation was

Table 6
Summary of the characteristics of the building to be studied.

Description of the building		
Location: Oslo	Oslo heating degrees days (18 °C): 4171 hr	
Basement	Ground floor	First floor
		
Floor area: 46 m2 Volume: 102.0 m3 Heating system: Electric panel heaters Ventilation system: Centralised mechanical extract ventilation U-values from the Norwegian standard TEK 87 (1987)	Floor area: 53 m2 Volume: 127.2 m3	Floor area: 47 m2 Volume: 112.8 m3 Heating source: Electricity *Airflow: 1.36 m3/hm2
Wall: 0.30 Window: 2.40	Basement wall: 0.38 Door: 2.00	Roof: 0.30 Floor: 0.20

[*] Standardised values in the EPC, used during the calculation of the energy demand.

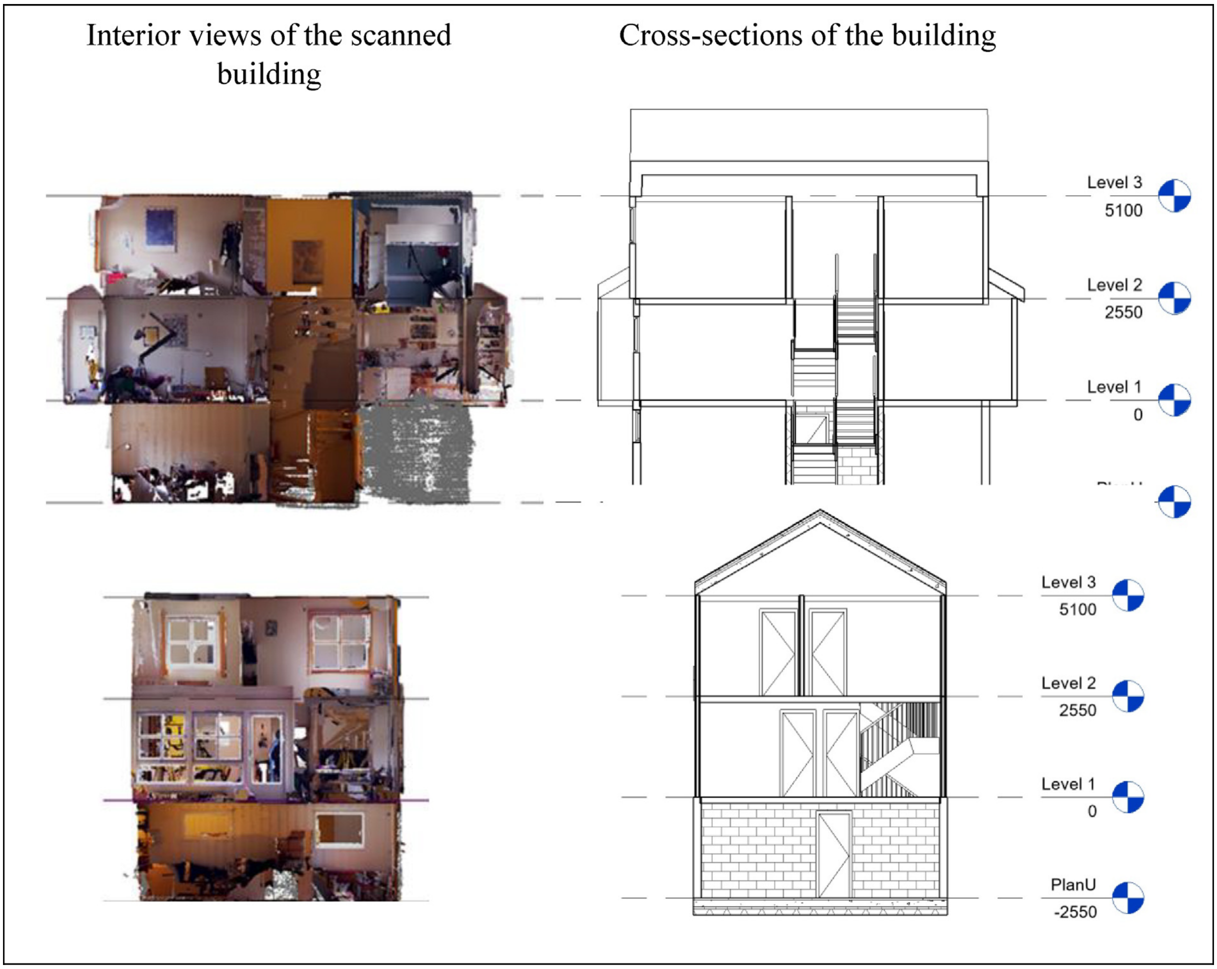


Fig. 11. Displays the images obtained during the scanning campaign and the BIM model resulting from that task.

Table 7
Comparison between the standard and the results from the measurements.

Input	Standard Tek17	Measurement
Airtightness (ACH)	4*	6.1
ventilation rate (m3/h)	199	98
Heating setpoints (°C)	21–19	21–19

* Based on the Norwegian building code from 1987 [63].

also checked and there were no gaps or problems with the installations concerned, confirming uniformity of the U-values of the building elements. This can be seen in Fig. 12.

4.3. Calibration

To achieve the acceptance tolerance during the calibration process, 35 simulations were performed in the DesignBuilder simulation software. For this, one parameter was tested at a time, following the order of the sensitivity analysis. The results can be seen in Table 8 where a number of indicators support the accuracy of the final simulation, as well as the tolerance recommended by ASHRAE [57], IPMVP and FEMP [64]. If the calibrated model is within these limits, it is capable of simulating real conditions [54]. Even though the calibration model did not reach the CV (RMSE) percentage recommended by the IPMVP, all other indices were achieved.

The comparison between the regression and the calibrated model shows a good degree of agreement. Several intervals of one week are presented as can be seen in Fig. 13, showing that the calibration can follow the regression trend during the year under different weather conditions. Using the blower door test and the ventilation rate greatly reduced sensitive parameter uncertainty, reducing the number of simulations needed.

As can be seen in Fig. 14, the scatter graph shows that the behaviour of the calibrated model maintains a relationship with the data measured by the smart meter. It is inferred that the data found in the most dispersed areas is the result of the irregular use of domestic electricity consumption. This can be corroborated by the comparison presented in Fig. 15, where the monthly measured data show similar values to the calibration plus the fixed consumption of electrical energy for domestic use, calculated based on summer consumption. The resulting parameter found through the calibration can be seen in Table 9.

4.4. Improvements

4.4.1. Energy savings

The results from the optimisation show the best combination of renovation measures in terms of cost and energy. The selected combinations were determined under various levels of infiltration due to the high impact of airtightness on energy reduction. The airtightness levels for the renovation packages were tailored based on the type of improvements implemented. At the end of the renovation process, the building is expected to gradually reach a tightness of 2.5 ACH. As can be seen in Fig. 16, the tested packages vary in type of solution and the number of measures included.

4.4.2. Packages

The cost-effective packages selected for the building renovation are designed to be carried out in stages. The criteria used for their classification is based on the useful life of each element and the owner's renovation plans. In this way, the original elements use their full life cycle, being replaced at the best time. Such is the case of the roof and wall cladding. Although such measures are not necessarily energy efficient, they were linked to improvements that could be made at the same time to reduce their costs, such as adding thermal insulation. Similar to this is the case of the renovation plans of an owner who intends to renovate the floor finish. This is explained in more detail in the renovation matrix in Table 10, where renovation measures are grouped according to their urgency and importance, as well as actions to be avoided.

4.4.3. LCC

The result from the lifecycle-cost shows that at the end of the 20-year evaluation period, not all package items will payback. Windows is the most expensive item and is not going to be cost-effective investment. However, at the end of their life cycle the windows will have to be renovated, which is why the most balance option was chosen between energy savings and implementation costs. Table 11 summarises the energy reductions expected for the packages, their IRR and implementation costs..

The results show that the house, despite being built to high energy efficiency standards, can be renovated in a cost-effective

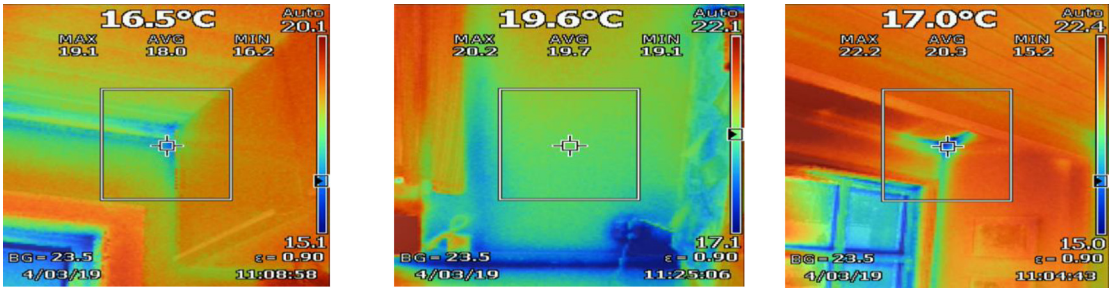


Fig. 12. Samples of the thermographic evaluation.

Table 8
Comparison between the accepted calibration tolerance and the obtained result.

Resolution	Index	Calibrated model	ASHRAE	IPMVP	FEMP
Hourly	NMBE	2.75	±10	±5	±10
	CV (RMSE)	30	30	20	30
	R^2	0.90	>0.75	>0.75	–

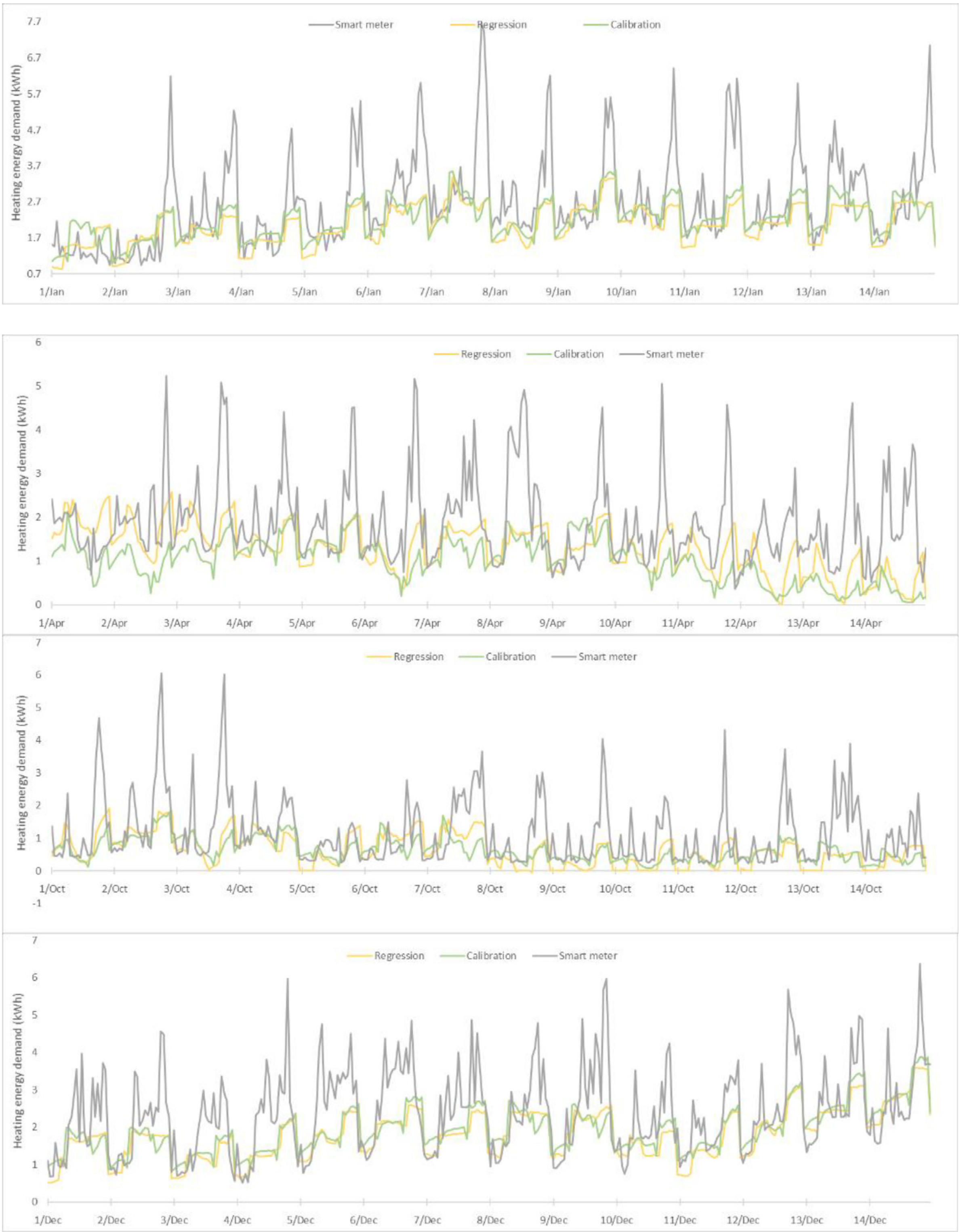


Fig. 13. Comparison between the smart meter, calibration and the regression model.

way. The collected material is able to be stored in a database to be used by different tools and stakeholders.

5. Discussion

The quality of the recommendation for renovation has been identified as one of the main drawbacks in the certification process. Despite this being automatically obtainable through the use of a reference building, these recommendations often do not reach the level that users expect. However, when the recommendations are prepared by the Certifiers, many obstacles prevent them from developing tailor-made advice ready to be used by building owners. The underlying objective of the study was to provide an assessment of the existing building that could be implemented in the

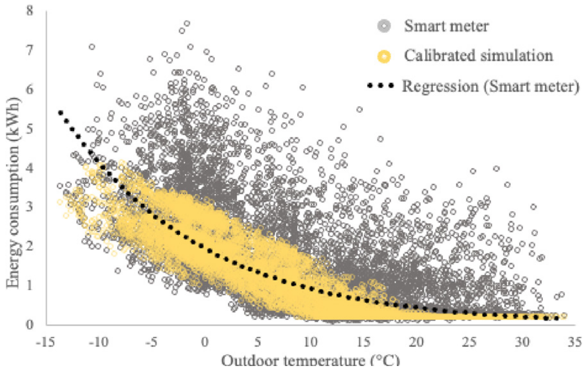


Fig. 14. Comparison between the measured data of the smart meter and the calibrated model.

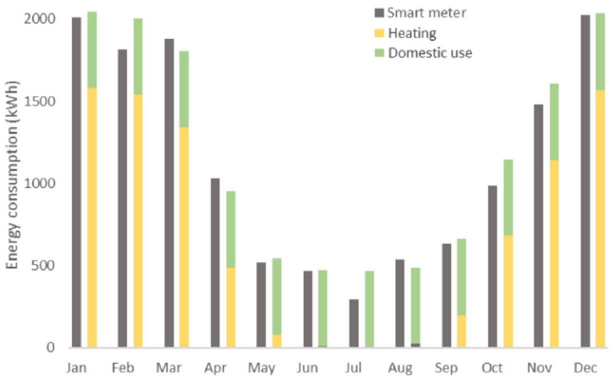


Fig. 15. Monthly comparison of the total energy used and the calibrated model plus the domestic energy used.

current certification system. It was developed considering the certification barriers and the data required to plan a long-term renovation map, providing reliable information to homeowners and policy makers. The main findings, limitations, implications on practice and future research are discussed below.

5.1. Summary of major findings

The case study in which the research was applied was more complex than a normal dwelling. For instance, the building had a relatively low energy requirement before any upgrading. This made it difficult to find cost-effective renovation measures. On top of this, the heating system set up by the building owner operated in an unusual fashion, which meant a more complicated model to calibrate and simulate. Given that these difficulties have been overcome, there is high confidence that the proposed procedure will respond effectively in other cases under more standard conditions.

5.2. Study limitations

The conditions of the case study were used as a basis for designing the methodology. This implies that projects with different components, the methodology would have to be adapted. For example, when the smart meter is able to individualise the data between heating and domestic energy, no regression is necessary. Another situation that requires adjustments is when the heating system uses another energy source such as gas or district heating. Another important aspect to consider is that the case study only uses heating. In countries with high cooling demand, it will be necessary to apply the methodology and check whether it requires modification, particularly in the regression step. A key aspect of the study is the calibration of the simulation model. It is this process that ensures that the cost of the renovation will be cost-effective. In order to perform the calibration, the use of the smart meter is essential, as it allows the actual consumption data to be matched with the simulation at an hour by hour resolution [68]. While not all homes in the EU have a smart meter installed, their implementation is within the commitments made by MS (80% of residential buildings must have smart meters by 2020). Smart

Table 9
Renovation matrix.

	Urgent		Not urgent	
	Action	Effect	Action	Effect
Important	-Exterior wall insulation -Measures related to wall, roofs, windows, and door should always improve the airtightness.	-The life span of the building envelope will soon be over. -Greater energy losses and potential damages may occur if these elements are not renovated.	-Insulation and renovation of the roof. -The most cost-effective method is insulating the interior floor.	-The life span of the roof is a critical measure; its replacement should not be scheduled after leaks have occurred. -The earlier the renovation of the interior floor is carried out, the less time it will take to recover the investment of other measures.
Not important	-Replace outer door -Replace windows	-High implementation cost and significant energy reduction -Implementation may cause delay of other more important measures.	-Renovate the building envelope without increasing its insulation. -Renovate building components without paying attention to airtightness. -Increase the insulation but to a lower level than suggested.	-Updating the roof covering without increasing the insulation would be a missed opportunity. -Changing seals and incorporating other measures to increase airtightness are very low-cost investments if they are made during the renovation of the building envelope.

🟨 Urgent 🟩 Necessary ▨ Suggested ☐ Avoid

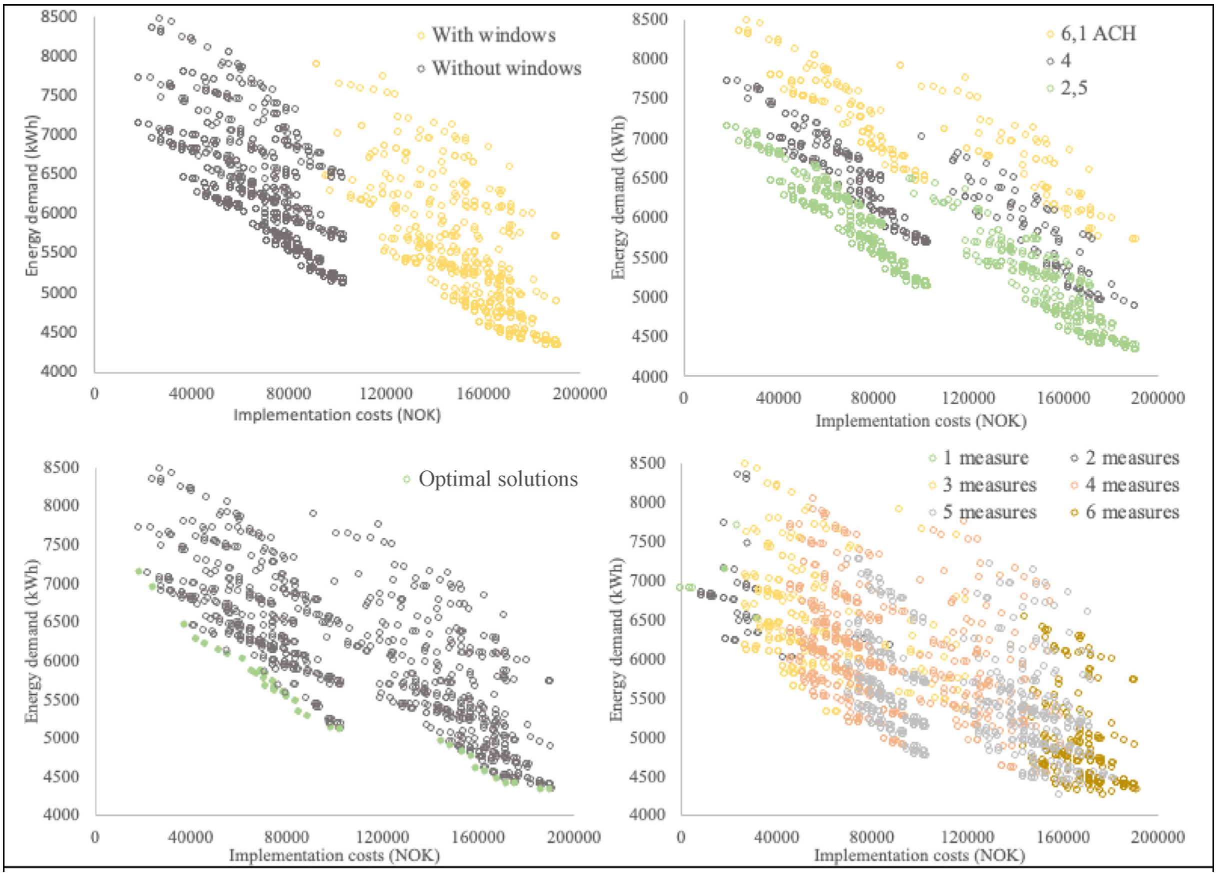


Fig. 16. It identifies all simulated combinations according to the characteristics of each renovation package. This allows to evaluate the impact of the measures used in the optimisation process.

Table 10
Results from the calibration.

U-value wall (W/ m2K)	U-value floor (W/ m2K)	U-value ceiling (W/ m2K)	U value windows (W/ m2K)	Airtightness (ACH)	Ventilation rate (ach)	Heating set point (°C)	Heating set back point (°C)
0.33	0.20	0.25	2.60	*6.10	0.30	22.40	20.60

[*] Value obtained from the blower door test.

meters are a key component, as they allow consumers to control their energy consumption and are one of the main tools for the development of digital twins [69].

5.3. Implications on practice

A clear obstacle to the implementation of this procedure is the cost it represents, which will undoubtedly be higher than that of the current system. However, it is not expected that it will simply be inserted into the certification system, but that the system must be rethought in some aspects. For example, the inspection campaign could be carried out on a large scale. Instead of individual inspections, entire neighbourhoods could be evaluated to reduce costs; in cases where the dwellings are the same, a few buildings could be used as representative buildings for measurements such as scanning and blower door test. Similarly, the current modality, where owners contact the certifier, would have to be modified. It would be more efficient for municipalities to contact the owners so that certificates could be issued in a coordinated manner through an area-based certification plan. This would allow energy certification to be linked to the inspection of HVAC systems and boilers so that these could be programmed and carried out under the same scheme. The model could not only store the data collected during inspections and economic analysis but also contain the invoices related to the measurements, maintenance and renovation process. This could be considered part of the investment in the maintenance of the building. In this way, stakeholders in the real estate transaction can see the certification system as a model of assurance and transparency about the condition, performance and cost of the building.

5.4. Future research

In the future, an automated evaluation of the dwelling with the smart meter data will be investigated. With this, a platform can be designed that runs the simulations automatically, requiring some input data from the certifier. This could be a new methodology for certifying houses on a large scale. It is also necessary to include other platforms that can make use of the full potential of the data collected. Such is the case of the Building Renovation Passport and

Table 11
Results from the LCC analysis.

Measure priority	Urgent	Necessary	Necessary	Suggested	Suggested
Implementation (Year)	0	0–5	7–10	10–20	0–15
Measure	Increase insulation of external walls and add seals to openings and ducts.	Add insulation to the exposed floor and the interior floor between the basement and the ground floor.	Add attic insulation and update duct and opening seals.	Replace the exterior door with a door having greater thermal performance.	Replace windows, especially if the price of electricity increases.
U-Value	0.22	0.18	0.18		1.20
Expected airtightness improvement (ACH)	4	4	2.50	2.50	2.50
	This task can be carried out in connection with the upgrade of the coating which already shows signs of deterioration and has already expired.	This can be done in connection with updating the wood floor finish, which is within the owner's plans.	This should be done in consideration of the performance of the roof covering (before it leaks), as its useful life should be over by this time.		At this point, the useful life of the windows will end. Because of this it is suggested that they be replaced.
Energy demand (kWh)	7448	6722	6021	5939	5058
Savings in comparison to the unrenovated model (%)	14.4%	22.4%	30.5%	31.5%	41.6%
Implementation costs (NOK)	24,652	43,182	61,872	70,533	147,634
IRR (%)	9.00	7.70	7.00	5.80	1.10

Digital Twin, which are strongly linked to BIM and are already being used in the construction industry. Also, it has to be considered that the collected data could be analysed under other indicators related to human comfort, and environmental aspects (LCA) and the application of dynamic electricity tariffs.

6. Conclusion

This research proposes a procedure to evaluate existing dwellings and propose cost-effective renovation measures. The study used as a case study a dwelling in Norway whose energy performance was already considered energy efficient. The design of the research was intended to complement the current certification system as well as the BRP, given the massive impact that both tools represent and the fact that they are already established systems. The study is composed of three main tasks: building inspection, calibration and economic analysis of renovation improvements. As a result, sufficient material was obtained for the development of a renovation plan for the remaining life cycle of the building.

As a product, sufficient material was obtained for the development of a renovation plan for the rest of the building's life cycle. During the building assessment stage, key data of the building was collected. First, a high-resolution point cloud was obtained, and a BIM model was created. This was used as the basis for the subsequent results. The second key data collected were measurements such as blower door test, thermal bridges, ventilation flow and hourly energy consumption data. These measurements were used to evaluate the performance of the building. In the next stage, a regression model was obtained to calibrate the dwelling based on electrical data obtained from the smart meter. The results indicated NMBE and CV (RMSE) values of 2.75 and 30 respectively, considered acceptable by standards such as ASHRAE and IPMVP. In the final stage, the process of obtaining the home renovation measures was detailed. Different improvement packages were tested, and optimal solutions adapted to the building conditions found. These were economically evaluated through the LCC over a 20-year period. It was estimated that the dwelling at the end of its renovation process could reduce its energy demand by 46.7% at an IRR of 5.7%. Finally, the results were stored in the BIM database, which can be shared and updated among the different stakeholders.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Below is the inspection sheet used as a guide for building assessment on site.

INSPECTION CHECKLIST							
Ceiling							
Element	Insulation Level						
	Quality	Maintenance	Installation	Leaks	Damage	Lifespan	Comments
Attic floor							
Attic roof							
Flat roof							
Pipes							
Element	Seal quality			Leaks	Damage	Lifespan	
Penetrations							
Access panel							
Vents	Yes		No				
Walls							
Element	Insulation Level			Leaks	Damage	Lifespan	Comments
	Quality	Maintenance	Installation				
Basement							
Main floor							
Second floor							
Floor							
Element	Insulation Level			Leaks	Damage	Lifespan	Comments
	Quality	Maintenance	Installation				
Basement							
Warm floor/Cold ceiling							
Windows							
Element	Sealing level			Leaks	Damage	Lifespan	Comments
	Quality		Maintenance				
Basement							
Entrance							
Living room							
Kitchen							
Bathroom							
Bedrooms							
Glass doors							
Skylight							
Doors							
Element	Sealing Level			Leaks	Damage	Lifespan	Comments
	Quality		Maintenance				
Main door							
Back door							
Heated/Unheated							
Heating system							
Element	Sealing level			Leaks	Damage	Lifespan	Comments
	Quality	Maintenance	Installation				
Fireplace							

Acknowledgements (*continued*)

INSPECTION CHECKLIST								
Stove								
Boiler								
HVAC								
Pipes								
Element	Heating set points							
	Weekdays		Weekend		Weekday schedule		Weekend schedule	
	Heating	Setback	Heating	Setback	On	Off	On	Off
Basement								
Main floor								
Second floor								

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2022.112071.

References

[1] BPIE. *97% of buildings in the EU need to be upgraded – Factsheet*. 2017 [cited 2018 10 September 2018]; Available from: http://bpie.eu/wp-content/uploads/2017/12/State-of-the-building-stock-briefing_Dic6.pdf.

[2] Economidou, M., et al., *Europe's buildings under the microscope. A country-by-country review of the energy performance of buildings*. 2011. p. 132.

[3] G. Salvalai, M.M. Sesana, G. Iannaccone, Deep renovation of multi-storey multi-owner existing residential buildings: A pilot case study in Italy, Energy and Buildings 148 (2017) 23–36.

[4] P. Moseley, Practical Approaches to the Building Renovation Challenge, European Commission EASME (2016) 13.

[5] European Commission, *Commission Staff Working Document: Impact Assesment. Accompanying the document Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/31/EU on the energy performance of buildings* 2016, European Union: European Commission. p. 121.

[6] H.E. Borgstein, R. Lamberts, Developing energy consumption benchmarks for buildings: Bank branches in Brazil, Energy and Buildings 82 (2014) 82–91.

[7] N.d.N. Batista, E.L.L. Rovere, J.C.R. Aguiar, Energy efficiency labeling of buildings: An assessment of the Brazilian case, Energy and Buildings 43 (6) (2011) 1179–1188.

[8] Arcipowska, A., et al., *Energy performance certificates across the EU. A mapping of national approaches*. 2014, Buildings Performance Institute Europe (BPIE): Brussels. p. 60.

[9] S. Semple, D. Jenkins, Variation of energy performance certificate assessments in the European Union, Energy Policy 137 (2020).

[10] Akram and Karin Farsäter and Åsa Wahlström and Petter, W., *Literature review on renovation of multifamily buildings in temperate climate conditions.* Energy and Buildings, 2018. **172**: p. 414-431.

[11] Eider Iribar and Isabel Sellens and Laura Angulo and Juan, M.H.a.J.M.S., *Nonconformities, Deviation and Improvements in the Quality Control of Energy Performance Certificates in the Basque Country.* Sustainable Cities and Society, 2021. **75**: p. 103286.

[12] Organ, S., *Minimum energy efficiency – is the energy performance certificate a suitable foundation?* International Journal of Building Pathology and Adaptation.

[13] Y. Li et al., Review of building energy performance certification schemes towards future improvement, Renewable and Sustainable Energy Reviews 113 (2019).

[14] P.A. Fokaides, C. Panteli, A. Panayidou, How Are the Smart Readiness Indicators Expected to Affect the Energy Performance of Buildings: First Evidence and Perspectives, Sustainability 12 (22) (2020).

[15] A. Gonzalez-Caceres, A.K. Lassen, T.R. Nielsen, Barriers and challenges of the recommendation list of measures under the EPBD scheme: A critical review, Energy and Buildings 223 (2020).

[16] Jenny and Carolina Holmberg and Mikael Mangold and Tim Johansson and Kristina, M., *The renewing of Energy Performance Certificates—Reaching comparability between decade-apart energy records.* Applied Energy, 2019. **255**: p. 113902.

[17] Jesús Las-Heras-Casas and Luis, M.L.-O.a.L.M.L.-G.a.J.P.P.-S., A tool for verifying energy performance certificates and improving the knowledge of the residential sector: A case study of the Autonomous Community of Aragón (Spain). Sustainable Cities and Society, 2018. **41**: p. 62-72.

[18] M. Hörner, M. Lichtmeß, Energy performance of buildings: A statistical approach to marry calculated demand and measured consumption, Energy Efficiency 12 (2019) 139–155.

[19] Ali, U., et al. *Application Of Intelligent Algorithms For Residential Building Energy Performance Rating Prediction*. in *Proceedings of Building Simulation 2019: 16th Conference of IBPSA*. IBPSA.

[20] O. Pasichnyi et al., Energy performance certificates — New opportunities for data-enabled urban energy policy instruments?, Energy Policy 127 (2019) 486–499

[21] G. Mutani, V. Todeschi, GIS-based urban energy modelling and energy efficiency scenarios using the energy performance certificate database, Energy Efficiency 14 (5) (2021).

[22] K. Qu et al., A novel holistic EPC related retrofit approach for residential apartment building renovation in Norway, Sustainable Cities and Society 54 (2020).

[23] Bianca-Elena Benzar and Moonseo Park and Hyun-Soo Lee and Inseok Yoon and Jongwoo, C., *Determining retrofit technologies for building energy performance.* Journal of Asian Architecture and Building Engineering, 2020. **19**: p. 367-383.

[24] P. Beagon, F. Boland, M. Saffari, Closing the gap between simulation and measured energy use in home archetypes, Energy and Buildings 224 (2020).

[25] J. Taylor et al., Application of an indoor air pollution metamodel to a spatially-distributed housing stock, Science of the Total Environment 667 (2019) 390–399.

[26] M. Monzon, B. Lopez-Mesa, Buildings performance indicators to prioritise multi-family housing renovations, Sustainable Cities and Society 38 (2018) 109–122.

[27] Ronan Oliver, Aidan Duffy, K. Ian, Statistical models to infer gas end-use efficiency in individual dwellings using smart metered data, Sustainable Cities and Society 23 (2016) 1–10.

[28] Buildings Performance Institute Europe (BPIE), *Energy Performance Certificates Across Europe: From Design to Implementation*. 2010: Belgium.

[29] M. Österbring et al., Stakeholder Specific Multi-Scale Spatial Representation of Urban Building-Stocks, ISPRS International Journal of Geo-Information 7 (5) (2018).

[30] Geissler, S. and N. Altmann, *How to make the best use of EPCs*. 2015. p. 13.

[31] Paulo Santos and Kim B. Wittchen, *The price of energy performance certificates*. 2011. p. 9.

[32] European Network for Energy Performance Certification of Building (ENFORCE), *Comparison of Building Certification and Energy Auditor Training in Europe*. 2010. p. 50.

[33] European Commission *Commission Staff Working Document: Evaluation of Directive 2010/31/EU on the energy performance of buildings. Accompanying the document Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/31/EU on the energy performance of buildings* 2016, European Union: European Commission: Brussels. p. 109.

[34] Ezilda Costanzo and Valerio Pfister, *BEST PRACTICES ON QUALITY SCHEMES AND EPC IN RENOVATION*. 2012. p. 83.

[35] Ö. Göçer, Y. Hua, K. Göçer, A BIM-GIS integrated pre-retrofit model for building data mapping, Building Simulation 9 (5) (2016) 513–527.

[36] Nguyen, T., et al. Interactive Syntactic Modeling With a Single-Point Laser Range Finder and Camera. in In Proceedings of 2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR),. 2013. Adelaide, SA, Australia.

[37] A. Borodinecs et al., Modular retrofitting solution of buildings based on 3D scanning, Procedia Engineering 205 (2017) 160–166.

[38] S. D'Oca et al., Technical, Financial, and Social Barriers and Challenges in Deep Building Renovation: Integration of Lessons Learned from the H2020 Cluster Projects, Buildings 8 (12) (2018).

[39] J. Rosser, J. Morley, G. Smith, Modelling of Building Interiors with Mobile Phone Sensor Data, ISPRS International Journal of Geo-Information 4 (2) (2015) 989–1012.

[40] European Commission, *Commission Staff Working Document: Evaluation of Directive 2010/31/EU on the energy performance of buildings. Accompanying the document Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/31/EU on the energy performance of buildings* 2016, European Union: European Commission: Brussels. p. 109.

[41] D. Coakley, P. Raftery, M. Keane, A review of methods to match building energy simulation models to measured data, Renewable and Sustainable Energy Reviews 37 (2014) 123–141.

[42] Jun Yuan, Victor Nian, Su. Bin, M. Qun, A simultaneous calibration and parameter ranking method for building energy models, Applied Energy 206 (2017) 657–666.

[43] Wancheng Li, Zhe Tian, Lu. Yakai, F. Fawei, Stepwise calibration for residential building thermal performance model using hourly heat consumption data, Energy and Buildings 181 (2018) 10–25.

[44] Nan Li and Zheng Yang and Burcin Becerik-Gerber and Chao Tang and Nanlin, C., *Why is the reliability of building simulation limited as a tool for evaluating energy conservation measures?* Applied Energy, 2015. **159**: p. 196-205.

[45] Giorgio Mustafaraj, Dashamir Marini, Andrea Costa, K. Marcus, Model calibration for building energy efficiency simulation, Applied Energy 130 (2014) 72–85.

[46] Daniel Coakley, Paul Raftery, K. Marcus, A review of methods to match building energy simulation models to measured data, Renewable and Sustainable Energy Reviews 37 (2014) 123–141.

[47] E. IEA, Annex 53 total energy use in buildings: analysis & evaluation methods, International Energy Agency (2016).

[48] Tao Yang and Yiqun Pan and Jiachen Mao and Yonglong Wang and Zhizhong, H., An automated optimisation method for calibrating building energy simulation models with measured data: Orientation and a case study. Applied Energy, 2016. **179**: p. 1220-1231.

[49] Escudero-Revilla, J.T.-Z.a.A.C.-C.a.I.G.-P.a.C., *Energy and economic assessment of the envelope retrofitting in residential buildings in Northern Spain.* Energy and Buildings, 2015. **86**: p. 194-202.

[50] Jianli Chen and Xinghua Gao and Yuqing Hu and Zhaoyun Zeng and Yanan, L., *A meta-model-based optimisation approach for fast and reliable calibration of building energy models.* Energy, 2019. **188**: p. 116046.

[51] , Applied Energy 182 (2016) 115–134.

[52] Shreshth Nagpal and Caitlin Mueller and Arfa Aijazi and Christoph, F.R., *A methodology for auto-calibrating urban building energy models using surrogate modeling techniques.* Journal of Building Performance Simulation. **12**(1): p. 1-16.

[53] da Silva, P.P.F.a.N.A.H.a.S.I.L., Evaluation of Model Calibration Method for Simulation Performance of a Public Hospital in Brazil, Energies 14 (13) (2021) 3791.

[54] F. Enrico, V. Monetti, Methodologies and Advancements in the Calibration of Building Energy Models, Energies 8 (4) (2015) 2548–2574.

[55] Wang, D.H.a.I.G.H.a.L., Review on building energy model calibration by Bayesian inference, Renewable and Sustainable Energy Reviews 143 (2021) 110930.

[56] Gloria and Antonio and Fernando and José Manuel and Yi, Z., *Uncertainties and sensitivity analysis in building energy simulation using macroparameters.* Energy and Buildings, 2013. **67**: p. 79-87.

[57] ASHRAE, *Guideline 14-2014, Measurement of Energy and Demand Savings.* American Society of Heating, Ventilating, and Air Conditioning Engineers, Atlanta, Georgia, 2014.

[58] G.R. Ruiz, C.F. Bandera, Validation of Calibrated Energy Models: Common Errors, Energies 10 (2017) 348–359.

[59] Ø, J. and R. O, *Norsk Prisbok*. 2019: Norconsult Informasjonssystemer AS and Bygganalyse AS.

[60] AB, C.E.M., *The Total Concept method – Guidebook for Implementation and Quality assurance*. 2017.

[61] International Organisation for Standardisation, ISO 16739-1:2018 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries – Part 1: Data schema. 2018: Geneva, Switzerland.

[62] Brunsell, J.T. and S. Uvsløkk, *Boligers lufttetthet. Resultater fra lufttetthetsmålinger av nyere norske boliger*. 1980: Oslo.

[63] Thyholt, M., et al., *Energy analysis of the Norwegian dwelling stock-IEA Task 37*. 2009, IEA SHC. p. 66.

[64] FEMP, *M&V Guidelines, Measurement and Verification for Performance-Based Contracts Version 4.0*. 2015, U.S. Department of Energy Federal Energy Management, Program: Washington, DC, USA.

[65] D.P. Jenkins, S.Semple, S. Patidar, P. McCallum, Changing the approach to energy compliance in residential buildings – re-imagining EPCs. Energy and Buildings,Volume 249,2021.https://doi.org/10.1016/j.enbuild.2021.111239.

[66] Francesco Goia, Search for the optimal window-to-wall ratio in office buildings in different European climates and the implications on total energy saving potential, Solar Energy,Volume 132,2016,Pages 467-492,ISSN 0038-092X, https://doi.org/10.1016/j.solener.2016.03.031.

[67] Paolo Maria Congedo, Cristina Baglivo, Aslıhan Kurnuc Seyhan, Raffaele Marchetti, Worldwide dynamic predictive analysis of building performance under long-term climate change conditions, Journal of Building Engineering, Volume 42,2021,ISSN 2352-7102, https://doi.org/10.1016/j.jobe.2021.103057.

[68] A. Neale, M. Kummert, M. Bernier, Discriminant analysis classification of residential electricity smart meter data, Energy and Buildings 258 (Mar. 2022), https://doi.org/10.1016/J.ENBUILD.2021.111823 111823.

[69] S. Vitiello, N. Andreadou, M. Ardelean, and G. Fulli, ''Smart Metering Roll-Out in Europe: Where Do We Stand? Cost Benefit Analyses in the Clean Energy Package and Research Trends in the Green Deal,'' *Energies 2022, Vol. 15, Page 2340*, vol. 15, no. 7, p. 2340, Mar. 2022, doi: 10.3390/EN15072340.

Further reading

[70] Marit Thyholt, Trine Pettersen, Trond Haavik, Bjørn Wachenfeldt, Energy analysis of the Norwegian dwellingstock-IEA Task 37. IEA SHC, IEA SHC Advanced Housing Renovation by Solar and Conservation (2009) 1–66.