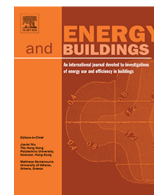
Energy & Buildings 269 (2022) 112253

Contents lists available at ScienceDirect

Energy & Buildings

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



Home energy retrofit: Reviewing its depth, scale of delivery, and sustainability

Mohammad Saffari [a,*], Paul Beagon [b]

[a] School of Mechanical and Manufacturing Engineering, Dublin City University, 630 Collins Ave Ext, Whitehall, Dublin 9, Ireland
[b] Sustainable Energy Authority of Ireland, 3 Park Place Hatch Street Upper, Dublin 2, Ireland

ARTICLE INFO

Article history:
Received 22 March 2022
Revised 30 May 2022
Accepted 11 June 2022
Available online 17 June 2022

Keywords:
Home energy retrofit
Residential energy use
Urban spatial scale
Home energy upgrade
Neighbourhoods
Districts
Sustainability

ABSTRACT

Home energy retrofit has been a publicly-funded policy in many countries since the 1990s. Government motivations have spanned from combating energy poverty to climate action and sustainability. Given the ambition of public policy, this paper reviews the targets, spatial scales and metrics used to deliver and evaluate home energy retrofit.

Large-scale retrofit projects do differ: by spatial area, by retrofit depth and in evaluation metrics (if used). This review surveys first, the quantities of homes and inhabitants in intermediate spatial scales used to plan retrofit programmes. Second, the optimal spatial scale and retrofit depth to deliver large-scale home retrofit. Third, the quantitative metrics to evaluate retrofits, and future trends in occupant-based metrics.

Neighbourhood is found to be the optimal spatial scale for home energy retrofit. Deep retrofit is described as 60% energy savings that, in synergy with energy supply decarbonisation, promises to deliver 80% or higher emission reductions. Recent evidence shows a shifting primacy from fabric-first retrofit to decarbonisation of heat generation and occupant health and well-being.

© 2022 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Contents

1. Introduction . . . 2
 1.1. Contribution of this paper . . . 2
2. Depth and evaluation of home energy retrofit . . . 3
 2.1. Policy targets to decarbonise home energy . . . 4
 2.2. Feasible energy retrofit targets . . . 4
 2.3. Absolute energy targets and evaluation of retrofit . . . 4
  2.3.1. Absolute energy retrofit targets . . . 4
 2.4. Comparison of relative and absolute energy targets . . . 6
3. Neighbourhoods—the intermediate scale for energy retrofit . . . 6
 3.1. Analysis and delivery of neighbourhood energy retrofit . . . 6
 3.2. Intermediate scales in energy analysis . . . 7
  3.2.1. Districts and neighbourhoods . . . 7
  3.2.2. Other intermediate scales . . . 7
 3.3. Other relevant characteristics of neighbourhoods . . . 7
4. Home energy retrofit for better health and improved quality of life . . . 8
5. Discussion . . . 10
 5.1. Retrofit targets and delivery synergies . . . 10
 5.2. Retrofit approach and role of fabric first . . . 10
 5.3. Home type selection for retrofit . . . 11
6. Conclusions . . . 11

* Corresponding author.
E-mail addresses: mohammad.saffari@dcu.ie (M. Saffari), paul.beagon@seai.ie (P. Beagon).

https://doi.org/10.1016/j.enbuild.2022.112253
0378-7788/© 2022 The Author(s). Published by Elsevier B.V.
This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

7. Future work and research 12
Declaration of Competing Interest 12
References 12

1. Introduction

In Europe, the building sector accounts for about 40% of overall energy use and 36% of greenhouse gas (GHG) emissions [1,2]. Such significant shares of energy and GHG emissions mean that energy retrofit of the building sector is a key mechanism to achieve European energy policy [3]. Furthermore, EU nations increased policy goals when adopting net-zero energy by 2050, at UN Climate Change Conference 2021 (COP26) in Glasgow [4].

Outside of Europe, energy retrofit has taken place repeatedly and at scale, for example New Zealand, China, Japan and US [5]. In fact, the actual implementation of the Better Buildings Neighbourhood Program in the US compares favourably to the UK's Green Deal [6]. In Australia, all scales of government have addressed energy retrofit programmes [7]. Local government demonstrated the most willingness and capacity to deliver these programmes, although governance challenges prevented the programmes reaching their potential. Public funding enables improvements in occupant thermal comfort (for example Korea [8]) or building energy performance – especially for occupants experiencing energy poverty or the high upfront costs of energy retrofit.

In addition to the upfront costs and potential savings of energy retrofit, Meles et al. [9] showed that non-financial concerns of disruption during its installation, its environmental sustainability, and its thermal comfort also influence its uptake. These non-financial concerns are addressed in two United Nations Sustainable Development Goals (SDG)—SDG 7: Affordable and clean energy, and SDG 11: Sustainable cities and communities [10].

According to the SDG report 2021 [11], nations will achieve the global energy-efficiency target only through substantial investment on a systematic scale. Systematic (or large) scale can be implemented and promoted by governments through new energy policies and energy retrofit grants necessitated by growing urbanisation. Systematic delivery is also intended to decrease housing inequalities by improving the life quality of low-income occupants living in inadequate housing [12]. Put simply, SDGs require governments to support large-scale home energy retrofit (HER).

Definitions of HER vary in spatial scale and domain, but agree on the need for "sustainablity". For example, in 2013 Dixon and Eames [13] reviewed urban retrofit and adopted Eames' 2011 [14, p.2] definition of **sustainable urban retrofitting**:

> "directed alteration of the fabric, form or systems which comprise the built environment in order to improve energy, water and waste efficiencies."

Examining its definition, sustainable urban retrofit comprises alterations that exceed the often "invisible" maintenance and repair of the *built environment*, and are completed across fabric, form and systems. *Fabric* means the physical building construction (excluding technical systems), whose quality affects building heat losses by air leakage, thermal bridging and thermal transmittance [15]. *Form* means the home type, such as single-family (SFH) or multi-family homes (MFH), whose shares of the national building stock vary across the EU countries [16]. EU research has split SFH and MFH forms into entire country-specific typologies [17]. *Systems*, in sustainable urban retrofitting, are the complex socio-technical systems that, comprise technology, regulation, user practices and markets, cultural meaning, infrastructure, maintenance networks and supply networks [18]. For example, a 2021 study of south-eastern Mediterranean countries highlighted the relationships between technology advancement, occupant income, and occupant behavioural responses to update HER design and policies [19]. Finally, sustainable urban retrofit spans three *domains*: energy, water and waste.

This review paper selects one domain – energy – and its GHG emissions. Therefore, it adopts the **sustainable retrofit** definition from a 2014 study of tenants' experiences with retrofit technology [20].

> "Sustainable retrofit can be defined as the upgrading of the building fabric, systems and/or controls to improve the energy performance of the property."

By this definition, sustainable retrofit shrinks spatial scale from the entire built environment to the building, and selects only the energy domain. Further, the definition substitutes the term "directed alteration" with the more optimistic "upgrade". Regarding the location of the upgrades, "form" is omitted, and the term "system" is combined with "controls", reflecting the smaller building scale and modern building controls. The *systems* implied by "sustainable retrofit" are energy-conversion systems for space and water heating, typified by heat pumps, combined heat and power, and the electricity and gas systems supplying them [21].

While sustainable retrofit closely describes the HER reviewed in this paper, it lacks an overarching purpose. In 2017, Galvin and Sunikka-Blank [5] provided that purpose, stating that **sustainable thermal retrofit** "must be good for *both* people and environment in the long run". They continued to list the competing *objectives* which a sustainable retrofit must balance:

1. Reducing non-renewable energy consumption,
2. Mitigating environmental damage (especially climate change),
3. Increasing thermal comfort and health, and
4. Keeping homes affordable and retaining architectural heritage.

Given the range of definitions and objectives, sustainable retrofit of homes are not uniform, even when confined to the energy domain. Despite adoption of the aforementioned *sustainable retrofit* definition, HER programmes still vary in depth, spatial scale, and evaluation metrics. This review focusses on the objectives of 1) reducing energy use and, 2) mitigating climate change (decarbonisation). The third objective of increasing thermal comfort and health is summarised in a later section.

1.1. Contribution of this paper

This paper compares the depth and spatial scales used to deliver home energy retrofit (HER) and the metrics used to evaluate it. It explores the assessment of occupant health and well-being, that should also benefit from HER. Finally, the paper discusses three HER trends: 1) synergy between energy-supply and energy-use systems to achieve decarbonisation targets, 2) declining primacy of fabric-first retrofit approaches and 3) older home types selected for retrofit. The geographical scale considered is the cool-temperate climate in Europe.

This review is organised as follows: Section 2, reviews HER depth , and the decarbonisation targets and practicalities determining that depth. Section 3 compares spatial scales and explains the rationale of HER delivery at neighbourhood scale. Section 4

reviews HER benefits to occupant health and well-being, and Section 5 discusses the aforementioned three HER trends. Section 6 closes with conclusions. Existing literature does contain a review of energy in the residential sector by Nejat et al. [22], that covers international policies and trends, but does not focus on home energy retrofit. More recently, Murto et al. [23] reviewed energy retrofit, but in terms of its complexity and counter-strategies to its complexity. Other literature has reviewed energy analysis at different spatial scales of the built environment: district energy systems [24], city scale [25], urban energy systems models [26] and urban building energy models [27]. Those four reviews and the spatial scales they focused on are discussed later (Section 3.2).

2. Depth and evaluation of home energy retrofit

The building energy literature is now surveyed to find: what is *deep retrofit*? Within the research literature, deep retrofit definitions vary and are generally expressed qualitatively. Government-funded deep retrofits are defined by the policy targets they are intended to achieve, often expressed as GHG reductions (Section 2.1). Whereas research studies have found *feasible* targets for home energy retrofit (HER), often expressed as energy-use reductions (Section 2.2). Before reviewing the quantitative targets, definitions of deep and shallow retrofit are introduced:

Deep retrofit is a combination or "package" of multiple energy measures that upgrade the physical fabric, heat generation system and lighting of a building. Upgraded fabric provides a consistent building envelope that reduces outside air infiltration and other heat losses. New heat generators, such as electric heat pumps, must be sized during design, and controlled during operation in order to deliver high-performance heating to the upgraded building.
According to the European directive on the energy performance of buildings (EPBD) [28], major renovations of existing buildings, regardless of their size, provide an opportunity to take cost-effective measures to improve energy performance. For cost-effectiveness, the minimum energy performance requirements can be limited to the renovated parts most relevant to the building's energy performance. EPBD defines *major renovation* as the renovation of a building where:

(a) the total cost of the renovation relating to the building envelope or the technical building systems is higher than 25% of the value of the building, excluding the value of the land upon which the building is situated.
(b) more than 25% of the surface of the building envelope undergoes renovation.

Member States may choose to apply either option (a) or (b) [28].
Shallow retrofit comprises one or two maintenance measures, such as increased boiler efficiency or new glazing. In contrast, a comprehensive deep retrofit is more likely to achieve policy reduction targets in energy and GHG emissions.

Retrofit for the Future (RfF), a 2009–2013 retrofit programme on UK social housing, used a "whole house" approach. Since RfF had targets of 80% GHG reductions, the terms "deep" and "whole house" describe the programme's reduction targets and package of retrofit measures respectively. Gupta et al. [29] summarised "whole house" as an interaction of multiple measures: fabric, ventilation, heating, lighting and micro-generation, to improve performance of all energy uses. In a contemporaneous retrofit programme of Dutch social housing, a deep retrofit combined innovative heat pumps or micro-CHP (combined heat and power) with improvements to the building thermal envelope [30]. This study found that common "maintenance measures" of improved boiler efficiency or replacement glazing would not achieve energy performance targets. One or two maintenance measures constituted merely a "shallow" retrofit. Likewise, the Irish Green Building Council (IGBC) defined deep retrofit as an extensive package of energy-efficiency improvements, using the term "deep renovation" in their 2017 report [31]. Furthermore, the IGBC included high upfront costs as a defining characteristic of deep renovation, and expected "significant" energy savings in return. This national industry group proposed *phased* retrofits that overcome high upfront costs by qualifying for existing funding schemes. A similar proposal has been endorsed by an international industry group; EURIMA (European Insulation Manufacturers Association) who supported *staged* approaches in order to — deliver deep retrofit — and avoid shallow retrofit [32].

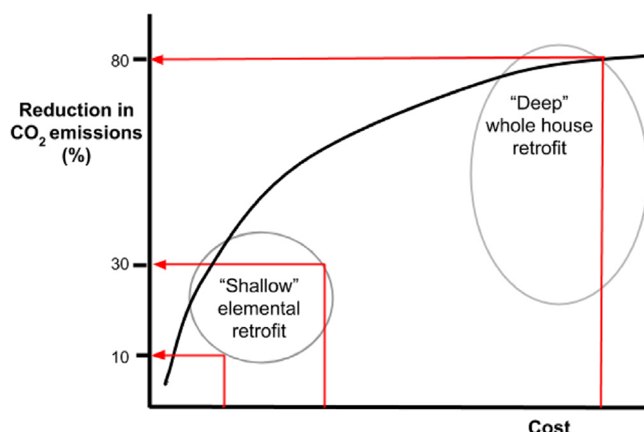


Fig. 1. The law of diminishing returns causes a non-linear increase in retrofit cost and complexity versus reduction in CO_2 emissions, adapted from [33].

Table 1
Decarbonisation policy targets—relative reductions in emissions. Policy targets are split by territory and ordered by target date.

Relative reduction and target date	Territory	Publication year	
30% CO_2 (and energy) reductions compared to existing	UK, local authority	1995	[37]
60% CO_2 reductions by 2025 compared to 1990 levels	UK, London	2007	[40]
80% CO_2 reductions by 2050 compared to 1990 levels	UK, nationwide	2008	[42]
20% GHG reductions by 2020 from 1990 levels	EU	2009	[44]
40% GHG reductions by 2030 from 1990 levels	EU	2014	[45]
55% GHG reductions by 2030 from 1990 levels	EU	2020	[46]
60% GHG reductions by 2040 from 1990 levels (2011 roadmap)	EU	2011	[47]
80% GHG reductions by 2050 from 1990 levels (2011 roadmap)	EU	2011	[47]
Net-zero GHG by 2050	EU	2021	[48]

In 2013, Jones et al. [33] separated shallow and deep retrofits into two ranges of CO_2 reductions: 10%–30% and 60%–80%. Their line plot, however, displayed deep retrofits with lower CO_2 reductions while retaining their high costs (Fig. 1). Shallow and deep retrofit were labelled "elemental" and "whole house", and delivered as standalone homes without considering larger energy systems. The split into two distinct categories of retrofit reflects the diminishing returns imposed by *non-linear* additional costs required by additional GHG reductions. Subsequent studies, by EU and Sustainable Energy Authority of Ireland (SEAI) [34,35], added the "med-

ium" category retrofit. In its model of consumer decision-making, SEAI switched the retrofit metric from emission reductions to financial costs. Shallow, medium and deep retrofits were mapped to three-, five- and ten-year payback periods [35].

2.1. Policy targets to decarbonise home energy

Over 25 years ago, the UK's Home Energy Conservation Act 1995 (c.10) compelled local authorities to report on measures that would result in "significant improvement" in residential energy efficiency [36]. (Assessments of costs and carbon dioxide reductions were also required, whereas assessments of job creation were optional.) The legislation did not quantify its "significant improvement", but a 30% improvement was typically assumed by the local authorities [37–39].

By early 2007, the Greater London Authority (GLA) was aspiring to 60% GHG reductions from 1990 levels by 2025 [40]. The urgent reduction deadline reflected the conclusions of then recent Stern Review [41]. Despite its confidence in low-carbon technology, the GLA assessed its target as *unachievable* without a "small number of key national regulatory and policy changes". Nevertheless, the GLA compared its target favourably to the contemporaneous UK government aspiration of 60% reductions from 2000 levels by the later date of 2050.

In 2008 however, further legislation committed the UK government to larger 80% CO_2 reductions by 2050, again compared to 1990 [42]. By directly adopting this 80% target [43], the RfF programme demonstrated the cascade of high-level decarbonisation policy targets to HER programmes. A sample of *decarbonisation policy targets* formulated at national and international levels appear in Table 1.

One source of international decarbonisation targets is the European Commission, notably its 2011 Roadmap to a low-carbon economy and thereafter [47]. Its escalating targets of relative GHG reductions act as milestones allocated per decade. In 2014, the EU initially set a 2030 target of 40% GHG reductions compared to 1990, doubling the 2020 target of 20% [49]. In 2021, the EU Green Deal justified raising the 2030 target from 40% to 55%, and the 2050 target from 80% to net-zero [46]. To achieve 55% GHG reductions by 2030, the EU cascaded 60% reductions target to the buildings sector and developed a building renovation strategy [50]. The Renovation Wave for Europe strategy will consider the introduction of a "deep renovation" standard to the EPBD (Energy Performance of Buildings Directive) [51], and is expected to create 160,000 "green" jobs [52].

Deep renovation was quantified, in a 2017 report to the EU, as delivering 60% reductions in primary energy use [34]. (The 60% reductions quantity had already appeared in a 2013 EU review of financing energy-efficient buildings [53].) Despite its source, a target of 60% reductions in primary energy remains ambitious when compared to *feasible energy retrofit targets* reviewed next.

2.2. Feasible energy retrofit targets

In his 2007 study, Lowe explored *feasible* reductions of 60%–70% in GHG emissions by UK housing. He credited his 2005 collaboration with Johnston et al. [54] as the *first such study* undertaken in the UK. That collaboration foresaw a requirement for "strategic shifts in both energy supply and demand side technology", resulting in a synergy between the energy-use and energy-supply systems which are discussed in Section 5.1.

In their 2015 assessment of the RfF programme, Gupta et al. [29] cited an industry estimate of 65%–95% energy savings [55]. The successor HER programme "Scaling up Retrofit" actually lowered the reductions target to 50% [5] (within a commercially viable range of 50%–75% energy savings [56]). Similarly during

Table 2
Feasible energy retrofit targets—relative reductions in primary and delivered energy use.

Energy type	Relative reduction	Source
Primary	60%	Deep renovation research, EU 2017 [34]
Delivered: total home use	65%–95%	Whole house energy retrofit, UK 2014 [55]
	50%	REMOURBAN research project, EU 2019 [57]
Delivered: space and water heating	40%	Buildings energy review, Denmark 2016 [60]
	40%	Academic research on homes, UK 2007 [21]
Delivered: space heating only	47%	Insulation manufacturers' estimate, Europe 2012 [58]

2015–2020, the EU research project REMOURBAN aimed for 50% energy-use reductions after retrofit [57]. Specific to delivered energy for heating, research studies have preferred more modest estimates by Industry of feasible energy reductions. Connolly et al. [58] replaced the 62% savings in space heating, assumed in an EU Heat Roadmap, by Industry's 47% estimate [59].

In summary, feasible retrofit targets expressed as energy-use reductions (Table 2) fall below decarbonisation policy targets of 80% reductions, let alone net-zero by 2050 (Table 1). Filling the gap to achieve policy targets requires decarbonisation of the energy supply to post-retrofit homes. In Europe this gap could persist while the EPBD (recast) [28] requires *cost-optimal* energy performance by buildings undergoing major renovations. (Cost-optimal levels should be calculated based on the comparative methodology framework referred to in Article 6 of the EPBD 2021.) In contrast, EPBD requires nearly zero-energy building (NZEB) by new buildings, achieved where their low energy use is covered mainly by renewable sources.

2.3. Absolute energy targets and evaluation of retrofit

Given such ambitious targets, Ma et al. [61] described the retrofit methodology to realise energy savings and emission reductions. They identified five key phases to deliver a retrofit programme, completed by a validation and verification stage (Fig. 2). As noted again in 2020, the performance of home energy retrofit packages remained difficult to assess [62].

Clear and consistent *absolute* carbon targets are used to avoid poorly performing homes meeting percentage (i.e. relative) reduction targets [29]. Therefore, deep retrofits programmes are often set absolute targets per home, to accompany relative reduction targets per programme (the latter often cascaded down from national policies). Absolute retrofit targets are now reviewed and compared to new-build targets.

2.3.1. Absolute energy retrofit targets

Absolute targets of the RfF programme covered year periods and were normalised (divided) by floor area in square metres (m^2). Two established methodologies differed in absolute targets for carbon emissions: 17 $kgCO_2/(m^2.a)$ by SAP (Standard Assessment Procedure) and 20 $kgCO_2/(m^2.a)$ by Passive House Planning Package (PHPP). The lower SAP target resulted from the methodology's lower carbon intensities of fuel. Both absolute targets covered operational carbon emissions, whereas Global Warming Potential covers all greenhouse gases usually spanning a building's entire life cycle.

Global Warming Potential is a weighted combination of the warming effect and atmosphere lifetimes of different GHGs, pro-

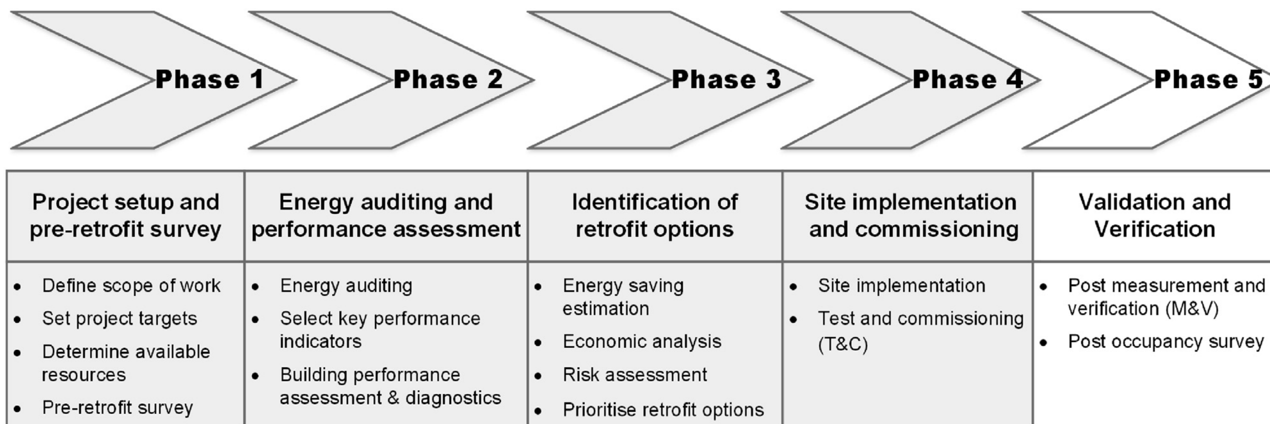


Fig. 2. Key phases of a building retrofit programme, completed by the validation and verification phase [61].

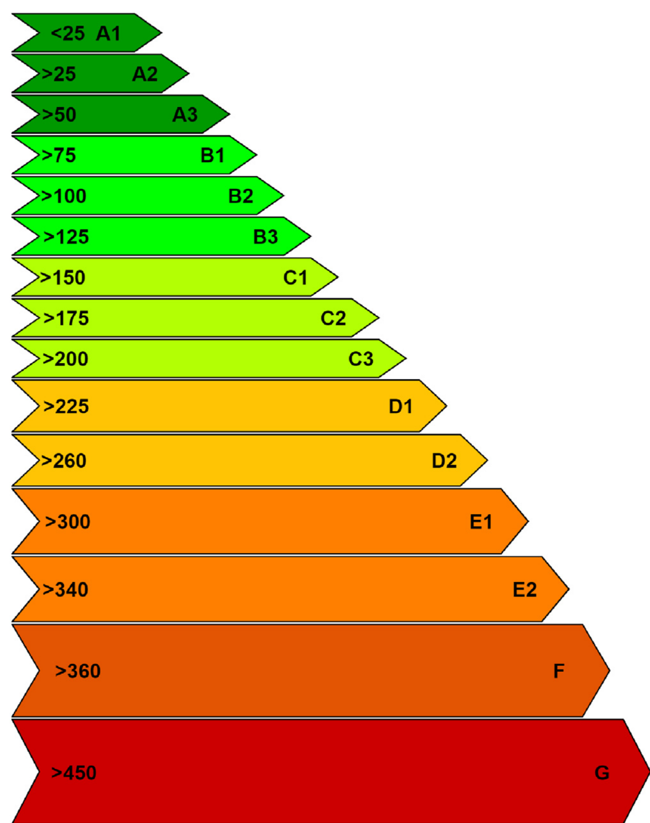


Fig. 3. Fifteen BER ratings of primary energy use intensity descending from high to low performance, adopted from [74]. Rating thresholds are expressed in kWh/(m^2.a).

ducing an equivalent carbon mass (kgCO_{2e}) [63]. The metric has been used by building assessments in warm and cool climates [64,65]. EU research benchmarked yearly operational Global Warming Potential within 100–10 kgCO_{2e}/(m^2.a) [66], referencing European average 35.2 kgCO_{2e}/(m^2.a) [67].

The remaining absolute metrics mostly consist of energy use intensities (EUIs). Energy performance certificates, mandated by the EPBD [68], are both EUIs and "calculated rating", whose definitions are presented next. (Note that the EUIs of primary energy in Fig. 3 and Table 3 cover the building energy services typically used according to the EPBD: heating, cooling, ventilation, hot water and lighting.).

Energy use intensity (EUI) is "a unit of measurement that describes a building's energy use for heating, ventilation, and air conditioning (HVAC), as well as hot water and lighting [28], relative to its size, on an annual basis" [69]. Normalisation by floor space makes the metric relative to the building size. Expressed in kWh/(m^2.a), energy use intensities enable ranking and comparison of buildings' total primary energy use.
Primary energy includes non-renewable energy and renewable energy. Where both energies are taken into account, as the case in this review, the sum is the *total primary energy* [70]. Given its applicability in comparing homes, EUI is an ideal metric in energy performance certificates — market tools intended to create demand for energy-efficient buildings [71].
Calculated rating of a building's energy performance is its theoretical energy use, calculated using building variables such as floorspace and construction date. Energy performance certificates are often calculated ratings; one-time calculations without the collection and storage of long-term energy measurements. For example, the Irish energy performance certificate for homes, Building Energy Rating (BER), splits calculated energy use intensity into 15 ratings from A1 to G (Fig. 3).

High-performance BER ratings provide memorable names for absolute targets. A2 equates to the 2018 EPBD standard[1], and previously A3 met the 2011 building regulations; both ratings apply to new builds (Table 3). Regarding retrofit targets, Ireland set the lower B2 rating of 100–125 kWh/(m^2.a) primary energy use intensity [72,73]. Although the BER B2 rating contains RfF's target value of 115 kWh/(m^2.a), the two methodologies differ slightly. Both BER and RfF cover home heating, lighting and hot water, but RfF also included appliances.

Along with its Passive House Planning Package (PHPP), the Passive House Institute (PHI) defined the EnerPHit retrofit standard and a Low Energy Building standard [75]. Primary energy demand is an important criterion within each standard; 60 kWh/(m^2.a) in PHPP Classic, and an easier 120 kWh/(m^2.a) in EnerPHit. In 2021, the Buildings Performance Institute Europe (BPIE) surveyed Long-Term Renovation Strategies across the EU [76]. Three absolute definitions of deep retrofit expressed as primary energy use intensities were found in cool temperate climates, all of which met EnerPHit's 120 kWh/(m^2.a) criteria. Comparison of primary energy criteria among the PHPP categories is complicated by renewable generation criteria within its Plus and Premium categories which are not discussed here.

[1] Nearly Zero Energy Building (NZEB) standard is required from end of 2020.

Table 3
Building performance targets—absolute emissions or energy use. All values are per year and normalised by floor space.

Metric type	Target	Home state	Source Methodology
GHG emissions:			
Total per home	17 $kgCO_2/(m^2.a)$	New build	SAP [29]
	20 $kgCO_2/(m^2.a)$	New build	PHPP [29]
	10–100 $kgCO_{2e}/(m^2.a)$	Retrofit	Global Warming Potential [66]
Primary energy use:			
Total per home	25–50 $kWh/(m^2.a)$	New build	EPBD's NZEB standard 2018 [78]
	50–75 $kWh/(m^2.a)$	New build	Irish regulations 2011 [78]
	60 $kWh/(m^2.a)$	New build	Passive House Classic, PHI 2016 [75]
	80 $kWh/(m^2.a)$	Retrofit	Deep renovation, France [76]
	100 $kWh/(m^2.a)$	Retrofit	Deep renovation, Belgium – Flanders [76]
	100–125 $kWh/(m^2.a)$	Retrofit	Climate Action Plan, Ireland 2019 [72]
	107 $kWh/(m^2.a)$	Retrofit	Deep renovation, Czechia (Czech Republic) [76]
	115 $kWh/(m^2.a)$	Retrofit	Retrofit for the Future, UK 2015 [29]
	120 $kWh/(m^2.a)$	Retrofit	Non-renewable demand, EnerPHit 2016 [75]
Delivered energy use:			
Space and water heating	80 $kWh/(m^2.a)$	Retrofit	Buildings energy review, Denmark 2016 [60]
Space heating only	25 $kWh/(m^2.a)$	Retrofit	Cool-temperate climate, EnerPHit 2016 [75]

The Passive House Institute is clear, however, in its criteria for maximum heating demand. EnerPHit limits delivered energy for space heating to 25 $kWh/(m^2.a)$ in a cool-temperate climate [75] that applies to Ireland, Britain and Denmark [77]. As expected, evidence-based Danish research avoided such an ambitious limit on delivered energy. Instead it cost optimised home retrofit to achieve average delivered energy of 80 $kWh/(m^2.a)$ for space and water heating [60].

One remaining absolute metric is *heating load*, that quantifies the *thermal performance* of a building's fabric and design. Calculation of this metric excludes heat generators and their energy supply such as boilers and natural gas — the system components determining energy use and emissions. Instead, heat load is building heat loss under certain conditions [79]. Sdei et al. [80] simplified the cold conditions of heat load into degree days, expressing heat load in kWh/degree day. The absence of floor-space normalisation, means the metric enables more accurate ranking of underperforming large homes than EUI metrics. Use of the heat load metric supported the three retrofit objectives, although the third was location specific [80].

- Enable parametric study of fabric retrofit measures.
- Emphasise thermal comfort for households experiencing energy poverty.
- De-emphasise carbon reductions because of the French national policy on nuclear energy.

2.4. Comparison of relative and absolute energy targets

Both relative and absolute targets for home energy retrofit in cool-temperate climates have been reviewed, a few of which are more relevant. The decarbonisation target for the *current* decade is 55% reductions (Table 1), similar in quantity to the retrofit target of 60% reductions in primary energy (Table 2). In terms of absolute targets (Table 3), the primary energy EUIs by retrofitted homes cluster around 100 $kWh/(m^2.a)$. That cluster ranges from 80 $kWh/(m^2.a)$ to 120 $kWh/(m^2.a)$, reflecting the different methodologies and cost-effectiveness criteria used by different countries. As a result, BPIE noted that "multiple conceptualisations" of deep renovation exist in the absence of a clear or legally binding definition [76].

Little relationship exists between the relative and absolute targets in Table 2 and Table 3 respectively. One Danish report did, however, provide values for both tables. That report proposed average heat-energy reductions of 40%, based on the heating of retrofitted homes using an average of 80 $kWh/(m^2.a)$ delivered energy. (80 $kWh/(m^2.a)$ had been evaluated as a *cost-effective* retrofit target [81].) Regarding any relationship between the first two tables, feasible energy-use reductions in Table 2 contribute to decarbonisation policy targets in Table 1. The shortfall in achieving decarbonisation targets then falls to the energy-supply systems, whose decarbonisation reduces the primacy of fabric-first HER as discussed in Section 5.2.

In order to achieve the presented HER targets, one publication proposed large-scale community or neighbourhood retrofit [80]. Accordingly, the next section reviews retrofit delivery at different intermediate spatial scales — especially neighbourhoods.

3. Neighbourhoods—the intermediate scale for energy retrofit

Neighbourhoods are important in urban planning, forming the cellular structure and building blocks of a compact city [82]. As an intermediate spatial scale, neighbourhoods enable analysis beyond an individual building, while remaining close enough to *examine concrete measures* [83]. Neighbourhoods are reviewed here as the scale to analyse and deliver home energy retrofit (Section 3.1) and compared to other intermediate spatial scales (Section 3.2). Neighbourhood characteristics affecting energy use, but not HER, are then presented for completeness (Section 3.3).

Koch et al. [84] conceptualised neighbourhoods as bundling the "spatially referenced" attributes of buildings structural characteristics with local infrastructure [85]. Importantly, they distinguished the spatial and social meanings of neighbourhoods that affect home energy retrofit as follows:

> **Neighbourhood** is a group of buildings, aggregated either spatially or by social understanding. Neighbourhoods comprise **"structurally similar homes"** sharing a standard thermal envelope and offering an intermediate scale to deliver homes energy retrofit. Energy use by a neighbourhood's homes is best expressed as a **"[statistical] distribution function around a mean value"**— not a single value [84].
> The social understanding sees a neighbourhood as a community containing social networks and valuable local knowledge that facilitate the delivery of low-carbon energy solutions.

3.1. Analysis and delivery of neighbourhood energy retrofit

When analysing home energy retrofit, the energy used by a neighbourhood's homes is best expressed as a statistical distribution. Where a neighbourhood comprises structurally-similar homes, a distribution's *spread* or *variation* in energy use is caused

by different occupant operation according to Koch et al. [84]. This assumption ignores factors such as different home orientations or different external wall area caused by a home's position in a block. Nevertheless, energy retrofit of a neighbourhood will reshape its home energy-use distribution, reducing its mean and variation.

Occupant-caused variations in building energy use were corroborated in a review of urban building energy modelling (UBEM) [27]. In order to simulate accurately, UBEMs must treat occupants as "individual agents rather than identical robots"—obviously all occupants do not repeat the all activities at the same time [27]. Other building performance research recommended using statistical distributions, by calculating their 95th-percentile values. Such values are more relevant than "typical" or "average" values because they 1) analytically increase robustness of performance calculations, and 2) practically identify overheating and other risks [86].

Neighbourhood scale has used for urban regeneration for at least two decades [87–89]. Tunstall [89] found the realisation of social-economic improvements very difficult, rendering the successful physical improvements even more important. The leadership of urban regeneration or retrofit programmes is recommended as a role for local authorities or housing associations, using area-based approaches such as neighbourhoods [13,90].

Finally, large-scale retrofit must improve the day-to-day lives of residents, most of whom conceptualise the traditional neighbourhood as a self-contained village. Ideal neighbourhoods offer their inhabitants shops, parks or recreation spaces, places of worship and schools; all accessible by walking [91]. Moreover, "walkablity" remains a defining characteristic of neighbourhoods that affects energy used for transport and further reviewed in Section 3.3.

3.2. Intermediate scales in energy analysis

Frayssinet et al. [25] categorised districts and neighbourhoods as intermediate or *meso* spatial scales of the build environment, and categorised buildings and cities as *micro* and *macro* scales. Small areas, urban quarters, and pocket neighbourhoods are also intermediate spatial scales, discussed in Section 3.2.2. Differences among the intermediate scales manifest in 1) energy supply systems or 2) quantities of inhabitants and buildings.

The ISO 52001-1 term *building portfolio*, extends the concept of spatial scale by including energy system interactions with buildings [70]. A building portfolio is a set of buildings and common technical building systems whose mutual interactions determine building energy performance. Examples of common technical systems are energy generators, such as solar panels, wind turbine or cogeneration units, that serve building portfolios [70]. This review focusses on traditional spatial scales of districts and neighbourhoods.

3.2.1. Districts and neighbourhoods

The urban spatial scale of a district demarcates an entire energy system, although an energy district has been characterised differently across the literature. Keirstead et al. [26] focussed on system optimisation of a district, whereas Allegrini et al. [24] emphasised the balancing of demand and supply, and Castaldo and Pisello [92] and Junker et al. [93] detailed energy production and storage of a district. The latter research selected districts as the aggregation scale for building energy flexibility.

Examples of neighbourhoods demarcating an entire energy system are rare. An IEA EBC Annex 51 project used a "large neighbourhood", also noting its economies of scale [94]. Additionally, energy systems of districts differ from those of neighbourhoods by their heterogeneous demands, in particular *anchor loads* [95]. High-demand anchor loads use significant energy year-round and complement low-demand customers, that together provide a permanent market and investment justification for local utilities. Likewise, Koch et al. [84] argued that the inclusion of an *energy-intensive* service distinguished a district from a neighbourhood that comprises structurally-similar buildings. Swimming pools and hospitals[2] typify energy-intensive service buildings for a district (Fig. 4).

Regarding empirical quantities of inhabitants and buildings, district inhabitants ranged from 3000 to 5000 range, and district properties approximated to 1800 [26,96]. For neighbourhoods, the quantity of buildings have been specified as 100, 72 or generalised from dozens to 1000's [94,25,27]. An EU sustainability audit assumed a high-density neighbourhood of fewer multi-family homes; its neighbourhood housed 200–1500 inhabitants in only 5–15 buildings [97]. Despite varying quantities, most literature agrees with a sustainability audit's ranking of urban spatial scales: 1-block, 2-neighbourhood, 3-district, 4-urban/region, 5-global [97]. Koch et al. [84] concurred that neighbourhoods were smaller than districts, where overlapping neighbourhoods form larger districts that enable administration.

3.2.2. Other intermediate scales

Small areas are used in government statistics of empirical data. Statistics include datasets of energy poverty, energy use and energy performance certificates — all relevant for retrofit planning [98]. Also called an *output area*, the small area comprises 50–200 homes in Ireland, with most demarcating 65–90 homes [99]. In England and Wales, statistical areas scale up from output area to "Super Output Area" or local authority area. Super output ares are categorised as lower layer comprising at least 400 homes, and 1000 inhabitants or middle layer super comprising at least 2000 homes and 5000 inhabitants [100, p. 10]. Table 4 presents spatial scales with numbers of homes and inhabitants.

In their population-based cohort study Hamilton et al. [101] used the lower layer super output area to link neighbourhoods' household characteristics with datasets on home energy use and retrofit measures. Unfortunately, government support for publication of lower layer super output area statistics ceased and its website[3] decommissioned.

Urban quarters were proposed as the scale to implement energy-efficiency and management measures over a decade ago [102]. By a German definition, urban quarters exceed 500 homes of homogeneous urban morphology but heterogeneous households — where occupants vary energy use per home. Given neighbourhood definitions now reaching 1000's of homes [27], urban quarters have been subsumed into large neighbourhoods and therefore redundant in contemporary energy analysis. Urban quarters rarely appear in energy analyses, except in a German study [24], or decade-old EnSURE research that referred to urban quarters in its title but discussed energy at district scale [103].

Finally, the smallest of the intermediate scales, a pocket neighbourhood, facilitates community engagement and support. According to Liddell [104], a pocket neighbourhood groups smaller homes in order to promote a sense of community and neighbourliness through fostering common values, experiences, interests and resources. The accompanying case study comprised five lower-income households in new 100 m^2-floor-area houses (Table 4).

3.3. Other relevant characteristics of neighbourhoods

An entire sustainability analysis of the built environment would cover transport and building interactions, in addition to building

[2] Koch et al. [84] labelled these buildings "tertiary" after the economic term for the service sector.

[3] http://www.neighbourhood.statistics.gov.uk/.

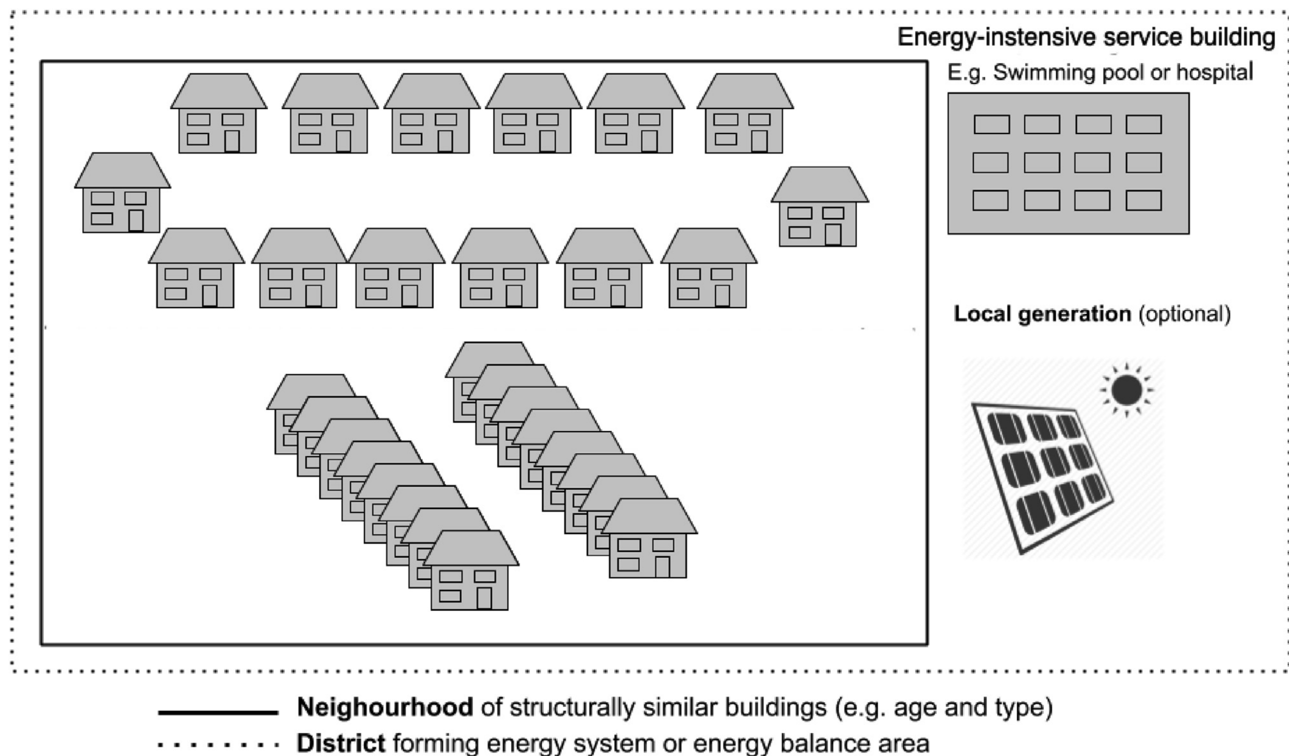


Fig. 4. Schematic description of overlapping layers defining neighbourhood and district, source Koch et al. [84]. The larger district contains an entire energy system including an anchor load, also termed energy-intensive service building.

energy retrofit. Accordingly, Sustainable Development Goal 11 identifies key roles for transport and mobility in sustainable development planning. However, neighbourhoods generally lack sustainability opportunities in transport and building interactions within their spatial scale.

Regarding transport, the ease of reaching amenities defines a neighbourhood. Balaras et al. [97] specified a 10–15 min walk time and 200–400 m length among their five neighbourhood criteria. Previously, Fonseca and Schlueter [95] had halved the neighbourhood length to 50–200 m. Other researchers used a qualitative *walkability* description of "how friendly an area is to walking" [109], complemented by a new 0–100 Walkscore metric. Their motivation was to penalise unconstrained street widths and oversized building offsets, both of which are costly and difficult to retrofit.

Energy-intensive transportation stems from an immutable neighbourhood characteristic: distance from a city centre, according to empirical research by Codoban and Kennedy [110]. This characteristic was termed "centrality" by Rey et al. [83]. Even when efficient public transport was available, inhabitants choose private transport because of lower travel time or higher comfort. Consequently, a sustainability strategy for an older neighbourhood should focus on its biggest energy users — buildings [110].

Regarding building interactions, Frayssinet et al. [25] argued that buildings — in urban areas — cannot be assumed to be stand-alone, as is done by most contemporary building models [25]. Urban micro-climates affect building energy demand [24], caused by wind sheltering and other inter-building effects [92]. Large offsets between buildings increase solar gains and daylight to nearby buildings, but for single-family homes, the small increases in solar gains hardly affect home energy use [111].

When large energy-use differences have been found between a home simulated as stand-alone or networked, the simulations actually used extreme climates [112]. Both climates differed distinctly from the cold temperate climates of Ireland, Britain or Germany. Moreover, the authors Pisello et al. [112] themselves predicted building interactions to be more substantial in the city centres, where tall buildings are more numerous. Given the preceding reasons, we see little benefit in analysing the interactions between single-family homes located in cool-temperate climates.

4. Home energy retrofit for better health and improved quality of life

Energy savings and CO_2 reductions are not the only benefits accrued from home energy retrofit. Home retrofit has a wide range of benefits for occupants such as improved physical and mental well-being, increased productivity at home due to improved sleep, improved home safety, reduced pollutant concentrations, studied recently by Outcault et al. [113]. Mental health benefits often arise from reduced energy (formerly fuel) poverty and home retrofit lifts occupants' sense of social standing and commitment to their property [5].

For instance, a study defined energy poverty as a household's inability to keep adequately warm at a reasonable cost [106]. The authors identified the interacting causes of energy poverty as: low income, high domestic fuel costs (esp. home heating oil) and low-performing homes. Home energy retrofit addresses the last cause, therefore indirectly reducing the physical and mental health risks to occupants that typically manifest as anxiety about energy bills. In their review of five large-scale studies of fuel poverty and human health, Liddell and Morris [114] recommended augmenting physical health measures with quality-of-life measures. Research conducted by The Academic - Practitioner Partnership [115] estimates poor health caused by poor housing costs $1.4 billion annually, of which $145 million and up to 35,000 excess winter deaths arise from cold homes alone.

Table 4
Spatial Scale of energy use analysis above standalone building.

Scale	Homes	Inhabitants	Purpose
Regional	> 10^6	> 10^6	Carbon reduction and affordable warmth [96] Policy making, predicting the effects of large-scale retrofit [27]
Urban or city	< 10^6	< 10^6	Design, system optimisation, policy assessment and urban climate [26] Identify buildings most causing emissions and effects of energy retrofit [27]
Middle layer super output area	2,000–6,000	5,000–15,000	Monitor and target small areas for further interventions [105]
District	> 1,000's	3,000–5,000	System design and optimisation or transportation [26] Administrative area overlapping neighbourhoods [84]
Quarter	> 500	500–2,000	Energy efficiency and management [102]
Neighbourhood	dozens to 1,000's	200–1,500 [97]	Scale: Between building and city, revealing new information [83] Technical: Relatively homogeneous buildings and infrastructure [84] Social: A community of social networks supporting energy solutions [84] Purpose: Examine concrete solutions [83], urban transformation [95] Purpose: Sustainability audit of an urban block [97]
Lower layer super output area	400–1,200	1,000–3,000	Monitor and target small areas for further interventions [105]
Output area or "small area"	50–200	100–500	Smallest census scale of social and home characteristics [106]
Ward	> 40	> 100	Administrative area [107] Consumer or economic analysis [108]
Pocket Neighbourhood	Five homes	Five families	Energy efficient housing [104]

Home energy retrofit is an essential energy policy in both developed and developing countries [2]. A policy intended to improve occupants physical and mental health and comfort, and to increase energy awareness within communities. Furthermore, home energy retrofit can address several energy-related sustainability and equality issues within the framework of Sustainable Development Goals (SDG): SDG 1 (No Poverty), SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), SDG 10 (Reduced Inequalities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [11].

Recent literature on home energy retrofit demonstrated that building envelope improvements, energy education, and additional acoustic insulation, improve occupants' physical and mental health. For example, Elsharkawy and Zahiri [116] investigated the retrofit of a social-housing tower block in the UK, where building envelope improvements were intended to overcome energy poverty and occupant discomfort. However, they also argued that high-performing thermal envelopes can jeopardise occupants' thermal comfort by overheating, especially during heat waves (made more likely by climate change) or in living spaces exposed to direct solar radiation. The same study concluded that occupancy patterns and tenants' socio-demographics influence both energy use and perceptions of thermal comfort. In addition, the lack of household-specific occupancy patterns causes inaccurate predictions of overheating and energy performance under climate change scenarios.

Elsharkawy and Zahiri [117] investigated the effect of occupant behaviour on the energy use in retrofitted homes. They recommended the use of non-standard occupancy patterns and energy-awareness education for occupants, especially in retrofitted homes. Walker et al. [118] published similar findings from interview-based qualitative research into tenants' energy-related practices after retrofit of social housing in England. When energy-saving practices were adopted, tenants were motivated by cost savings. The research also highlighted that an information intervention led to slightly higher self-reported engagement with retrofit and existing technologies. More interestingly, opportunities to disrupt energy-intensive practices should be recognised in any retrofit programme because it "enables households to reconfigure their routines and practice".

A study by Fisk et al. [119] reviewed empirical data from evaluations of home energy retrofit on indoor environmental quality and self-reported thermal comfort and health. It concluded that occupants in retrofitted homes experienced warmer indoor temperature during winter, and reduced levels of indoor dampness and mould. Overall, the study's results indicated that thermal discomfort, asthma and non-asthma symptoms, general and mental health improved after building retrofits. In their 2010 review of the available evidence, Liddell and Morris [114] found retrofit improved the physical health of the young, and the mental health of all occupants. Nevertheless, increased concentrations of indoor radon and carbon dioxide were found after retrofits but data was insufficient. Additionally, indoor radon and formaldehyde concentrations tended to rise after retrofits without new ventilation systems — demonstrating the need for effective ventilation systems.

Vakalis et al. [120] illustrated the importance of improved indoor environmental quality, especially for vulnerable occupants. After surveying occupants of 180 dwellings in seven blocks, they found that blocks that contained occupants reporting higher rates of olfactory and thermal discomfort, were more likely to contain occupants suffering health symptoms. Regarding summer-time overheating, this was resolved by upgrades to technical systems and building fabric and, in the surveyed homes, frequent natural ventilation by occupants only negligibly affected thermal comfort.

However, to better understand the role of occupants and their interaction with retrofitted homes and energy systems, a more detailed understanding is needed, especially at urban scale. Increasing the spatial scale introduces the critical role of data science. Advancements in the internet of things and big data, provide a unique opportunity for detailed study of occupant behaviour and energy-use patterns at large spatial scale and with community perspectives, according to Salim et al. [121]. Valuable results from such studies enables data-driven building and energy system models to represent macro-climate and community-level energy use and behavioural patterns; capabilities beyond that of available tools to dynamically model buildings [121].

Dynamic building simulation tools have been used by numerous researchers to study and analyse building's fabric and technical system energy performance and occupants behaviour and interactions. Studies showed that to close the gap between simulation and measured energy use in buildings and produce reliable energy performance results, various factors should be taken into account such as weather data and occupancy patterns [122,123].

In summary, home energy retrofit promises to fulfil multiple sustainability themes. In addition to savings in energy use, energy costs, and greenhouse gases, effective retrofit programmes enhance occupant health. Such programmes cover a *diversity* of sustainability narratives, as recommended by Holden et al. [124]. Finally, HER programmes must use their opportunities to educate occupants in energy practices and home operation, especially heating and ventilation.

5. Discussion

We now discuss the tempering of building retrofit targets and the shift to synergistic delivery strategies. Synergy exists when building energy demand is reduced while simultaneously energy supply is decarbonised. The decarbonisation of the energy supply means that the fabric-first approach to retrofit loses primacy. Simultaneously, the selection of older low-performing homes for retrofit reduces GHG emissions by the entire housing stock, instead of achieving absolute targets by individual homes.

5.1. Retrofit targets and delivery synergies

Attempts to deliver 80% reductions in GHG emissions by home energy retrofit (HER) have proved unsuccessful. A consensus has therefore emerged, whereby home energy retrofit delivers the bulk of residential GHG reductions by cutting energy usage, while the remaining GHG reductions result from decarbonisation of the supplied energy. Such a synergy is not new; fifteen years ago Lowe [21] explored these synergies for UK housing and electricity grid. Nowadays, similar synergies are being quantified and formalised into sustainability policy.

An 80% target in GHG reductions adopted by HER programme in the UK was described as "radical" Gupta et al. [29]. It also proved to be mainly unachievable, as evidenced by only three of 37 studied homes meeting that target [125]. Sdei et al. [80] split the 80% reduction target: 60% from home energy retrofit (building fabric and efficient boilers), and 20% from renewable energy sources and occupant "positive energy-aware behaviour". The 60% value was actually cited from Lowe [21], who foresaw possible 60–70% GHG reductions by synergies across the 1) electrical supply system, 2) intermediate energy-conversions systems and 3) improved build fabric (or "envelope").

As a comparison, a Danish review recommended an average energy saving of 40% for heating (including hot water) [60]. Instead of aspiring to a higher policy target, energy reductions were constrained to an average of 40% where retrofit costs exceed heat supply costs. Likewise, the Danish review was pragmatic in targeting the worst performing homes, identifying detached houses built before 1980. The review's plan for a Smart Energy System in Denmark does entail synergies, but of a more general nature than Lowe [21].

In terms of high-level policy, the EU allocated a 60% GHG reduction to the building sector to support an aggregate 55% reduction over all sectors [50]. EU policy continues to perceive energy inefficiencies in the building sector generally, and in homes particularly. As a result, the largest decarbonisation synergies are quantified (compared to 2015) in the residential sector: heating and cooling demands fall by between −19% to −23%, while the their shares of renewable *and* waste heat rises to within 38%–42% [50, p.24].

Reuse of waste heat has gained recent attention, whereas 15 years ago Lowe [21] mentioned only the waste heat from combined heat and power. In response to growing energy demand by data centres [126], policy makers propose reusing their heat energy [50], despite the waste heat's low grade [127]. (Unfortunately, the reuse of waste heat is impeded by the lack of business models [128], thus data centre operators have continued to reduce waste heat, rather than reuse it [126].).

Regarding renewable generation, evidence exists of a policy shift *towards* local or building-level, and *away* from grid-connected. One mechanism to facilitate local renewable generation is the Renewable Energy Community. EU Directive 2018/2001 [129] outlines the community as an open and voluntary legal entity which should be enabled by member states.

Lowe [21] merely footnoted the comparison of generation locations as a "debate" of secondary importance to the goal of reducing CO_2 emissions. Nevertheless, grid integration is a serious challenge to system operators. For example, Baetens et al. [130] simulated the bottlenecks in the electricity distribution grid caused by aggregated solar PV (photovoltaic) generation at neighbourhood scale. Likewise, Mathiesen et al. [60] recommended installation of solar PV where it is most *cost-effective* and appropriate for the *system*, arguing that installation of solar PV in all buildings would incurr inefficiencies.

In summary, Lowe [21], and his earlier collaboration with Johnston [54], first explored the synergy strategy to reduce GHG emissions by homes, namely: 1) building energy retrofit and 2) energy supply decarbonisation. Apart from including the reuse of waste heat in the heat supply, the EU has adopted identical strategies during the following 15 years [131,132].

5.2. Retrofit approach and role of fabric first

What depth of home energy retrofit persists as an important question, complicated by the diminishing returns of increasing depth. We believe that, nowadays, retrofit depths are determined by funding policies or pragmatic calculations of cost-effectiveness and time-effectiveness (exempting zero depth caused by behavioural inertia or planned demolition).

In the second of their ten questions on home thermal retrofit, Galvin and Sunikka-Blank [5] compared deep retrofit to incremental retrofit. After considering economic viability, market demand and diminishing returns, they concluded that both deep retrofit and *incremental* retrofit should be promoted by public policies. They pointed out that most thermal retrofitting in the UK is incremental, an approach they labelled "over-time", and also known as *phased* according to the Irish Green Buildings Council [31].

As early as 2013, the EU cited incremental retrofit as an approach to deliver deep retrofit — labelled *staged deep renovations* [53]. In 2021, an industry part-funded report defined staged deep retrofit as a specified number of steps started by a significant first step. According to Building Performance Institute Europe (BPIE), an ideal staged retrofit delivers a pre-planned final design in *three steps* and is tracked by a building passport [76]. The lead author of the BPIE report foresaw compatibility between staged and deep retrofit, stating "one way of renovating deeply could indeed be in stages" [32], notwithstanding the lock-in risk of low-energy measures at an early stage [76]. Building passports would manifest as Digital Building Logbooks, already defined in 2020 [133], and improve the construction sector's underdeveloped digitalisation [134].

If HER is to achieve sustainability targets, it must reduce energy use across space heating, lighting and domestic hot water. Of the three energy services, most retrofit resources are expended on space heating; the energy service also the most sensitive to self-rationing and rebound effects (especially the prebound effect) [135,5,136]. Nevertheless, prioritisation of space heating manifests in the hitherto popularity of the "fabric first" approach [137,29]. Generally, fabric-first design maximises the performance of the components and materials that form the physical building fabric (or envelope), before considering mechanical building services [138]. Gupta et al. [29] supported the fabric-first approach because — even post-retrofit — the high air permeability of homes renders mechanical ventilation both redundant and costly. Likewise, most of the six homes installed with solar PV generation without heat pumps actually increased electricity use. In another review of a HER programme, Sdei et al. [80][p. 65] recommended fabric first in these words:

"Getting the insulation right is the most important prerequisite, it is not even worth considering additional measures such as solar PV panels on roofs until basic improvements to the fabric and performance of the buildings have been made."

Regarding the second service of lighting, its upgrades are typical energy-efficiency measures in retrofit, especially in cold (heating dominant) and temperate climates [62]. Examples are Retrofit for the Future and Green Deal in the UK [29,139], REMOURBAN in five countries [57] and Better Energy Homes in Ireland [140]. Furthermore, efficient lighting contribute to better energy performance certificates rankings, which are in turn used to formulate absolute targets (Section 2.3.1).

Given the known building regulations, in 2007 Lowe [21] predicted that the dominance of home energy use would shift *from* space heating *to* water heating, lighting and appliances. Limited evidence of this shift exists in the example of Ireland's modelled data. For the average Irish home, lighting and appliances were estimated at 17% of energy and 68% of electricity usage in 2016 [141], up from 13% of energy and 50% of electricity usage in 2013 [142]. Furthermore, the categorisation of lighting with appliances implies *energy-efficient* modern lighting, now estimated to account for only 15% of UK home electricity use [143].

Regarding the third service of domestic hot water (DHW), its share of home energy use is evidently increasing. Taking the example of Ireland, energy modelling estimated the DHW share at 19% of home energy use in 2016 [141], up from 16% in 2013 [142]. (Simultaneously, the DHW share of home electricity use actually fell as cheaper gas-fired boilers replaced electrical immersion heaters.).

Separately from fuel and heat generators, occupant demand also affects DHW energy use. Connolly et al. [58] listed five reasons why quantities of DHW demand will persist after retrofit, two of which are that occupants will use more hot water for washing and previous hot water demand has been constrained by household finances. Increasing occupant demand for DHW or space heating after retrofit are manifestations of the rebound or prebound effects, both of which hinder the achievement of energy-use reduction targets. Rebound effect is occupant-caused *overheating* after retrofit [144], whereas prebound effect is occupant-caused *underheating* before retrofit [136]. A review of these occupant-caused effects is beyond this paper's scope; an interested reader is provided literature examples [101,145,135,146,140].

Returning to the fabric-first approach, it suffers from at least two drawbacks. Firstly, the effectiveness of multiple retrofit measures is interactive not additive, and secondly, well-designed heat pumps now offer quicker paths to reduce energy use and GHG emissions. Energy savings from combined retrofit measures are not the sum of savings by individual measures [147], despite the extra cost and disruption to the household. For example, a shallow fabric retrofit combined with a heat pump, achieves energy-use targets for an Irish home built in the 1980s [123]. Similar results were found in a 2022 plan for net-zero heating in Ireland by 2050 [148].

In summary, calculation of energy savings before a deep retrofit requires a building model, simulated under the climate conditions. Fabric or envelope upgrades must be *complemented*, if not preceded, by decarbonisation of home heat generators to eliminate fossil fuels use in buildings [149].

5.3. Home type selection for retrofit

Ambitious targets of GHG reductions placed upon home retrofit programmes, have prompted these programmes to select particular home types. Many national and EU reduction targets set 2030 completion dates that bring urgency alongside public funding. Retrofit for the Future (RfF) demonstrated that relative reduction targets are easier to achieve with older and lower-performing homes [29], thus justifying additional absolute targets. Recently, retrofit policies aim primarily to reduce GHG emissions, and therefore identify home types to achieve the reductions cost-effectively.

In an example of this pragmatic approach, a Danish study recommended "energy retrofits should only be invested in until the point in which the cost of supplying heat to the building is cheaper than further renovation" [60]. That study translated the recommendation into a relative target of 40% average saving in home heating demand (including DHW) by 2050[4]. While that target was more modest than RfF, it supported dual benefits to the Danish energy system: reducing energy demand *and* matching energy demand to new and more efficient district heating. The Danish study concluded that retrofit efforts should focus on pre-1980 buildings, especially older detached homes built in early 20th century. Likewise in Germany, a review of building stock forecast that single-family homes will account for approximately two thirds of heat demand until 2050 [150]. In Ireland, single-family homes are also recommended for retrofit, although constructed before 1997–2002 building regulations [151].

In 2014, a review of EU building stock's energy performance, split the stock into three categories, using two construction dates. The first pre-1970 split preceded thermal regulations, and the second post-2000 split was during modern construction [16]. The implication is that the half of homes constructed pre-1970 require retrofit, while the 15% constructed post-2000 do not. That implication assumes that post-2000 regulations were enforced, especially in countries with a high share of modern homes, such as Spain and Ireland. The same review split homes into a typology of single- or multi-family because external walls affect space-heating energy use. Ireland and the UK had the highest shares of single-family homes, leading to more external walls (building envelope) requiring retrofit.

Notwithstanding the EU review splitting housing stock by construction date, the European Commission delegated the selection of the "worst-performing" buildings to Member States, suggesting three selection criteria [152]. Construction date was the third criterion, behind energy performance certificate and primary energy use intensity. In practice, the latter two criteria are closely aligned, meaning that a Member State will likely use their national energy performance certificates to 1) select homes for energy retrofit, and 2) evaluate post-retrofit energy performance.

6. Conclusions

Home energy retrofit (HER) is not new, and has been publicly funded in cool-temperate climates since at least the 1990s. In the intervening years, deep retrofit has evolved in terms of depth, policies drivers and delivery approaches.

When quantifying depth of retrofit, most literature on home energy retrofit recommends deep retrofit instead of shallow retrofit. Deep retrofit packages combine upgrades to building fabric and heat generator to achieve reductions of up to 80%, or more realistically 50%–60%, in energy use or GHG emissions. Recently the EU specified retrofit depth and energy type as 60% reductions in primary energy use intensity.

Policies targets have cascaded into ambitious energy retrofit targets, and unlocked government funding support. Current policy targets driving decarbonisation have increased the focus on energy supply and decreased the primacy of the fabric-first approach. HER programmes using purely fabric-first approaches have also strug-

[4] Accompanied by an absolute target of 80 kWh/(m^2.a) average heat demand density.

gled to meet energy-use targets because of occupant-caused rebound and prebound effects. Modern strategies to decarbonise homes utilise the synergy between energy-use systems and energy-supply systems, as explored for UK housing in 2007 [21].

Approaches to HER vary in timescales and spatial scale. Given the general failure of one-off deep retrofit, "staged" retrofit approach is now recommended in the EU. The latter approach imposes structure on incremental approaches, also known as over-time or phased approaches [5,31]. Large-scale retrofit is best delivered using area-based approaches.

This review focuses on the meso or intermediate spatial scales such as district and neighbourhood. A district contains an entire energy system, including an energy source and possibly storage, whereas a neighbourhood is smaller spatial group of buildings combined with a social network. Neighbourhoods offer the ideal scale for home energy retrofit, because of their structurally-similar homes and potential for community participation and fostering occupant trust. Neighbourhoods may contain 200–1,500 homes (Table 4), with 431 homes a typical example [98].

Finally and importantly, occupant comfort, health and quality of life are important metrics in evaluating a HER programmes. Unfortunately, such human factors are difficult to measure, and rarely translate into policies to fund HER. Policies to combat energy poverty are the exceptions, but still eclipsed by decarbonisation and energy-efficiency policies. Nevertheless, we surveyed the more tangible quality of life factors that include sleep, human productivity, and mental health.

7. Future work and research

Research must optimise the retrofit depth of similar homes in order to minimise costs to the energy system [60,33]. Large-scale retrofit projects should evaluate the *performance* of retrofit technology such as electric heat pumps, that offer theoretical high performance and low GHG emissions assuming decarbonisation of the electrical grid. This paper does not attempt to review retrofit metrics outside the domain energy and associated GHG emissions during building *operation*. Calculation of GHG emissions during a home's entire *lifecycle* have already been attempted [65]. Job creation is a positive byproduct of HER, but not a energy performance metric. Nevertheless, separate studies of on actual "green jobs" could make the difference in securing Government funding for HER. Finally, occupant comfort and well-being cannot be neglected, because of predicted heat waves and population ageing.

Moving from technology to occupants, empirical measurement of occupants' post-retrofit DHW demand should feed back to retrofit design packages. Long-term planning of the energy system decarbonisation also requires managing the shift of home-energy dominance from space heating to DHW and appliances.

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.

References

[1] T.M. Cristino, F.A. Lotufo, B. Delinchant, F. Wurtz, A. Faria Neto, A comprehensive review of obstacles and drivers to building energy-saving technologies and their association with research themes, types of buildings, and geographic regions, Renew. Sustain. Energy Rev. 135 (2021) 110191.
[2] M.A.J.Q. Franco, P. Pawar, X. Wu, Green building policies in cities: A comparative assessment and analysis, Energy Build. 231 (2021) 110561.
[3] H. Zhang, K. Hewage, H. Karunathilake, H. Feng, R. Sadiq, Research on policy strategies for implementing energy retrofits in the residential buildings, J. Build. Eng. 43 (2021) 103161.
[4] COP26, United Nations Climate Change Conference, 2021..
[5] R. Galvin, M. Sunikka-Blank, Ten questions concerning sustainable domestic thermal retrofit policy research, Build. Environ. 118 (2017) 377–388.
[6] A. Gillich, M. Sunikka-Blank, A. Ford, Lessons for the UK Green Deal from the US BBNP, Build. Res. Inf. 45 (2017) 384–395.
[7] R. Dowling, P. McGuirk, H. Bulkeley, Retrofitting cities: Local governance in Sydney, Australia, Cities 38 (2014) 18–24.
[8] Y. Choi, D. Song, A. Ozaki, H. Lee, S. Park, Do energy subsidies affect the indoor temperature and heating energy consumption in low-income households?, Energy Build 256 (2022) 111678.
[9] T.H. Meles, L. Ryan, S.C. Mukherjee, Heterogeneity in preferences for renewable home heating systems among Irish households, Appl. Energy 307 (2022) 118219.
[10] UN Department of Economic and Social Affairs, THE 17 GOALS – Sustainable Development, https://sdgs.un.org/goals, 2015. Online; accessed 2022-03-15..
[11] UN, The Sustainable Development Goals Report, https://unstats.un.org/sdgs/report/2021/The-Sustainable-Development-Goals-Report-2021.pdf, 2021. Online; accessed 2022-03-15..
[12] R. Bardhan, R. Debnath, J. Malik, A. Sarkar, Low-income housing layouts under socio-architectural complexities: A parametric study for sustainable slum rehabilitation, Sustain. Cities Soc. 41 (2018) 126–138.
[13] T. Dixon, M. Eames, Scaling up: the challenges of urban retrofit, Build. Res. Inf. 41 (2013) 499–503.
[14] M. Eames, Developing Urban Retrofit Scenarios: an Outline Framework for Scenario Foresight and Appraisal, Technical Report, Retrofit 2050, Cardiff, Wales, 2011.
[15] R. Gupta, A. Kotopouleas, Magnitude and extent of building fabric thermal performance gap in UK low energy housing, Appl. Energy 222 (2018) 673–686.
[16] European Commission, EU Buildings Factsheets—Building Stock Characteristics, https://ec.europa.eu/energy/eu-buildings-factsheets_en, 2016. Online; accessed 2022-03-22..
[17] T. Loga, B. Stein, N. Diefenbach, TABULA building typologies in 20 European countries – Making energy-related features of residential building stocks comparable, Energy Build. 132 (2016) 4–12.
[18] B. Elzen, F.W. Geels, K. Green, System Innovation and the Transition to Sustainability: Theory, Evidence and Policy, Edward Elgar, 2004.
[19] B. Ozarisoy, H. Altan, Developing an evidence-based energy-policy framework to assess robust energy-performance evaluation and certification schemes in the South-eastern Mediterranean countries, Energy Sustain. Develop. 64 (2021) 65–102.
[20] P. Brown, W. Swan, S. Chahal, Retrofitting social housing: reflections by tenants on adopting and living with retrofit technology, Energ. Effi. 7 (2014) 641–653.
[21] R. Lowe, Technical options and strategies for decarbonizing UK housing, Build. Res. Inf. 35 (2007) 412–425.
[22] P. Nejat, F. Jomehzadeh, M.M. Taheri, M. Gohari, M.Z. Muhd, A global review of energy consumption, CO2 emissions and policy in the residential sector, with an overview of the top ten CO2 emitting countries, Renew. Sustain. Energy Rev. 43 (2015) 843–862.
[23] P. Murto, M. Jalas, J. Juntunen, S. Hyysalo, Devices and strategies: An analysis of managing complexity in energy retrofit projects, Renew. Sustain. Energy Rev. 114 (2019) 109294.
[24] J. Allegrini, K. Orehounig, G. Mavromatidis, F. Ruesch, V. Dorer, R. Evins, A review of modelling approaches and tools for the simulation of district-scale energy systems, Renew. Sustain. Energy Rev. 52 (2015) 1391–1404.
[25] L. Frayssinet, L. Merlier, F. Kuznik, J.L. Hubert, M. Milliez, J.J. Roux, Modeling the heating and cooling energy demand of urban buildings at city scale, Renew. Sustain. Energy Rev. 81 (2018) 2318–2327.
[26] J. Keirstead, M. Jennings, A. Sivakumar, A review of urban energy system models: Approaches, challenges and opportunities, Renew. Sustain. Energy Rev. 16 (2012) 3847–3866.
[27] C.F. Reinhart, C. Cerezo Davila, Urban building energy modeling - A review of a nascent field, Build. Environ. 97 (2016) 196–202.
[28] The European Parliament and of the council of the European Union, Directive of the European Parliament and of the council on the energy performance of buildings (recast), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0802, 2021. Online; accessed 2022-05-09..
[29] R. Gupta, M. Gregg, S. Passmore, G. Stevens, Intent and outcomes from the Retrofit for the Future programme: key lessons, Build. Res. Inf. 43 (2015) 435–451.
[30] F. Filippidou, N. Nieboer, H. Visscher, Energy efficiency measures implemented in the Dutch non-profit housing sector, Energy Build. 132 (2016) 107–116.
[31] IGBC, Towards Large Scale Deep Energy Renovation Unlocking Ireland's Potential, https://www.igbc.ie/wp-content/uploads/2017/03/IGBC-BUILD-Upon-Final-Web-24.02.17-1.pdf, 2017. Online; accessed 2022-03-15..
[32] Gladushenko, Roland, Deep Renovation: The New Normal, https://www.euractiv.com/section/energy-environment/opinion/deep-renovation-the-new-normal/, 2021. Online; accessed 2022-03-15..
[33] P. Jones, S. Lannon, J. Patterson, Retrofitting existing housing: how far, how much?, Build Res. Inf. 41 (2013) 532–550.
[34] A. Arcipowska, O. Rapf, M. Faber, M. Fabbri, C. Tigchelaar, T. Boermans, N. Surmeli-Anac, K. Pollier, F. Dal, C. Sebi, J. Karásek, Support for setting up an observatory of the building stock and related policies, 2017..
[35] Sustainable Energy Authority of Ireland (SEAI), Heating and Cooling in Ireland Today, Archetype Profiles, Spatial Analysis, and Energy Efficiency Potential,

https://www.seai.ie/publications/Heating-and-Cooling-in-Ireland-Today.pdf, 2022. Online; accessed 2022-03-15..
[36] The National Archives, Home Energy Conservation Act 1995 c.10, https://www.legislation.gov.uk/ukpga/1995/10/section/2/enacted, 2021. Online; accessed 2022-03-15..
[37] P.J. Jones, S. Lannon, J. Williams, Modelling Building Energy Use At Urban Scale, Seventh International IBPSA Conference (2001) 175–180.
[38] London Borough of Hillingdon, Home Energy Conservation Act (HECA) Further Progress 2013, https://archive.hillingdon.gov.uk/media/28578/Home-Energy-Conservation-Act-report/pdf/hecareport.pdf, 2013. Online; accessed 2022-03-15..
[39] Stratford on Avon District Council, Home Energy Conservation Act Report of Stratford on Avon District Council – 2017, https://www.stratford.gov.uk/doc/173348/name/HECAReport2017.pdf/, 2017. Online; accessed 2022-03-15..
[40] Greater London Authority, Action Today to Protect Tomorrow—The Mayor's Climate Action Plan Executive Summary, http://www.energyforlondon.org/wp-content/uploads/2016/07/CCAP-2007.pdf, 2007. Online; accessed 2022-03-15..
[41] N. Stern, The Economics of Climate Change: The Stern Review, Cambridge University Press, 2007.
[42] UK Government, Climate Change Act 2008, https://www.legislation.gov.uk/ukpga/2008/27/section/1, 2008. Online; accessed 2022-03-15..
[43] Innovate UK, Retrofit for the Future – Reducing energy use in existing homes, https://retrofit.innovateuk.org/, 2013. Online; accessed 2022-03-15..
[44] European Commission, 2020 climate and energy package,https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2020-climate-energy-package_en, 2012. Online; accessed 2022-03-15..
[45] President of the European Commission, Climate and energy priorities for Europe: the way forward, https://ec.europa.eu/clima/system/files/2016-11/climate_energy_priorities_en.pdf, 2014. Online; accessed 2022-03-22..
[46] European Commission, Architecture Factsheet: Delivering the European Green Deal, https://ec.europa.eu/commission/presscorner/detail/en/fs_21_3671, 2021. Online; accessed 2022-03-22..
[47] European Commission, Roadmap for Moving to a Competitive Low-carbon Economy in 2050: Key Facts & Figures, https://ec.europa.eu/clima/system/files/2016-11/roadmap_fact_sheet_en.pdf, 2011. Online; accessed 2022-03-22..
[48] European Commission, Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), 2021a..
[49] European Commission, Climate strategies & targets, https://ec.europa.eu/clima/eu-action/climate-strategies-targets_en, 2021. Online; accessed 2022-03-22..
[50] European Commission, A Renovation Wave for Europe – greening our buildings, creating jobs, improving lives, Technical Report, European Commission, 2020. Online; accessed 2022-03-22..
[51] European Commission, Annex: The Renovation Wave: key Commission actions and indicative timelines, https://eur-lex.europa.eu/resource.html?uri=cellar:0638aa1d-0f02-11eb-bc07-01aa75ed71a1.0003.02/DOC_2&format=PDF, 2020. Online; accessed 2022-03-22..
[52] European Commission, Renovation Wave Factsheet, https://ec.europa.eu/commission/presscorner/detail/en/FS_20_1844, 2020. Online; accessed 2022-03-22..
[53] European Commission, Financial support for energy efficiency in buildings (COM(2013) 225 final), https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1575044841597&uri=CELEX:52013SC0143, 2013. Online; accessed 2022-03-22..
[54] D. Johnston, R. Lowe, M. Bell, An exploration of the technical feasibility of achieving CO_2 emission reductions in excess of 60% within the UK housing stock by the year 2050, Energy Policy 33 (2005) 1643–1659.
[55] NEF, Breaking barriers: An industry review of the barriers to Whole House Energy Efficiency Retrofit and the creation of an industry action plan, Technical Report, National Energy Foundation, 2014..
[56] The IET and Nottingham Trent University, Scaling Up Retrofit 2050, https://www.theiet.org/media/8758/retrofit.pdf, 2018. Online; accessed 2022-03-22..
[57] REMOURBAN, Overall Remourban actions in low energy districts, http://www.remourban.eu/actions/energy/energy.kl, 2022. Online; accessed 2022-03-22..
[58] D. Connolly, H. Lund, B.V. Mathiesen, S. Werner, B. Möller, U. Persson, T. Boermans, D. Trier, P.A. Østergaard, S. Nielsen, Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system, Energy Policy 65 (2014) 475–489.
[59] T. Boermans, K. Bettgenhäuser, M. Offermann, S. Schimschar, Building renovation in Europe – what are the choices? (Technical Report), Ecofys, 2012
[60] B.V. Mathiesen, D. Drysdale, H. Lund, S. Paardekooper, I. Ridjan, D. Connolly, J. S. Jensen, Future Green Buildings, https://www.energyplan.eu/buildings/, 2022. Online; accessed 2022-03-22..
[61] Z. Ma, P. Cooper, D. Daly, L. Ledo, Existing building retrofits: Methodology and state-of-the-art, Energy Build. 55 (2012) 889–902.
[62] A. Carratt, G. Kokogiannakis, D. Daly, A critical review of methods for the performance evaluation of passive thermal retrofits in residential buildings, J. Clean. Prod. 263 (2020).
[63] IPCC, A Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Technical Report, IPCC, Geneva, Switzerland, 2007..
[64] C. De Wolf, C. Cerezo, Z. Murtadhawi, A. Hajiah, A. Al Mumin, J. Ochsendorf, C. Reinhart, Life cycle building impact of a Middle Eastern residential neighborhood, Energy 134 (2017) 336–348.
[65] P. Moran, J. Goggins, M. Hajdukiewicz, Super-insulate or use renewable technology? Life cycle cost, energy and global warming potential analysis of nearly zero energy buildings (NZEB) in a temperate oceanic climate, Energy Build. 139 (2017) 590–607.
[66] G. Barbano, N. Eßig, P. Mittermeier, M. Orova, P. Beagon, L. Claudi, J. Feliú Gómez-Salcedo, F. Kiedaisch, Definition of Sustainable Key Performance Indicators, Technical Report, NewTREND Project, H2020 Programme, European Comission, Brussels, Belgium, 2016.
[67] OPEN HOUSE, OPEN HOUSE Assessment Guide Version 1.2, https://www.ace-cae.eu/fileadmin/user_upload/eu_funded_projects/OPEN_HOUSE_AG1.2.pdf, 2013. Online; accessed 2022-03-22..
[68] European Union (EU), Directive 2010/31/EU of the European Parliament and of the council of 19 May 2010 on the energy performance of buildings 2010, 2010..
[69] J. Granderson, M.A. Piette, B. Rosenblum, L. Hu, D. Harris, P. Mathew, P. Price, G. Bell, S. Katipamula, M. Brambley, Energy Information Handbook Applications for Energy-Efficient Building Operations, Lawrence Berkeley National Laboratory, 2011.
[70] ISO - ISO 52000–1, ISO - ISO 52000–1:2017 - Energy performance of buildings – Overarching EPB assessment – Part 1: General framework and procedures, https://www.iso.org/standard/65601.html, 2017. Online; accessed 2022-05-10..
[71] A. Arcipowska, F. Anagnostopoulos, F. Mariottini, S. Kunkel, Energy performance certificates across the EU, http://bpie.eu/publication/energy-performance-certificates-across-the-eu/, 2014. Online; accessed 2022-03-22..
[72] DCCAE, Climate Action Plan To Tackle Climate Breakdown, https://assets.gov.ie/10206/d042e174c1654c6ca14f39242fb07d22.pdf, 2019. Online; accessed 2022-03-22..
[73] DECC, Climate Action Plan 2021, https://www.gov.ie/en/publication/6223e-climate-action-plan-2021/, 2021. Online; accessed 2022-03-22..
[74] Building Energy Ireland, BER certificates, http://www.buildingenergyireland.ie/BERCerts.htm, 2008. Online; accessed 2022-03-22..
[75] Passive House Institute, Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, https://passiv.de/downloads/03_building_criteria_en.pdf, 2016. Online; accessed 2022-03-22..
[76] BPIE, Deep Renovation: Shifting from exception to standard practice in EU Policy, https://www.bpie.eu/publication/deep-renovation-shifting-from-exception-to-standard-practice-in-eu-policy/, 2021. Online; accessed 2022-03-22..
[77] Passive House Institute, HW-Climate Zones List and Map, Technical Report, Passive House Institute, Darmstadt, Germany, 2019. Online; accessed 2022-03-22..
[78] Department of Housing, Planning and Local Government, Energy Performance of Buildings – Implementation of the revised EPBD (2018/844/EU), 2019..
[79] B.D. Hunn, Fundamentals of building energy dynamics, MIT Press, 1996.
[80] A. Sdei, F. Gloriant, P. Tittelein, S. Lassue, P. Hanna, C. Beslay, R. Gournet, M. McEvoy, Social housing retrofit strategies in England and France: A parametric and behavioural analysis, Energy Res. Soc. Sci. 10 (2015) 62–71.
[81] H. Lund, J.Z. Thellufsen, S. Aggerholm, K.B. Wittchen, S. Nielsen, B.V. Mathiesen, B. Moller, Heat Saving Strategies in Sustainable Smart Energy Systems, Int. J. Sustain. Energy Planning Manage. 4 (2014) 3–16.
[82] N. Taylor, Urban Planning Theory Since 1945, SAGE Publications Ltd, London, 1998.
[83] E. Rey, S. Lufkin, P. Renaud, L. Perret, The influence of centrality on the global energy consumption in Swiss neighborhoods, Energy Build. 60 (2013) 75–82.
[84] A. Koch, S. Girard, K. McKoen, Towards a neighbourhood scale for low- or zero-carbon building projects, Build. Res. Inf. 40 (2012) 527–537.
[85] G. Galster, On the Nature of Neighbourhood, Urban Stud. 38 (2001) 2111–2124.
[86] M. Donn, S. Selkowitz, B. Bordass, The building performance sketch, Build. Res. Inf. 40 (2012) 186–208.
[87] I.G. Ellen, M.A. Turner, Does Neighborhood Matter? Assessing Recent Evidence, Housing Policy Debate 8 (1997) 833–866.
[88] S. Musterd, W. Ostendorf, Integrated urban renewal in The Netherlands: a critical appraisal, Urban Res. Practice 1 (2008) 78–92.
[89] R. Tunstall, Are neighbourhoods dynamic or are they slothful? The limited prevalence and extent of change in neighbourhood socio-economic status, and its implications for regeneration policy, Urban Geogr. 37 (2016) 769–784.
[90] F. Fylan, D. Glew, M. Smith, D. Johnston, M. Brooke-Peat, D. Miles-Shenton, M. Fletcher, P. Aloise-Young, C. Gorse, Reflections on retrofits: Overcoming barriers to energy efficiency among the fuel poor in the United Kingdom, Energy Res. Soc. Sci. 21 (2016) 190–198.
[91] R. van Kempen, G. Bolt, M. van Ham, Neighborhood decline and the economic crisis: an introduction, Urban Geogr. 37 (2016) 655–663.
[92] V.L. Castaldo, A.L. Pisello, Uses of dynamic simulation to predict thermal-energy performance of buildings and districts: a review, Wiley Interdiscip. Rev.: Energy Environ. 7 (2018) e269.

[93] R.G. Junker, A.G. Azar, R.A. Lopes, K.B. Lindberg, G. Reynders, R. Relan, H. Madsen, Characterizing the energy flexibility of buildings and districts, Appl. Energy 225 (2018) 175–182.
[94] G. Zucker, F. Judex, M. Blöchle, M. Köstl, E. Widl, S. Hauer, A. Bres, J. Zeilinger, A new method for optimizing operation of large neighborhoods of buildings using thermal simulation, Energy Build. 125 (2016) 153–160.
[95] J.A. Fonseca, A. Schlueter, Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts, Appl. Energy 142 (2015) 247–265.
[96] J. Keirstead, C. Calderon, Capturing spatial effects, technology interactions, and uncertainty in urban energy and carbon models: Retrofitting Newcastle as a case-study, Energy Policy 46 (2012) 253–267.
[97] C.A. Balaras, K.G. Droutsa, E.G. Dascalaki, S. Kontoyiannidis, A. Moro, E. Bazzan, Urban Sustainability Audits and Ratings of the Built Environment, Energies 12 (2019) 4243.
[98] R. Gupta, M. Gregg, Local energy mapping for enabling area-based energy reductions, in: BSO2019, pp. 3690–3697..
[99] Ordnance Survey Ireland, Census Small Area, https://data.gov.ie/dataset/census-small-area, 2020. Online; accessed 2022-03-22..
[100] DECC, MSOA/IGZ and LSOA gas and electricity statistics - Methodology and guidance, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/175414/Sub-national_methodology_and_guidance_booklet_-_SOA_chapter.pdf, 2013. Online; accessed 2022-03-22..
[101] I.G. Hamilton, A.J. Summerfield, D. Shipworth, J.P. Steadman, T. Oreszczyn, R.J. Lowe, Energy efficiency uptake and energy savings in English houses: A cohort study, Energy Build. 118 (2016) 259–276.
[102] A. Koch, Energy Balance of Urban Quarters for the Development of Energy Efficiency and Management Strategies, in: Fifth Urban Research Symposium, Marseille, France, p. 1..
[103] EnSURE, EnSURE project: Development of a joint transnational energy concept on district level, http://www.ensure-project.eu, 2011. Online; accessed 2022-03-22..
[104] C. Liddell, Human factors in energy efficient housing: Insights from a Northern Ireland pocket neighbourhood, Energy Research & Social, Science 10 (2015) 19–25.
[105] Department for Business, Energy and Industrial Strategy, Sub-national consumption statistics: methodology and guidance booklet, https://www.gov.uk/government/publications/regional-energy-data-guidance-note, 2019. Online; accessed 2022-03-22..
[106] R. Walker, P. McKenzie, C. Liddell, C. Morris, Area-based targeting of fuel poverty in Northern Ireland: An evidenced-based approach, Appl. Geogr. 34 (2012) 639–649.
[107] Office for National Statistics, Population estimates by output areas, electoral, health and other geographies, England and Wales, https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/annualsmallareapopulationestimates/mid2015/pdf, 2016. Online; accessed 2022-03-22..
[108] W. Gans, A. Alberini, A. Longo, Smart meter devices and the effect of feedback on residential electricity consumption: Evidence from a natural experiment in Northern Ireland, Energy Econ. 36 (2013) 729–743.
[109] C.F. Reinhart, T. Dogan, A. Jakubiec, T. Rakha, A. Sang, UMI - An Urban Simulation Environment For Building Energy Use, Daylighting and Walkability, in: 13th Conference of International Building Performance SImulation Association, pp. 476–483..
[110] N. Codoban, C.A. Kennedy, Metabolism of Neighborhoods, J. Urban Plann. Develop. 134 (2008) 21–31.
[111] T. Rakha, C.F. Reinhart, A carbon impact simulation-based framework for land use planning and non-motorized travel behaviour interactions, in: Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association, Chambery, France, pp. 1248–1255..
[112] A.L. Pisello, J.E. Taylor, X. Xu, F. Cotana, Inter-building effect: Simulating the impact of a network of buildings on the accuracy of building energy performance predictions, Build. Environ. 58 (2012) 37–45.
[113] S. Outcault, A. Sanguinetti, N. Dessouky, C. Magaña, Occupant Non-Energy Impact Identification Framework: A human-centered approach to understanding residential energy retrofits, Energy Build. 263 (2022) 112054.
[114] C. Liddell, C. Morris, Fuel poverty and human health: A review of recent evidence, Energy Policy 38 (2010) 2987–2997.
[115] The Academic – Practitioner Partnership, Good Housing and Better Health, Technical Report, Housing and Communities Research Group, Birmingham, 2016..
[116] H. Elsharkawy, S. Zahiri, The significance of occupancy profiles in determining post retrofit indoor thermal comfort, overheating risk and building energy performance, Build. Environ. 172 (2020) 106676.
[117] F. Ascione, N. Bianco, R.F. De Masi, M. Mastellone, G.M. Mauro, G.P. Vanoli, The role of the occupant behavior in affecting the feasibility of energy refurbishment of residential buildings: Typical effective retrofits compromised by typical wrong habits, Energy Build. 223 (2020) 110217.
[118] S.L. Walker, D. Lowery, K. Theobald, Low-carbon retrofits in social housing: Interaction with occupant behaviour, Energy Res. Soc. Sci. 2 (2014) 102–114.
[119] W.J. Fisk, B.C. Singer, W.R. Chan, Association of residential energy efficiency retrofits with indoor environmental quality, comfort, and health: A review of empirical data, 2020..
[120] D. Vakalis, M. Touchie, E. Tzekova, H.L. MacLean, J.A. Siegel, Indoor environmental quality perceptions of social housing residents, Build. Environ. 150 (2019) 135–143.
[121] F.D. Salim, B. Dong, M. Ouf, Q. Wang, I. Pigliautile, X. Kang, T. Hong, W. Wu, Y. Liu, S.K. Rumi, M.S. Rahaman, J. An, H. Deng, J. WeiShao, F.C. Dziedzic, M.B. Sangogboye, M. Kjærgaard, C. Kong, A.L. Fabiani, D. Yan Pisello, Modelling urban-scale occupant behaviour, mobility, and energy in buildings: A survey, Build. Environ. (2020) 106964.
[122] N. Jain, E. Burman, S. Stamp, D. Mumovic, M. Davies, Cross-sectoral assessment of the performance gap using calibrated building energy performance simulation, Energy Build. 224 (2020) 110271.
[123] P. Beagon, F. Boland, M. Saffari, Closing the gap between simulation and measured energy use in home archetypes, Energy Build. 224 (2020).
[124] E. Holden, K. Linnerud, B.J. Rygg, A review of dominant sustainable energy narratives, Renew. Sustain. Energy Rev. 144 (2021) 110955.
[125] R. Gupta, M. Gregg, Do deep low carbon domestic retrofits actually work?, Energy Build 129 (2015) 330–343.
[126] E. Masanet, A. Shehabi, N. Lei, S. Smith, J. Koomey, Recalibrating global data centre energy-use estimates, Science 367 (2020) 984–986.
[127] K. Ebrahimi, G.F. Jones, A.S. Fleischer, A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities, Renew. Sustain. Energy Rev. 31 (2014) 622–638.
[128] M. Wahlroos, M. Pärssinen, S. Rinne, S. Syri, J. Manner, Future views on waste heat utilization – Case of data centers in Northern Europe, Renew. Sustain. Energy Rev. 82 (2018) 1749–1764.
[129] The European Parliament and of the council of the European Union, Directives Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast), https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN, 2018. Online; accessed 2022-05-10..
[130] R. Baetens, R. De Coninck, J. Van Roy, B. Verbruggen, J. Driesen, L. Helsen, D. Saelens, Assessing electrical bottlenecks at feeder level for residential net zero-energy buildings by integrated system simulation, Appl. Energy 96 (2012) 74–83.
[131] European Commission, Heating and cooling, https://ec.europa.eu/energy/topics/energy-efficiency/heating-and-cooling_en, 2021a. Online; accessed 2022-03-22..
[132] European Commission, Decarbonising our energy system to meet our climate goals, https://ec.europa.eu/commission/presscorner/detail/en/fs_21_3672, 2021b. Online; accessed 2022-03-22..
[133] European Commission, Executive Agency for Small and Medium-sized Enterprises, J. Volt, Z. Toth, J. Glicker, M. De Groote, G. Borragán, S. De Regel, S. Dourlens-Quaranta, G. Carbonari, Definition of the digital building logbook: report 1 of the study on the development of a European Union framework for buildings' digital logbook, 2020a..
[134] European Commission, Executive Agency for Small and Medium-sized Enterprises, G. Carbonari, S. De Regel, Z. Toth, A. Lodigiani, M. Calderoni, T. Loureiro, R. Sterling, B. Vandevelde, C. Spirinckx, I. Kondratenko, N. Rajagopalan, O. Rapf, S. Dourlens-Quaranta, M. De Groote, G. Borragán, J. Volt, J. Glicker, Study on the development of a European Union framework for digital building logbooks: executive summary, 2020b..
[135] K.C. O'Sullivan, J. Stanley, G. Fougere, P. Howden-Chapman, Heating practices and self-disconnection among electricity prepayment meter consumers in New Zealand: A follow-up survey, Utilities Policy 41 (2016) 139–147.
[136] M. Sunikka-Blank, R. Galvin, Introducing the prebound effect: the gap between performance and actual energy consumption, Build. Res. Inf. 40 (2012) 260–273.
[137] M. Sunikka-Blank, J. Chen, J. Britnell, D. Dantsiou, Improving Energy Efficiency of Social Housing Areas: A Case Study of a Retrofit Achieving an "A" Energy Performance Rating in the UK, Eur. Plann. Stud. 20 (2012) 131–145.
[138] P. Karakusevic, A. Batchelor, Social housing: definitions & design exemplars, Riba Publishing (2017).
[139] R.D. Marchand, S.C. Koh, J.C. Morris, Delivering energy efficiency and carbon reduction schemes in England: Lessons from Green Deal Pioneer Places, Energy Policy 84 (2015) 96–106.
[140] P. Beagon, F. Boland, J. O'Donnell, Quantitative evaluation of deep retrofitted social housing using metered gas data, Energy Build. 170 (2018) 242–256.
[141] SEAI, Energy in the Residential Sector – 2018 Report, https://www.seai.ie/resources/publications/Energy-in-the-Residential-Sector-2018-Final.pdf, 2018. Online; accessed 2022-03-22..
[142] E. Dennehy, M. Howley, S. Lyons, Energy in the Residential Sector 2013, http://www.seai.ie/Publications/Statistics_Publications/Energy-in-the-Residential-Sector/, 2013. Online; accessed 2022-03-22..
[143] Energy Saving Trust, Guide to energy efficient lighting, https://energysavingtrust.org.uk/advice/lighting/, 2022. Online; accessed 2022-03-22..
[144] S. Sorrell, J. Dimitropoulos, M. Sommerville, Empirical estimates of the direct rebound effect: A review, Energy Policy (2009).
[145] R. Galvin, M. Sunikka-Blank, Quantification of (p)rebound effects in retrofit policies – Why does it matter?, Energy 95 (2016) 415–424
[146] D. Teli, T. Dimitriou, P. James, A. Bahaj, L. Ellison, A. Waggott, Fuel poverty-induced 'prebound effect' in achieving the anticipated carbon savings from social housing retrofit, Build. Services Eng. Res. Technol. 37 (2016) 176–193.

[147] S.E. Chidiac, E.J. Catania, E. Morofsky, S. Foo, Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings, Energy 36 (2011) 5037–5052.
[148] SEAI, Net Zero by 2050—Exploring Decarbonisation Pathways for Heating and Cooling in Ireland, https://www.seai.ie/data-and-insights/national-heat-study/net-zero-by-2050/, 2022. Online; accessed 2022-03-22..
[149] W. Nijs, D. Tarvydas, A. Toleikyte, EU challenges of reducing fossil fuel use in buildings, https://publications.jrc.ec.europa.eu/repository/handle/JRC127122, 2021. Online; accessed 2022-03-22..
[150] R. McKenna, E. Merkel, D. Fehrenbach, S. Mehne, W. Fichtner, Energy efficiency in the German residential sector: A bottom-up building-stock-model-based analysis in the context of energy-political targets, Build. Environ. 62 (2013) 77–88.
[151] D. Dineen, B.P.Ó. Gallachóir, Modelling the impacts of building regulations and a property bubble on residential space and water heating, Energy Build. 43 (2011) 166–178.
[152] European Commission, Commission Recommendation (EU) 2019/786 on Building Renovation, https://op.europa.eu/en/publication-detail/-/publication/4a4ce303-77a6-11e9-9f05-01aa75ed71a1/language-en/format-HTML, 2019. Online; accessed 2022-03-22..