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Predicting Energy Savings of the UK Housing Stock under a Step-by-Step Energy Retrofit Scenario towards Net-Zero

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Abstract: The UK has one of the least energy-efficient housing stocks in Europe. By 2030, the emissions from UK homes need to fall by at least 24% from 1990 levels to meet the UK's ambitious goal, which is reaching net-zero emissions. The originality of this paper is to apply the building typology approach to predict energy savings of the UK housing stock under a step-by-step energy retrofit scenario, targeting the Passive House Standard for refurbishments of existing buildings, namely the EnerPHit "Quality-Approved Energy Retrofit with Passive House Components." The typologies consist of twenty reference buildings, representative of five construction ages and four building sizes. The energy balance of the UK residential buildings was created and validated against statistical data. A building stock retrofit plan specifying the order in which to apply energy efficiency measures was elaborated, and energy savings were calculated. The predicted total energy demand for the UK residential building stock for the year 2022 is 37.7 MTOE, and the carbon emissions estimation is 65.33 $MtCO_2e$. The energy-saving potential is 87%, and carbon reductions are about 76%, considering all the steps of renovation applied. It has been demonstrated that the step that provides the biggest savings across the housing stock is the one that involves replacing windows, draught-proofing, and installing mechanical ventilation with heat recovery.

Keywords: net zero; UK housing stock; step-by-step energy retrofit; EnerPHit; building typology; energy-saving

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1. Introduction

1.1. Context

Space and water heating for UK homes make up 25% of total energy use and 15% of greenhouse gas emissions. To meet the UK's ambitious goal of reaching zero emissions from existing buildings in the UK by 2050, by 2030, UK homes' emissions need to fall by at least 24% from 1990 levels [1]. In 2017, there were some 28.5 million homes in the UK, and the great majority of these were in England [2]. The UK has one of the least energy efficient housing stocks in Europe, resulting in high energy bills and a large number of households affected by fuel poverty, fundamentally owning to space heating. According to the latest estimations, around 13% of households in England are classified as fuel poor, with 25% in Scotland, 12% in Wales, and 18% in Northern Ireland [3]. It is estimated that more than 3000 people in the UK die every year due to the cold, as they are unable to afford heating their homes [4].

To meet its climate targets, the UK has the ambition to retrofit almost all homes to achieve at least the Energy Performance Certificate (EPC) band C by 2035. However, only 29% of homes today meet this standard, and the UK's current renovation rates are far below the ambitious target to tackle the remaining 71%, which is around 19 million homes [5]. The current rate of renovation progress is around 9000 improvements installed per week across the whole UK housing stock, and this needs to increase by around seven times to reach the EPC band C standard by 2035 [6].

During the last decade, the UK has applied various instruments and policies to reach its carbon reduction target. A new target for energy efficiency has been introduced by the Living Housing Association following the Clean Growth Strategy by 2030, which aims at building stock that is above the EPC C-rating [7]. The Association for Environment Conscious Buildings (AECB) launched a new AECB Retrofit Standards, seemingly based on the Passive House Standards, that aims at achieving 50 kWh/m^2/year for space heating, with a maximum of 2 ach @50 Pa (PH UK, 2021). The standard compliance relied on using the Passive House Planning Package (PHPP) as a modelling tool [8]. The London Energy Transformation Initiative (LETI) has published a Climate Emergency Retrofit Guide that aims to provide a practical standard for the retrofitting of the UK housing stock where, unlike AECB Retrofit and EnerPHit standards, detailed PHPP modelling is not be undertaken [9].

The UK Government's Department for Business, Energy, and Industrial Strategy (BEIS) sponsored PAS 2035:2019, which is an essential standard in a framework of new and existing standards on how to perform the energy renovation of existing buildings. The standard includes aspects on how to evaluate dwellings for retrofit, define renovation solutions, and monitor retrofit projects. The standard drives the "whole house approach" including the "fabric first" methodology [10]. However, the current UK building regulation for retrofitting (Part L2B) brings relatively low standards to meet the country carbon emissions target for 2050. Passivhaus Trust, which is an independent industry-leading organisation that promotes the adoption of Passivhaus in the UK, recommends that an EnerPHit Retrofit Plan (EiRP) is created for all retrofit projects. If the full EnerPHit standard is not considered feasible as a single-stage project initially, the possibility of a step-by-step retrofit should be considered [11]. Designing and demonstrating compliance with the Passivhaus standard EnerPHit is achieved using PHPP, which was developed by the Passive House Institute (PHI) in 1988 and is based on EN 832 (ISO 13790). Furthermore, there are several government-funded schemes that target social and private housing in the UK, mostly those that were rated under band D in the SAP (Standard Assessment Procedure), such as the Green Homes Grant Scheme in England, Warmer Homes programme in Scotland, Warm Homes Nest in Wales, and Energy Efficiency Grants in Northern Ireland.

Making the appropriate decision about the most suitable energy retrofit policy, defining ambitious and realistic carbon reduction targets, and evaluating whether these objectives are likely to be achieved necessitate developing accurate scenarios that indicate the buildings to be renovated and the renovation measures to be implemented, as well as the constraints such as the total annual budget, renovation rate, and energy-savings [12]. This requires a deep understanding of available energy efficiency measures, their state of maturity, economic viability, and their benefits in terms of carbon reduction and energy saving. It is also crucial to develop detailed models of the current energy performance of building stocks to estimate the energy-saving potential and economic impact of different retrofit policies to make informed decisions towards decarbonisation [13].

1.2. Literature Review

Different methods have been developed to model the energy consumption of residential building stocks. According to Kavgic et al. [14], these methods can be classified as bottom-up and top-down approaches. In the top-down approach, the energy consumption of the residential stock is defined through the regression of historic cumulative energy assessment as a function of national energy statistics, gross domestic product, population, and climate. The top-down approach does not offer the possibility to predict the impact of specific energy retrofitting measures on individual end-uses, whereas bottom-up models are more suitable for this task [15]. Bottom-up methods predict the energy consumption of various building typologies representative of a specific housing stock (e.g., semi-detached house, terrace house, etc.), which are then extrapolated according to the frequency of each building typology to define the effect of thermal retrofit measures on residential housing stock energy consumption, which can then be used as part of an evidence-based approach for a medium- to long-term energy supply strategy [16]. To define the energy consumption of a housing stock, bottom-up approaches can use two different methods, namely statistical and building physics-based methods. Most of the bottom-up statistical models are based on regression techniques and while these methods can be used to model housing stocks, they do not provide accurate details for estimating the impact of different carbon reduction measures [14]. Building physics-based methods include the modelling of a set of reference buildings representative of a housing stock using building energy calculations to estimate current and future energy consumption of the housing stock [17].

As indicated in Table 1, the use of reference building typologies to predict energy consumption and economic impact at the scale of a housing stock according to different policies and scenarios (e.g., standard retrofit, advanced retrofit, etc.) is widely applied in the literature. Although most applied methodologies overlap, the review of the literature has indicated that the available studies differ according to various aspects.

First, the geographical location that has an impact on building typologies, climate, national standards, and other aspects varies between studies. Studies have been conducted for Greece [18], Ireland [19], Italy [12,20–22], Sweden [23], Spain [24,25], UK [9], Bulgaria, Serbia, Hungary, and the Czech Republic [26].

Second, renovation scenarios also differ between studies. Some studies aimed to meet the specific energy targets of national regulations [19,23,24], while others modelled more ambitious scenarios targeting higher energy efficiency standards [9,12,18,20,21,25,26].

Third, the evaluation criteria of different scenarios also vary. Some studies focused solely on energy saving and carbon reductions, whereas other research included detailed economic calculations using indicators such as payback period, global cost reduction [22], the Net Present Value method [21], and the Levelized Cost of Saved Energy [12].

Finally, the literature review has revealed a very important gap; until now, to predict energy savings in housing stocks, most studies have used building typologies assuming a single-step approach for performing standard or deep renovation, where all renovation measures are performed at once, without considering the lifecycle concept or a long-term strategy, while in reality, 80–90% of all retrofits undertaken are partial retrofit measures, known as step-by-step retrofits, rather than complete one-time energy refurbishments [27].

Different barriers might lead to step-by-step retrofitting instead of single step retrofitting, such as the incapacity of the homeowner to finance a complete retrofitting, discomfort during the project, or a particular influential situation, such as leaky roof, a malfunctioning boiler, a family situation, or a lack of knowledge about how to perform the measures [28]. Therefore, the concept of Building Renovation Passport, with a step-by-step renovation roadmap, has been introduced in several European countries for building stock decarbonisation. A step-by-step renovation roadmap is defined as a renovation plan with a long-term vision of up to 15–20 years that evaluates a building through a global approach and proposes the implementation of renovation measures in a chronological order to make sure that at any stage of renovation, the installation of an additional measure is not compromised by a previous work [29].

Similarly, the Passive House Institute also suggests a pre-certification process of the building as an EnerPHit project if energy retrofits are carried out in several individual, consecutive steps. The preparation of a comprehensive EnerPHit Retrofit Plan (ERP) is essential in order to verify the possibility to achieve the EnerPHit Standard at the final completion [30].

Table 1. Available studies on the use of reference building typologies to predict energy consumption at the scale of a housing stock.

Source	Location	Objective/Originality	Retrofitting Approach	Evaluation Criteria	Scenarios	Number of Reference Buildings
[18]	Greece	To use reference buildings of the Hellenic building stock for demonstrating the energy performance and the potential energy savings from typical and advanced energy conservation measures (ECMs).	Single-step renovation	−Thermal energy consumption savings (%) −Thermal energy consumption savings (%)	−Existing situation −Standard scenario (meets the requirements of the Greece national regulations) −Advanced scenario (higher energy efficient measures)	24
[19]	Ireland	To investigate the economic and carbon case for thermal retrofit measures to the Irish existing detached, oil centrally heated, rural housing stock.	Single-step renovation	−Heat energy consumption (kWh/m^2) −Cost savings (Millions €) −Carbon savings (Millions of tonnes of CO_2)	−Existing situation −Standard scenario (meets the Irish National Insulation Programme Better Energy Homes grant-aided scheme)	10
[12]	Region of South Tyrol in northern Italy	To generate retrofit scenarios for building stocks according to available budget for building retrofit. The methodology creates a step-by-step retrofit plan and prioritises the buildings to be retrofitted using a Levelized Cost of Saved Energy (LCSE).	Step-by-step retrofit plan	−Energy saved in % Specific cost (€/m^2) −Levelized Cost of Saved Energy (€/kWh)	−Existing situation −Standard scenario (minimum legal and normative requirements) −Deep renovation scenario (nearly zero-energy building)	16
[23]	Sweden	To describe in detail the current energy usage of Swedish residential buildings, and to assess the technical energy savings and cost-effectiveness associated with implementing the EEMs in the Swedish residential stock.	Single-step renovation	−Technical energy saving potentials (TWh/year) −CO_2 emissions (Mt CO_2/year) −Potential reductions (% of baseline)	−Existing situation −Standard scenario (meets the specific energy targets of Swedish regulations)	300

Table 1. *Cont.*

Source	Location	Objective/Originality	Retrofitting Approach	Evaluation Criteria	Scenarios	Number of Reference Buildings
[20]	Piedmont region. (Italy)	To use reference buildings to investigate potentialities of energy savings and CO_2 emission reductions from the present state to a renovated state of the residential building stocks of the Piedmont region.	Single-step renovation	−CO_2 emissions for space heating and Domestic Hot Water (DHW) in tonnes −Annual primary energy demand for space heating and DHW in Gwh −Potential energy saving (% of baseline)	−Existing situation −Standard scenario (minimum legal and normative requirements) −Deep renovation scenario (nearly zero-energy building)	32
[21]	Southern Italy (Bari)	To obtain an estimate, on an urban scale, of the energy needs and CO_2 emissions of the public residential buildings of Bari.	Single-step renovation	−CO_2 emissions (tonnes/year) −Specific primary energy demand (kWh/m^{2}a) −Cost-benefit analysis was performed using the Net Present Value method (€)	−Existing situation −Standard scenario (minimum legal and normative requirements) −Deep renovation scenario (nearly zero-energy building)	5
[22]	Italy	To investigate the energy saving and global cost reduction associated with the implementation of different energy refurbishment actions on the existing Italian residential buildings.	Single-step renovation	−Energy saving (%) −Payback period (years) −Primary energy savings [kWh/m^{2}a] −Global cost reduction [€/m^2]	−Existing situation −Deep renovation scenario (meet the requirements of Italian National Agency for New Technologies, Energy, and Sustainable Economic Development)	120
[26]	Bulgaria, Serbia, Hungary, and the Czech Republic	To analyse heterogeneous data sources and collect the information of the housing stock under a common comparison framework of building typology data between countries.	Single-step renovation	−Primary energy saving potential (%) −The total primary energy demand for heating and DHW of the residential building stock (petajoule /year).	−Existing situation −Deep renovation (nearly zero-energy building)	7

Table 1. *Cont.*

Source	Location	Objective/Originality	Retrofitting Approach	Evaluation Criteria	Scenarios	Number of Reference Buildings
[25]	city of Bilbao, northern Spain	To propose the application of the cost optimal method on an urban scale, aiming to identify the suitable range of energy performance reasonable to promote in different types of buildings.	Single-step renovation	−Space heating demand (kWh/m^2) −DHW solar contribution factors −Annual photovoltaic outputs (kWh/kW) −Global cost (€) −Payback period −Energy saving potential (%)	−Existing situation −Renovation levels ranging between the Spain Building Technical Code regulation compliance and EnerPHit levels.	34
[24]	Catalonia (Spain)	To evaluate the potential of energetic savings of the dwellings in Catalonia and its economic impact, according to different scenarios of efficiency that have been defined according to current regulations.	Single-step renovation	−Heating and cooling energy demand (GWh/year) −CO_2 Emissions (tonnes/year) −Total individual investment for each category dwelling (€) −Total investment for all building stock (€) −Cost of kg CO_2 saved (€/kg CO_2)	−Existing situation −Renovation according to Technical Code of Buildings (CTE) for Spain [8] −Renovation according to Ecoefficiency Decree (DEC) for Catalonia −Technical potential savings considering 100% rehabilitation −Potential savings considering 2% rehabilitation	13
[9]	UK	To produce a UK stock model to evaluate the impact of LETI retrofit targets at a national level.	Single-step renovation	−Space heating demand (kWh/m^2/year) −Energy use intensity (kWh/m^2/year)	−Existing housing stock −LETI target range for retrofit	486

1.3. Originality of the Work

As indicated in Table 1, only the research conducted by Oberegger et al. [12] simulated energy savings of a housing stock using a step-by-step retrofit scenario. The researchers ranked retrofit steps for a whole housing stock according to the government's annual available budget for building retrofit using the Levelized Cost of Saved Energy (LCSE). However, the generated scenarios are not applicable at the scale of individual properties, as indicated in EnerPHit step-by-step standard or the Building Renovation Passport and do not guide homeowners through the renovation process by foreseeing and sequencing future renovation activities. Furthermore, the chronological order of the renovation measures suggested by Oberegger et al. [12] depends solely on the available budget for the government, while other parameters, such as health and comfort, are not considered. For instance, for window replacement with airtight windows, the installation of a mechanical ventilation system will also be necessary at the same time to ensure a good quality of indoor air. Finally, the method considers only the insulation of the thermal envelope and does consider the installation of energy-efficient systems, such as heat pumps and Mechanical Ventilation with a Heat Recovery system (MVHR).

The originality of this paper is to apply the building typology approach to predict energy savings of the UK housing stock under a step-by-step energy retrofit scenario targeting the EnerPHit standard.

2. Materials and Methods

The methodology used to apply the building typology approach to predict energy savings of the UK housing stock under a step-by-step energy retrofit scenario consists of different steps: first, the UK national residential building typology is created. Then, the energy balance of the UK residential buildings is calculated and validated against national statistical data. Finally, a building stock retrofit plan specifying the order in which to apply energy efficiency measures is elaborated, and the energy savings are calculated. A detailed explanation of the different steps is presented below:

2.1. The National Residential Building Typology

In this paper, the building types developed by BRE as part of the participation of the UK in the European project EPISCOPE [31] were used to represent the housing stock of the UK for their geometric data, construction, and thermal systems features. The energy-related properties of dwelling types in Wales, Scotland, and Northern Ireland were assumed to be the same as for England, as suggested in the UK housing stock modelling performed in [9]. There are 32 UK residential building types in the EPISCOPE, split by eight construction periods (i.e., pre–1919, 1919–1944, 1945–1964, 1965–1980, 1981–1990, 1991–2003, 2004–2009, post–2010) and four building sizes, including Single-Family House (SFH), Terraced House (TH), Multi-Family House (MFH), and Apartment Block (AB). For the research presented in this paper, the number of building types was further reduced due to the lack of data regarding the housing stocks in Scotland, Wales, and Northern Ireland. The construction periods 1981–1990, 1991–2003, 2004–2009, and post–2010 were merged into one construction period, which is post–1980, resulting in 20 building typologies (see Table 2). The characteristics of the building typologies are summarised in Supplementary Materials, Annexe S1.

Table 2. The UK permanent housing stock, by nation (thousands of dwellings).

Dwelling Type	England	Scotland	Wales	Northern Ireland	Existing Permanent UK + Predicted
SFH Pre–1919	646	122	82	46	896
SFH 1919–1944	644	50	33	12	739
SFH 1945–1964	1086	33	32	41	1192
SFH 1965–1980	1502	115	92	69	1778
SFH Post 1980	1915	255	150	159	2479 + 124.36
TH Pre–1919	3211	116	245	30	3602
TH 1919–1944	2767	96	63	54	2980
TH 1945–1964	2674	313	166	80	3233
TH 1965–1980	1971	291	171	111	2544
TH Post 1980	1592	202	131	125	2050 + 102.84
MFH Pre–1919	996	58	18	inc. within other categories	1072

Table 2. *Cont.*

Dwelling Type	England	Scotland	Wales	Northern Ireland	Existing Permanent UK + Predicted
MFH 1919–1944	317	93	inc. within other categories	inc. within other categories	410
MFH 1945–1964	563	78	inc. within other categories	inc. within other categories	641
MFH 1965–1980	943	44	inc. within other categories	inc. within other categories	987
MFH Post–1980	1169	42	inc. within other categories	inc. within other categories	1211 + 60.75
AB Pre–1919	12	184	inc. within other categories	5	201
AB 1919–1944	21	34	inc. within other categories	2	57
AB 1945–1964	73	95	20	4	192
AB 1965–1980	187	98	40	9	334
AB Post–1980	97	177	60	32	366 + 18.36
				Total permanent 2020	26,964
				Estimated permanent 2022	27,270

2.2. Energy Balance of Residential Buildings and Validation of the Model

In this paper building typologies are used for the assessment of the UK housing' energy balance as indicated in Dascalaki et al. [18]. The procedure includes the following steps:

(1) Use the Standard Assessment Procedure (SAP) software for the calculation of the energy consumption of the 20 typologies representing the UK housing stock. The Standard Assessment Procedure (SAP) is the UK Government's National Calculation Methodology for assessing the energy performance of dwellings.
(2) Use the frequencies expressing the number of buildings per typology to derive the total energy consumption per typology. National statistics are used to quantify the number of buildings. The numbers of buildings in England, Scotland, Wales, and Northern Ireland (see Table 2) were taken from the English Housing Survey 2019–20 [32], the Welsh Housing Conditions Survey 2017–18 [33], the Scottish House Condition Survey 2019 [34], and the Northern Ireland House Condition Survey 2016 [35], respectively. The heated floor area, the values of expenditure coefficient (for the space and water heating systems), and the characteristics of permanent dwellings for each of 20 typologies are based on information from BRE [36].
(3) Sum up the thermal energy consumption of all classes to derive the balance of the energy consumption in the residential building sector.
(4) Validate the energy balance against national data on energy consumption taken from the UK national statistics [37].

2.3. Elaboration of Step-by-Step Renovation Packages and Energy Performance Assessment

The SAP assessment tool was used following EnerPHit step-by-step methodology for retrofitting a wide range of housing typologies, with recommendations on how to improve building envelopes and systems in a cost-effective way. Improvements for existing UK housing have been suggested to be taken step-by-step in a medium-term plan, starting with the fabric first approach, as recommended by PAS2035. The existing housing structure and construction detailing was derived from the Tabula database on UK housing stock, with amendment according to current housing statistics, as Tabula counts the structural detailing as built in the first place. However, renewable options were limited to installing photophobic panels, which only considers the south-oriented roof area. The five improvement steps follow the EnerPHit and PAS2035 recommendations for a medium-term retrofit plan that considers sequencing and unintended consequences. This has been referred to as the risk management strategy in PAS2035, so that there will be no reverse impact of implementing certain measures on other health or energy aspects. Replacing windows with high efficiency and air-tight sealings will reduce infiltration air, which will result in a decrease in draught air, with a risk of less ventilation. Therefore, ensuring sufficient fresh air supply is necessary to maintain this balance. It is also recommended that replacing windows should be carried out prior to EWI whenever possible to ensure that windows are installed within the insulation layer for avoiding thermal bridge occurrence. The characteristics of retrofit steps considered in this paper are summarised in Supplementary Materials, Annexe S1.

3. Results and Discussion

3.1. Energy Balance Results

The buildings considered in the paper are permanent dwellings with a continuous occupancy throughout the year. The physical surveys of England and Northern Ireland include vacant dwellings, while the figures from Scotland and Wales are for occupied stock only. In 2016, 3.7% (28,500) of Northern Ireland housing stock was considered as vacant, whilst statistics published by the Ministry of Housing, Communities, and Local Government (MHCLG) reported the number of unoccupied homes in England in October 2020 at 665,600 (2.7%). For this paper, it is assumed that vacant buildings are distributed equally through the 20 typologies [38]. The sum of the frequencies of each building type resulted in a stock of 26,964 permanent dwellings, which correlates with actual data for 2020 that estimated the housing stock in the UK of 27,792 permanent and vacant dwellings. The vacant dwellings average about 3% of the total dwelling stock throughout the country. Given that the current analysis aims to reflect the building stock for the year 2022, the corresponding data for the years 2021 and 2022 were estimated based on the assumption that the annual growth rate of the number of dwellings during the years 2021 and 2022 is equal to the Average Annual Growth Rate (AAGR) of the years 2010–2020, which is 0.57%. Using the AAGR of 0.57% and 3% of vacant dwellings, the predicted total permanent housing stock for 2022 is about 27,270.30644. For this paper, it is assumed that predicted buildings are distributed through the building typologies according to post 1980 trends (40% SFH, 33% TH, 19% MFH, 6% AB).

The SAP software was used to calculate the total energy consumption and the space heating demand in kWh/m^2/year of the 20 building typologies. Then, using the frequency and average heated floor area of each building typologies, the energy balance of the housing stock was calculated and expressed in Kilo Tonnes of Oil Equivalent (KTOE). The conversion from kWh to KTOE was done by dividing the values in kWh by 11,630 to obtain the values in KTOE. The results are summarized in Table 3.

Table 3. Calculated total energy consumption and the space heating demand in kWh/m^2/year of the 20 building typologies.

Dwelling Type	Number of Dwellings in Thousands	Average Heated Floor Area (m^2)	Total Heated Floor Area—Entire UK Building Stock (Thousands m^2)	Space Heating Demand (kWh/m^2 Heated Floor Area)	Final Energy Consumption (kWh/m^2 Heated Floor Area)	Total Space Heating Demand—Entire UK Building Stock (KTOE)	Total Final Energy Consumption—Entire UK Building Stock (KTOE)
SFH Pre–1919	896	198	177,408	211.65	284.99	3229.16	4348.13
SFH 1919–1944	739	153.41	113,369.99	251.2	323.11	2449.15	3150.30
SFH 1945–1964	1192	134.4	160,204.8	263	340.63	3623.51	4693.01
SFH 1965–1980	1778	123.08	218,836.24	192.83	273.15	3629.04	5140.58
SFH Post 1980	2603	149.35	388,758.05	64.43	105.41	2154.10	3524.08
TH Pre–1919	3602	104.62	376,841.24	249.12	349.53	8073.57	11,327.81
TH 1919–1944	2980	93.01	277,169.8	254.47	359.39	6065.70	8566.63
TH 1945–1964	3233	87.72	283,598.76	257.67	365.01	6284.44	8902.30
TH 1965–1980	2544	85.32	217,054.08	189.18	278.03	3531.36	5189.83
TH Post–1980	2121	98.4	208,706.4	62.96	114.88	1130.05	2061.91
MFH Pre–1919	1072	70	4200	189.44	196.48	68.43	70.97
MFH 1919–1944	410	60	24,600	211.98	156.23	448.46	330.53
MFH 1945–1964	641	63	40,383	203.77	210.46	707.68	730.93
MFH 1965–1980	987	62	61,194	168.6	174.34	887.29	917.50
MFH Post–1980	1271	62	78,802	59.79	81.16	405.20	550.04
AB Pre–1919	201	68	13,668	149.84	156.86	176.13	184.38
AB 1919–1944	57	59	3363	118.68	140.06	34.32	40.51
AB 1945–1964	192	56	10,752	186.29	188.52	172.26	174.32
AB 1965–1980	334	63	21,042	154.26	177.11	279.15	320.50
AB Post–1980	384	68	26,112	74.11	90.96	166.42	204.26
Total calculated (KTOE) =						43,515.43	60,428.51
Total statistics =						22,394.24	37,751.49
Overestimation						48%	37%

To validate the energy model, the results of the energy balance obtained using SAP were compared with UK national statistics on final energy consumption and space heating demand, as reported by the UK government [37]. Table 4 indicates the official final energy consumption and space heating demand for the UK housing sector for the years 2010–2020. Based on the data indicated in Table 4, the average annual growth rates were calculated:

AAGR (total final energy consumption) 2010–2020 = −2%.

AAGR (space heating demand) 2010–2020 = −3.05%.

Since this paper aims to represent the UK housing stock for the year 2022, AAGRs were used to predict the final energy consumption and space heating demand of the UK housing stock for the year 2022. The results are indicated in Table 5.

Table 4. The official energy consumption balance reported for the UK residential building sector from 2010 to 2020 [37].

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Final energy consumption (KTOE)	49,410	40,883	44,441	44,891	38,680	40,281	39,713	38,446	39,507	38,395	39,276
Space heating demand (KTOE)	34,627.33	25,694.56	28,456.15	28,522.22	23,904.19	25,386.24	26,133	23,640	24,232	23,386	23,826

Table 5. The predicted final energy consumption and space heating demand for the UK residential building sector for the years 2021 and 2022.

Year	Estimated Total Final Energy Consumption (KTOE)	Estimated Space Heating Demand (KTOE)
2021	38,506.20	23,099.03
2022	37,751.49	22,394.24

A comparison between the results obtained using SAP (see Table 3) and the prediction for 2022 (see Table 5) indicates an overestimation of 48% for the space heating demand and 37% for the final energy consumption. This could be explained by the fact that energy efficiency characteristics of building typologies taken from the EPISCOPE project have been defined for an un-modernised condition [39]. However, in reality, loft insulation has been installed in about 90% of homes across the UK [30], 70% of cavity walls have been insulated [40], and 85% of homes already have full double-glazing [6]. To adapt the calculated energy balance to national statistics, assumptions were changed compared to the EPISCOPE project. The simulation of all building typologies has considered the improvements made to some of existing housing. For instance, loft insulation has been added to all properties, but in 90% thickness, as statistics shows that over 90% of UK existing housing stock have loft insulation installed. In addition, about 70% of existing external cavity walls are filled with insulation, where those cavities were found to be in an average width of 60 mm, so we assumed filling 40 mm of this type of external walls. Thus, the insulation thickness was assumed based on the percentage of houses insulated to reflect the current condition of UK housing stock, which in turn reflect more accurate assumptions. The EPISCOPE project also assumed most pre–1945 as having an old boiler, whereas most of those houses actually have a condensing boiler, if not a combi-type of boiler, installed. The general assumptions of the model simulation are detailed in Supplementary Materials, Annexe S1.

The results of the adapted energy balance are presented in Table 6. A comparison of the adapted energy balance and the statistics reveals an overestimation of 4% regarding the space heating demand and an underestimation of 6% concerning the final energy consumption, which is considered acceptable as indicated in Mata et al. [41].

Table 6. Adapted calculation results for the space heating energy balance for the permanent dwellings.

Dwelling Type	Number of Dwellings in Thousands	Average Heated Floor Area (m^2)	Total Heated Floor Area—Entire UK Building Stock (Thousands m^2)	Adapted Space Heating Demand	Adapted Final Energy Demand (kWh/m^2 Heated Floor Area)	Adapted Total Space Heating Demand—Entire UK Building Stock (KTOE)	Adapted Total Final Energy Consumption—Entire UK Building Stock (KTOE)
SFH Pre–1919	896	198	177,408	172	223	2627.12	3416.66
SFH 1919–1944	739	153.41	113,369.99	134	183	1306.77	1790.46
SFH 1945–1964	1192	134.4	160,204.80	108	155	1490.46	2147.10
SFH 1965–1980	1778	123.08	218,836.24	118	169	2232.23	3189.03
SFH Post–1980	2603	149.35	388,758.05	60	95	2030.73	3191.03
TH Pre–1919	3602	104.62	376,841.24	109	172	3538.34	5578.64
TH 1919–1944	2980	93.01	277,169.80	101	157	2426.57	3750.78
TH 1945–1964	3233	87.72	283,598.76	105	172	2581.38	4196.21
TH 1965–1980	2544	85.32	217,054.08	91	146	1703.33	2733.08
TH Post–1980	2121	98.4	208,706.40	68	114	1236.85	2060.62
MFH Pre–1919	1072	70	4200	68	96	24.64	622.32
MFH 1919–1944	410	60	24,600	93	12	198.57	270.79
MFH 1945–1964	641	63	40,383	109	147	378.72	511.42
MFH 1965–1980	987	62	61,194	91	132	483.64	697.49
MFH Post–1980	1271	62	78,802	71	95	487.40	650.39
AB Pre–1919	201	68	13,668	88	138	104.29	163.26
AB 1919–1944	57	59	3363	87	133	25.36	38.59
AB 1945–1964	192	56	10,752	84	125	78.08	115.87
AB 1965–1980	334	63	21,042	108	131	196.80	238.50
AB Post–1980	384	68	26,112	70	86	158.72	194.12
Total calculated (KTOE) =						23,309.99	35,556.38
Total statistics =						22,394.24	37,751.49
Over/Underestimation						4%	−6%

3.2. Energy Saving Potential

The present paper aims at determining the energy-saving potential achievable throughout the UK housing stock with step-by-step renovation targeting the EnerPHit standard. The chronological order of the steps was based on the EnerPHit methodology.

By applying all the retrofit steps, the total annual energy demand of the housing sector can be reduced by 31,069.32 KTOE (87% see Figure 1), while the potential of CO_2 emissions reduction is about 49.6508 million tonnes carbon dioxide equivalent ($MtCO_2e$) (76%). The various renovation steps provide energy savings between 15,083 KTOE and 695 KTOE.

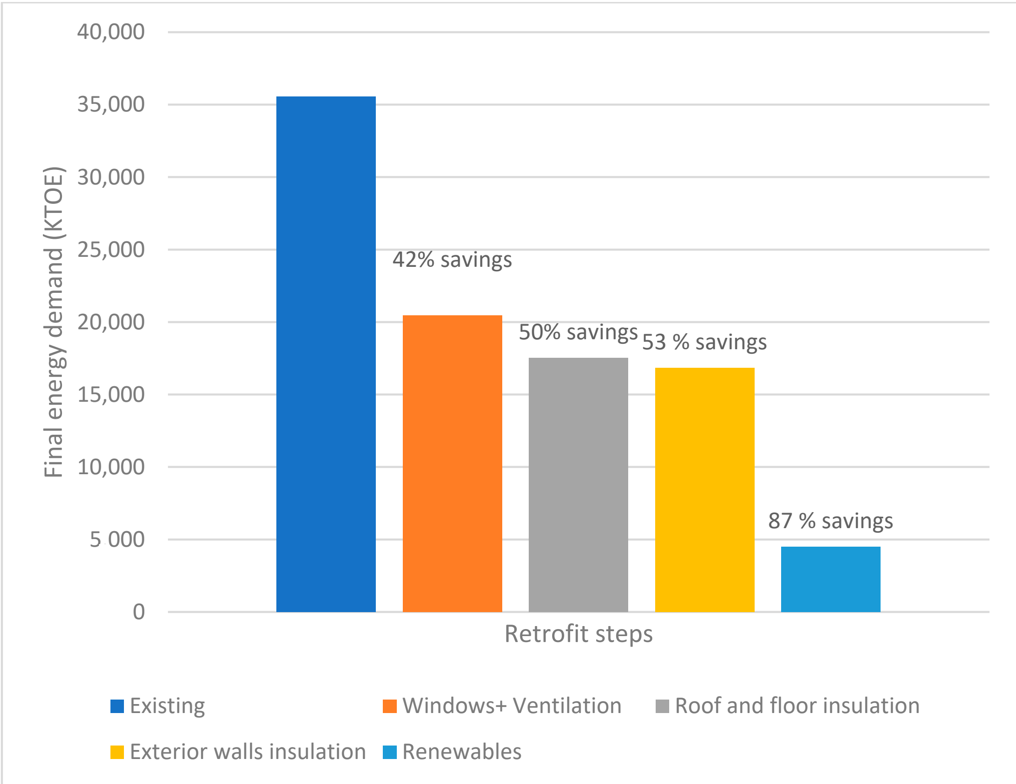

Figure 1. Predicted total annual energy consumption of the UK housing sector by applying a step-by-step retrofit.

The step that provides the biggest savings across the housing stock is the one that involves replacing windows, draught-proofing, and installing mechanical ventilation with heat recovery (15,083 KTOE). This could be explained by the fact that, although about 85% of homes in the UK already have full double-glazing [6], most installed double-glazing windows present poor U-values, thermal breaks within window frames, air leakages, and poor quality of installation. Hence, replacing existing windows with triple-glazing and airtight sealing is assumed to provide significant energy savings. As the installation of efficient windows improves airtightness, the installation of mechanical ventilation is necessary to ensure a comfortable and healthy environment for occupants and to preserve buildings from damages related to high moisture levels produced by households.

Currently, about 1 million homes in the UK have solar PV panels installed, which represent only 3.6% of the housing stock [42]. According to the findings of this paper, deploying rooftop solar PV panels across the rest of the housing stock in the UK could reduce the total energy by 12,353.47 KTOE. Hence, this paper agrees with the report from Element Energy [43] on the fact that rooftop solar PV is expected to play a key role in the UK reaching net zero by 2050. Furthermore, the potential to drive greater adoption of solar PV to help meet net-zero is promising, as the cost of solar panel installation has declined by 60% since 2010, and there have been very positive experiences among users [44].

The step of installing roof and floor insulation yields a savings of 2937.27 KTOE across the housing stock. This could be explained by the fact that even through loft insulation has been installed in about 90% of homes across the UK, the typical depth of insulation installed is relatively modest (about 100 mm to 250 mm) and can easily be improved to reach higher standards through the application of additional insulation [30]. The step of walls insulation installation and external door replacement provides the least energy savings (695.15 KTOE about 3%). This is because about 70% of cavity walls in the UK are already insulated, representing a significant portion of the housing stock (70%) [2]. However, most of those filled cavity walls do not consider moisture transmittance through the wall assembly, so installing a closed/open vapour layer is suggested on the warm side of the wall.

Both TH belonging to the construction period pre–1919 and ABs belonging to the construction period pre–1919 and 1919–1945 present the highest energy saving potential (about 97%), with windows replacements, draught-proofing, and mechanical ventilation with heat recovery as the best energy efficiency measures. The least-effective renovation actions are the ones applied to SFH built between 1945–1964. Literature does not provide any data on energy savings and CO_2 emissions of the UK housing stock disaggregated into SFH, TH, MFH, and AB that could be compared to the results obtained in the present work. Figure 2 and Table 7 show the energy saving potentials of each retrofit step by housing type.

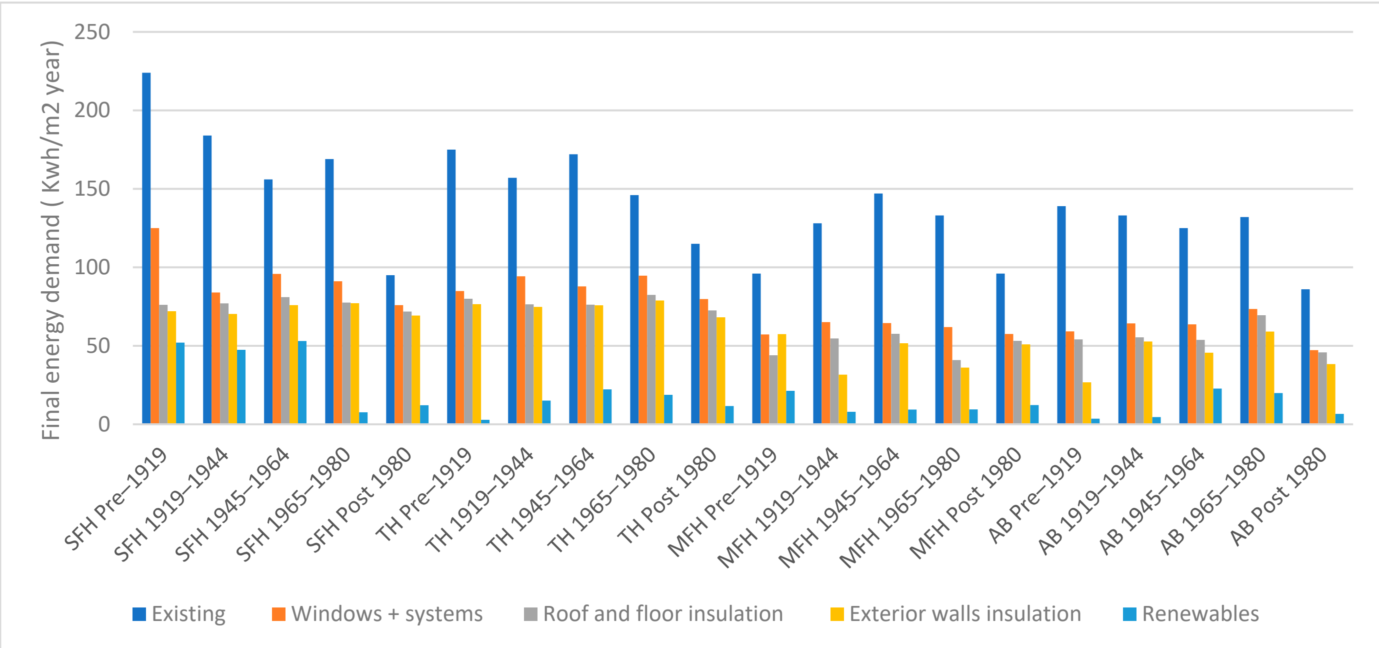

Figure 2. Energy savings by housing type and retrofit step.

There are some issues related to the application of renovation steps in the housing stock. In this paper, energy savings and carbon reduction are calculated assuming that measures are applied to all building typologies, while in reality, it may be difficult to achieve a high standard, such as the EnerPHit, in some cases due to various reasons, such as conservation aspects, reduced floor area, excessive inconvenience to occupants, and so on. Thus, the effect of some renovation steps may be overestimated. Furthermore, another issue is the chronological order of the renovation steps that is similarly applied to the different typologies of the housing stock following the EnerPHit methodology, which, in this paper, is mainly focused on the interdependency between the retrofitting steps. In reality, each house should have its particular renovation plan, with a specific chronological order of renovation steps according to parameters such as budget restrictions, the lifetime of different building assemblies, the construction age, and specific retrofit opportunities (a malfunctioning boiler, a leaking roof, etc.). Moreover, the savings attributable to each renovation step are greatly influenced by the sequencing of the steps, as the law of diminishing returns applies. In other words, the first retrofit measures will always appear to be much more cost-effective than later ones [45].

Table 7. Energy savings by housing type and retrofit step.

Dwelling Type	Existing	Windows + Systems		Roof and Floor Insulation		Exterior Wall Insulation + Door		Renewables	
	Final Energy Demand (kWh/m^2/year)	Final Energy Demand (kWh/m^2/year)	Energy Saving%	Final Energy Demand (kWh/m^2/year)	Energy Saving%	Final Energy Demand (kWh/m^2/year)	Energy Saving%	Final Energy Demand (kWh/m^2/year)	Energy Saving%
SFH Pre–1919	224	125	44	76	66	72	68	52	77
SFH 1919–1944	184	84	54	77	58	70	62	47	74
SFH 1945–1964	156	96	39	81	48	76	51	53	66
SFH 1965–1980	169	91	46	78	54	77	55	8	95
SFH Post–1980	95	76	20	72	25	69	27	12	87
TH Pre–1919	172	85	51	80	54	77	56	3	98
TH 1919–1944	157	94	40	76	51	75	52	15	90
TH 1945–1964	172	88	49	76	56	76	56	22	87
TH 1965–1980	146	95	35	82	44	79	46	19	87
TH Post–1980	115	80	30	73	37	68	41	12	90
MFH Pre–1919	96	57	41	44	54	57	40	21	78
MFH 1919–1944	128	65	49	55	57	32	75	8	94
MFH 1945–1964	147	64	56	58	61	52	65	9	94
MFH 1965–1980	133	62	53	41	69	36	73	9	93
MFH Post–1980	96	58	40	53	45	51	47	12	87
AB Pre–1919	139	59	57	54	61	27	81	4	97
AB 1919–1944	133	64	52	55	58	53	60	5	97
AB 1945–1964	125	64	49	54	57	46	64	23	82
AB 1965–1980	132	73	44	69	47	59	55	20	85
AB Post–1980	86	47	45	46	47	38	56	7	92

Finally, the cost aspect which is crucial in any renovation work has not been discussed in this paper, as the scope has been only to evaluate the achievable energy saving and carbon reduction throughout the UK housing stock by applying a step-by-step renovation plan. For a fair comparison across all building typologies' energy savings, parameters such as location, orientation, shadings, and urban structure are assumed typical.

4. Conclusions

The current practice in retrofit policy decisions and studies in the UK have been focused on the single-step building retrofitting approach to predict energy savings and carbon reductions of the housing stock. While one-stage deep renovation allows for fast

CO_2 reductions once the retrofit takes place, studies have presented empirical evidence that step-by-step retrofit is a practical and logical approach in real-life scenarios. The literature review did not identify any model covering the step-by-step retrofitting focusing on interdependencies between the retrofitting steps, and that is the main contribution of the present paper to the existing literature. The present paper aims to determine the energy-saving potentials achievable throughout the UK housing stock with step-by-step renovation targeting the EnerPHit standard.

The predicted total energy demand for the UK residential building stock for the year 2022 is 37,751 MTOE, and the carbon emissions are 65.33 $MtCO_2e$. The energy-saving potential is 87% and carbon reductions are about 76%, considering all the steps of renovation applied. It has been demonstrated that the step that provides the biggest savings across the housing stock is the one that involves replacing windows, draught-proofing, and installing mechanical ventilation with heat recovery.

Both TH belonging to the construction period pre–1919 and ABs belonging to the construction period pre–1919 and 1919–1945 represent the highest energy saving potential (about 97%), with windows replacements, draught-proofing, and mechanical ventilation with heat recovery as the best energy efficiency measures. The least effective renovation actions are the ones applied to SFH built between 1945–1964.

The study described in the paper could be a starting point to develop policy actions. However, further analysis is needed, especially a financial assessment of the different steps. In addition, other scenarios considering various locations and building orientations would provide more accurate anticipation of energy demand and the effectiveness of renewable energy generation. The predicted energy savings in this paper are to be considered as technical maximums, and further work is needed to clarify how these potentials could be achieved and to identify a robust approach to implementing these measures.

The average cost to upgrade each individual home is GBP 85 k, a challenging figure for most households. Achieving a net-zero society is feasible; however, a clear financial plan needs to be in place. The historic personalised grants towards retrofitting existing housing stock were removed, substituted, and replaced in record time, while net-zero was projected a half-century ahead. Future plan should consider homeowners' readiness to upgrade their homes. This decision-making process could take a decade, and the retrofitting step-by-step process over three decades, to be achieved.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15093082/s1, Annexe S1: The model simulation general assumptions.

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