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Article

Future-Proofed Energy Design Approaches for Achieving Low-Energy Homes: Enhancing the Code for Sustainable Homes

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Abstract: Under the label "future-proofing", this paper examines the temporal component of sustainable construction as an unexplored, yet fundamental ingredient in the delivery of low-energy domestic buildings. The overarching aim is to explore the integration of future-proofed design approaches into current mainstream construction practice in the UK, focusing on the example of the Code for Sustainable Homes (CSH) tool. Regulation has been the most significant driver for achieving the 2016 zero-carbon target; however, there is a gap between the appeal for future-proofing and the lack of effective implementation by building professionals. Even though the CSH was introduced as the leading tool to drive the "step-change" required for achieving zero-carbon new homes by 2016 and the single national standard to encourage energy performance beyond current statutory minima, it lacks assessment criteria that explicitly promote a futures perspective. Based on an established conceptual model of future-proofing, 14 interviews with building practitioners in the UK were conducted to identify the "feasible" and "reasonably feasible" future-proofed design approaches with the potential to enhance the "Energy and CO_2 Emissions" category of the CSH. The findings are categorised under three key aspects; namely: coverage of sustainability issues; adopting lifecycle thinking; and accommodating risks and uncertainties and seek to inform industry practice and policy-making in relation to building energy performance.

Keywords: code for sustainable homes; energy design; future-proofing; policy and practice; zero-carbon

1. Introduction

There is increasing reference to future-oriented design in current research agendas and policies related to low-energy and/or zero-carbon construction. In the Hannover Principles, McDonough and Braungart [1] emphasise the importance of long-term sustainability in design, as the ability to adapt to the unknown future. A major recent report entitled “Future Proofing Cities” [2] underlined that cities should take serious actions to deliver tangible social and economic benefits in the short and longer term, with building energy performance being a key priority area. Another area of significant concern is the delivery of design that is able to cope with the uncertain global, regional and local consequences of climate change for the environment, human health, and the economy [3]. In this regard, the Institute of Building Science and Energy Efficiency [4] state cites should performance effectively in both present and future climate. Lisø [5] also refers to the need for future-proofed design as currently building design codes and standards are based on historic data whilst in the next few decades existing buildings should cope with different climatic strains due to climate change.

Planners and property developers have also to deal with an increasingly stringent regulatory framework, especially in the context of “zero-carbon” new-builds and the impacts of climate change. Future-proofed design is promoted implicitly within the increasingly stringent environmental legislation, building regulations and standards, which mandate the expected energy performance levels both at European and national levels up to at least 2050. The revised European Performance Building Directive (EPBD) 2010/31/EU, previously EPBD 2002/91/EC, sets out a rigorous policy framework for both new and existing buildings. It provides a comprehensive methodology for buildings that undergo major renovation, the minimum energy performance requirements for technical systems (e.g., boilers) and a target for all new buildings to be nearly zero-energy by 2020 [6]. In particular, the UK policy framework has introduced long-term thinking into key policies, mechanisms and targets, which include:

- The regular update of *Part L (Conservation of Fuel and Power)* of the Building Regulations to higher standards [7];
- The *Code for Sustainable Homes (CSH)* [8]; and
- The target for *zero-carbon* new homes from 2016 and new non-domestic buildings from 2019 onwards [9,10].

1.1. What Is Future-Proofing?

“Future-proofed” design or “designing for the future” refers to sustainable, low-energy buildings, able to accommodate social, technological, economic, environmental, and regulatory changes over the long-term, thus maximising lifecycle value [11–13]. This affects decision-making at an early design stage and seeks to increase the likelihood of buildings remaining “fit-for-purpose” under a set of plausible energy futures, rather than delivering ones that just meet particular short-term needs. Given the slow turnover of the building stock, a design that cannot respond to both present and future circumstances is vulnerable to becoming poorly utilised and prematurely obsolete [14]. Hence, buildings able to respond to future energy challenges may, for instance: avoid costly, disruptive and energy-intensive refurbishments; comply more easily with increasingly stringent legislation; be flexible for “technology-readiness” and occupants’ changing behaviours; and be resilient to rising energy costs.

A significant barrier to incorporating long-term thinking into the energy design of buildings is the lack of common understanding regarding the meaning of the term "future-proofing". This is an evolving concept, which has neither been explored sufficiently by researchers nor applied by building professionals; hence, a widely accepted definition is not yet agreed. Jewell *et al.* [15] define future-proofing as "*designing something to be resilient to future climate uncertainty, including both mitigation of negative impacts and taking advantage of future opportunities*". In a similar vein, the Royal Academy of Engineering (RAE) [16] and Jenkins *et al.* [17] present adaptation to climate change as a means to future-proof new designs to deal with predicted warming and a range of expected temperature conditions. Pelsmakers [18] argues that future-proofing reconciles adaptation with mitigation efforts with cost-effective measures that enable thinking over the building's lifecycle.

A future-proofed design refers to flexible buildings and energy systems that can to respond to changing technologies and occupants' energy needs [11]. Similarly, a study by Town and Country Planning Association (TCPA) [19] underlines the importance of future-proofing new extensions to large urban development projects so that they can be compatible with district heating systems in the future. Kingspan Insulation Ltd. [20] highlight the need for early design decisions to be future-proofed so that new homes can be refurbished practicably to comply with ever more stringent building regulations. A report from the Zero Carbon Hub (ZCH) [21] incorporated "future-proofed construction" as one of the nine criteria affecting the roadmap to zero-carbon homes in the UK by 2016, together with building practices; building at mass scale; health and well-being; desirability; upfront costs; maintenance and energy costs; energy security; and broader environmental impacts. In particular, the term "future-proofing" is used to refer to the process of minimising future performance upgrades and the risk of summertime overheating, together with designing for internal space flexibility to enable future occupants to modify easily the layout of the home.

From the above, it is apparent that existing definitions of future-proofed design focus mostly on a particular trend or driver, such as overheating due to future climate impacts, the launch of new technologies or regulatory requirements. It is only recently that more inclusive definitions have been suggested. In particular, a recent report by Godfrey and Savage [2] defines future-proofing, albeit in relation to cities, as the cost-effective response to risk associated with climate change, resource scarcities and damage to ecosystems.

As the future is unpredictable, there is a risk that decisions based on today's predictions will turn out to be ill-informed [22]. Future-proofing aims to prevent housing developments from being locked into traditional development paths; whereby vulnerabilities or redundancies are only tackled once they arise (*i.e.*, after the design stage). This should not be seen as an end-state but as an ongoing process of adding adaptive capacity with robust strategies, which can bring value via long-lasting designs [23]. As Godfrey and Savage argue ([2], p. 114), the strategy based on "*grow first, tackle environmental challenges later*" is unlikely to be effective, so rather than predicting what the future will be, it is about designing now to avoid higher costs and inconvenience that might occur in the future. Hence, to address effectively the long-term impacts that domestic buildings can cause and experience, future-proofing needs to be applied as early as possible in the lifecycle. In this context, the authors define *future-proofing*, comprehensively, as:

> *A design approach that entails "stress*-testing*" building solutions against a range of plausible futures to ensure that they remain functional over the lifecycle of a housing development; hence, avoiding disruptive refurbishments or premature decommissioning.*

This definition is also aligned with assertions made by Gil and Beckman [24], who argue that one should not design assuming that predictions about future scenarios are 100% reliable. Rather, the aim is to have a design-support framework or conceptual model in place that ensures serious thinking about foreseeable scenarios and informs design decision-making.

1.2. Barriers to Future-Proofing

Despite compelling arguments linking long-term thinking with sustainability, future-proofing is still not common practice in the mainstream construction industry. There is currently lack of clarity and no indication on the levels of knowledge in industry and policy circles regarding what is meant by "future-proofing". Little research has been carried out on identifying future-proofed design approaches and there is currently no established decision-support framework to readily incorporate a long-term perspective into the energy design of buildings. The term "design approaches" refers to criteria, decision-support techniques and tools and assessment methods that aid the selection of building solutions. The barriers to future-proofing are distinguished between technical, cultural and organisational.

1.2.1. Technical Barriers

There is a disconnect between the appeal of future-proofing as a principle or "philosophy" aligned with Sustainable Development (SD) at a policy level and readily-available design approaches required for its effective implementation by building professionals. This is also underpinned by the lack of integrated design approaches that cover both the thematic and temporal aspects of SD. Existing design approaches are typically limited to consider the thematic component (*i.e.*, the "Triple Bottom Line") and often only measures that address financial and environmental considerations at a particular lifecycle stage, such as carbon emissions during operation [25]. This, however, overlooks the wider environmental and socio-economic impacts of the design, which can only be realised over a (very) long period of time [26].

Assessing comprehensively the whole building design across the full lifecycle is central to future-proofing. There has been progress made with respect to emerging decision-support techniques regarding embodied energy and carbon calculations as well as Lifecycle Assessment (LCA) methods. Examples include: the Inventory of Carbon and Energy (ICE) database, Building Research and Establishment's (BRE) Green Guide to specification, and LCA tools, such as Gabi, SimaPro, TEAM, LCAiT, Envest, ATHENA, and BEES [27,28]. LCA, in particular, was mainly developed to design low environmental products and it is only recently that it has been applied to larger scale and more complex structures, such as buildings [27,29]. Nevertheless, existing methodologies and commercial bespoke software tools provide predominantly data from "cradle-to-gate"; *i.e.*, emissions from mining, raw materials extraction, processing and manufacturing. There are limited data available for composite and/or novel materials and the energy used and carbon emitted during transport to site, assembly on-site and other construction activities, maintenance, component replacements and finally deconstruction, demolition and/or final disposal. Moreover, existing LCA tools incorporate various building types, functions, geographical areas, cultural consumption patterns and traditional construction techniques but they cannot be transferred directly to other context without confirming the validity of assumptions or adopting regional modifications. Hauschild [29] argues that LCA outcomes can be inaccurate due to:

- "parameter uncertainty" introduced by measurement errors in input data;
- "scenario uncertainty" reflecting choices in the modelling procedure, such as time horizon or geographical scale; and
- "model uncertainty", in which many aspects of the "real world" cannot be modelled by present LCA models.

A number of recent studies on the LCA ISO 14040/44 framework have sought to address the above types of uncertainties [29–33]. These are novel tools and currently complex and costly to apply, particularly to whole building systems. In addition, LCA tools are poorly linked with mainstream Building Environmental Assessment Methods (BEAMs), which is an area that requires further research.

1.2.2. Organisational and Cultural Barriers

Another issue impacting negatively on future-proofing is the short-term perspective prevalent in the construction sector often conflicts with the long-term principles of SD. As early design decisions impact significantly on the commissioning, construction, and operational phases, there is a need for design approaches that anticipate and proactively accommodate future trends and drivers affecting energy performance, thus shifting from the current "build-it-now and fix-it-later" philosophy [19,34,35].

Building professionals, and particularly residential developers, often have little interest in properties once the post-construction sale is complete due to decisions being driven by short payback periods and the desire for quick revenue generation [22,35–39]. In addition, contracts and project appraisals focus mostly on upfront costs, as it has proven difficult to convince developers, contractors, and their clients to commission sustainability-oriented studies over the building's lifecycle, unless it is a regulatory requirement. A substantial section of the UK construction industry still barely meets existing regulatory requirements, impeding efforts towards sustainability, in general, and future-proofing, in particular [36,40,41].

2. Methodological Approach

This paper seeks to address the gap in integrating futures thinking into the energy design of domestic buildings and has two key objectives:

- To present a wide spectrum of design approaches to future-proof the energy design of domestic buildings; and
- To examine the extent to which these design approaches can be practically integrated into the UK mainstream practice, in general, and the CSH tool, as current leading design practice, in particular.

Since the research is concerned with the early planning and design stages, it focuses on new rather than existing buildings, even though some of the research findings could be relevant to retrofits. For the first objective, the research builds on a previously published conceptual model for future-proofed design [42]. This framework provides a justification of why future-proofing needs to be proactively integrated into the energy design of housing developments and introduces a classification of future-proofed design approaches, as compiled from the seminal literature. To address the second objective, the paper presents a gap analysis in future-proofed design approaches in mainstream UK design and construction practice using the example of the CSH tool. Data gathered from 14 semi-structured interviews with building professionals are then used as part of a feasibility analysis to examine the extent to which it is feasible to transfer the identified future-proofed design approaches given the barriers that have to be address by the house building industry.

Fourteen in-depth interviews using open-ended questions were carried out and the target group included building professionals; *i.e.*, senior planning officers, developers, contractors, energy and sustainability consultants involved in the energy and sustainability design and delivery of domestic buildings in the UK. The interactive and non-rigid nature of interviews permitted the researcher to elicit issues of particular importance to interviewees and allowed them to express freely their experience and perspectives. Table 1 contains the list of interviewees, their affiliation and interview date. All meetings were one-to-one and a recording device was used, after receiving permission from participants. Interviews ranged in duration from 45 min to 2 h, with the average being approximately one hour. Where possible, introductory informal discussions were held, usually by email or telephone, to explain the research objectives.

Table 1. Interview respondents.

Interview Number	Affiliation	Organisation	Date
1	Project Director	Developer of large mixed-use development	16 February 2011
2	Senior Sustainability Officer	City Council	18 February 2011 23 March 2012
3	Associate Director	Sustainability, Building and Engineering Construction and Engineering Company	3 March 2011
4	Associate Director		3 March 2011 6 March 2012
5	Team Leader Sustainable Communities	District Council	23 March 2012
6	Associate Director	Sustainability and Alternative Technologies Group Engineering Consultancy	4 November 2011
7	Sustainability Consultant		
8	Group Director	Architectural practice	7 November 2011
9	Design Delivery Director		
10	Environmental Designer		
11	Planning Delivery Manager	City Council	8 November 2011
12	Head of Planning and Regeneration		
13	Assistant Planner	Developer of large mixed-use development	
14	Eco-Communities Project Manager	Project Services Team Development Company	

The data analysis included assessment of the "real-world" perspective generated by the four cases against the conceptual framework for future-proofed design, using what Yin calls pattern matching logic [43]. The analysis involved "looking for groupings and relationships", in three levels: description; classification; and establishment of logical connections between the classified data [43]. The qualitative data from documents, transcribed interviews, and field notes were entered into MS Word documents. "Coding" was then used to provide order and structure. Analysis of coding was undertaken using MS Excel through the creation of bespoke templates. The data analysis was undertaken solely by the researcher providing consistency in coding and data linkages.

3. Conceptual Model

Building solutions cannot be easily revised and have long-term consequences [44]. In particular, there are two general categories of long-term impacts that domestic buildings can cause and experience, which are often erroneously treated interchangeably, namely:

- The impacts of domestic buildings on the environment due to their long lifecycles; and
- The impacts on domestic buildings due to risks and uncertainties affecting the energy performance.

The former relates to mitigating the adverse impacts of building solutions throughout their long lifecycles [26]; whilst the latter concerns the exploration of risks and uncertainties, which can affect building energy performance due to the occurrence of (predictable and/or unforeseeable) high-impact events [45].

According to the Chartered Institution of Building Services Engineers, a good low-energy design offers the best future-proof solutions [46]. Nonetheless, a low-energy design demonstrating exemplary thermal performance does not necessarily constitute a future-proofed one, but does represent a baseline from which to develop further this concept. Table 2 presents a tri-axial "conceptual model", which summarises the future-proofed design approaches as extracted from recent and seminal literature. The model is adapted from Georgiadou *et al.* [42] showing that there are three axes (or features) that characterise comprehensive future-proofing, namely:

- ***X-Axis—Coverage of SD Issues*****:** Degree to which the three sustainability "pillars" (social economic, environmental) and their financial implications are covered in order to achieve a holistic energy design process.
- ***Y-Axis—Adopting Lifecycle Thinking*****:** Extent to which the implications of the energy design are considered throughout all lifecycles stages; *i.e.*, from "cradle-to-grave" or "cradle-to-cradle" so as to minimise the associated environmental impacts. "Cradle-to-grave" refers to the lifecycle process from extraction up to final disposal (demolition and landfill); whereas "cradle-to-cradle" includes processes for future deconstruction and reuse at the end of the materials' and components' lifecycle [18,47].
- ***Z-Axis—Accommodating Risks and Uncertainties*****:** Degree to which predictable, reasonably foreseeable, and uncertain trends and drivers that can affect the energy use are accommodated over the long-term.

It is important to note that the conceptual model does not represent a "model solution" for energy design, but rather reveals a spectrum of design approaches to help building professionals future-proof the design. Existing literature addresses, extensively, the *X*-axis, which covers the thematic component of SD. However, the contribution of the conceptual model is that it introduces the *Y*- and *Z*-axes to account for the temporal aspect of sustainability. These are based on the two categories of long-term impacts in buildings, as presented above, which are often neglected in design decision-making for low-carbon construction.

Table 2. Categorisation of future-proofed design approaches. Adapted from [42].

***X*-Axis: Coverage of SD Issues**	***Y*-Axis: Adopting Lifecycle Thinking**	***Z*-Axis: Accommodating Risks and Uncertainties**
X_1: Financial considerations	Y_1: Operational energy performance	Z_1: Steady-state modelling
X_{1a}: Capital cost assessment	Y_{1a}: Predictive studies	Z_2: Adoption of standards
X_{1b}: Cost-effectiveness analysis	Y_{1b}: Post-construction audit/	beyond statutory minima
X_{1c}: Financial incentives	post-occupancy evaluation	Z_3: Design for adaptive capacity
X_2: Environmental considerations	Y_2: Embodied energy and carbon	Z_{3a}: Design for resilience
hierarchical approach to	Y_{2a}: Design for “cradle-to-gate”	to overheating
low-energy design	Y_{2b}: Design for “cradle-to-grave”	Z_{3b}: Design for flexibility
X_3: Socio-economic considerations	Y_{2c}: Design for “cradle-to-cradle”	Z_4: Advanced future-oriented
X_{3a}: Sustainability information	Y_3: Lifecycle assessment	analysis
and education	Y_{3a}: Building material and/or	Z_{4a}: Dynamic building
X_{3b}: Demand-side management	construction component scale	performance evaluation
strategies	Y_{3b}: Building scale	Z_{4b}: Stochastic modelling of
X_{3c}: Assessment of energy-related	Y_{3c}: District scale	future overheating risk
social impacts	Y_4: Lifecycle costing	Z_{4c}: Use of futures techniques

Along each axis are design approaches with varying degrees of future-proofing that can be used, with their position from the top reflecting the degree of complexity typically associated with their use. The extent to which an energy design has been future-proofed can be elucidated by identifying the degree to which the approaches found within the framework are used in combination. Nevertheless, mainstream construction practice employs future-proofed design approaches that focus predominantly on financially-viable (X_{1a}) and readily-available solutions (“low-hanging fruit”), with lifecycle impacts being limited to predictions of operational energy performance (Y_{1a}); whilst predictions are based on steady-state models which do not accommodate risks and uncertainties (Z_{1a}).

4. The Gap in Future-Proofed Design Approaches

Future-proofing is theoretically part of current environmental legislation, standards and policy mechanisms for achieving zero-carbon homes. According to Greenwood, UK policy-makers understand the need to develop future-proofing policies in an increasingly complex, uncertain, and unpredictable world [48]. He argues that policy mechanisms should adopt criteria for long-term thinking so as to “*stand the test of time and work in practice from the start*” [49]. In practice, however, there is a gap in future-proofed design approaches, as BEAMs currently underestimate or even overlook the temporal aspect of sustainability. This, in turn, results in limited integration of full lifecycle perspectives and use of methods to accommodate high-impact risks and uncertainties into the energy design [26,45]. Key reasons for this gap are:

- The lack of incentives for future-proofed design;
- The short-term mindset of the construction industry;
- The confusion between the two categories of long-term impacts, which are often treated erroneously as the same (Section 2); and
- Legislation focusing on regulating operational energy and assessment methods dealing with the design (or, at best, construction) stage rather than ongoing performance over the full lifecycle.

4.1. The Example of the Code for Sustainable Homes

To better reveal this gap between the need for future-proofing and the lack of effective implementation by building professionals, the example of the CSH is further analysed. There is a wide range of tools and policy mechanisms currently used in the UK practice and by UK building authorities. Examples are: SAP to inform the production of Energy Performance Certificates (EPCs); BREEAM; LEED; and other industry bespoke tools. Nonetheless, this study focuses on the CSH because it represents the best available platform as it:

- Examines new domestic buildings;
- Was a planning requirement in projects that the 14 interviewees were working on;
- Is the leading tool to drive the "step-change" required for achieving zero-carbon new homes from 2016 onwards [8]; and
- Is the single national standard to drive continuous improvement and innovation towards achieving sustainable house building practice and encourage energy performance beyond the current regulatory minima, thus meeting the Z_2 design approach (Table 2).

The CSH is a checklist-type environmental assessment tool for rating and certifying the performance of new dwellings in England, Wales and Northern Ireland [8]. It became legally binding in 2008, taking over from the EcoHomes version of the Building Research Establishment Environmental Assessment Method (BREEAM) [50]. The tool is also expected to become the compulsory standard for all dwellings so as to meet the target of zero-carbon by 2016.

The Code uses a star system (1 to 6 stars) to rate performance with the highest ranking (Level 6) being "zero-carbon". The Code contributes to future-proofing the energy design of new dwellings in England, Wales and Northern Ireland by setting the minimum standards for compliance above Part L. The CSH is also aligned with European schemes and legislation, such as the German PassivHaus standard and the EPBD 2010/31/EC [8,50–53]. At present, local authorities are also empowered to set their own CSH Levels for new housing developments [48].

The CSH assessment comprises a limited number of mandatory assessment criteria in nine categories of sustainable design, namely: Energy and CO_2 Emissions; Water; Materials; Surface Water Run-off; Waste; Pollution; Health and Well-Being; Management; and Ecology. The assessment is carried out in two stages [8]: Design Stage and Post Construction Stage. The latter seeks to provide an evidence-based evaluation of the design specification stage onwards, even though it does not extend to monitoring of the in-use energy. Code Level 6 meets the Zero Carbon Hub's definition of a "zero-carbon" home; *i.e.*, zero net carbon emissions over a year at the end of the two stages including unregulated loads). Energy is the most important category in the CSH with the maximum available credits (31) that translates to 36.4% of all nine categories (Table 3). The total available contribution is expressed as 100%. This conversion is achieved by the use of weighting factors, which assign the contribution made by each criterion to the total performance certified by the Code.

Table 3. The "Energy and CO_2 Emissions" category of the Code for Sustainable Homes. Data from [8].

Assessment Criteria	Available Credits	Description
Dwelling Emission Rate	10	To limit CO_2 emissions arising from the operation of a dwelling and its services in line with current policy on the future direction of regulations
Fabric Energy Efficiency	9	To improve fabric energy efficiency performance thus future-proofing reductions in CO_2 emissions for the life of the dwelling.
Energy Display Devices	2	To promote the specification of equipment to display energy consumption data, thus empowering dwelling occupants to reduce energy use.
Drying Space	1	To promote a reduced energy means of drying clothes.
Energy Labelled White Goods	2	To promote the provision of energy efficient white goods, thus reducing the CO_2 emissions from appliance use in the dwelling.
External Lighting	2	To promote the provision of energy efficient external lighting, thus reducing CO_2 emissions associated with the dwelling.
Low and Zero Carbon technologies	2	To limit CO_2 emissions and running costs arising from the operation of a dwelling and its services by encouraging the specification of low and zero carbon energy sources to supply a significant proportion of energy demand.
Cycle storage	2	To promote the wider use of bicycles as transport by providing adequate and secure cycle storage facilities, thus reducing the need for short car journeys and the associated CO_2 emissions.
Home Office	1	To promote working from home by providing occupants with the necessary space and services thus reducing the need to commute.
Category Total (Weighting Factor)	31 (36.4%)	–

Although the CSH represents current leading design practice in sustainable construction, it lacks assessment criteria that explicitly promote a futures perspective (Table 3). The only criterion with implicit potential temporal characteristic is "Home-Office", which assigns only one credit for internal space flexibility. As the Code is the best available design tool for new dwellings, it is expected that mainstream decision-support frameworks would underestimate or even overlook future-proofed design approaches. It is therefore evident that there is poor expression of future-proofing in the energy design of domestic buildings due to the gap in design approaches that cover the temporal aspect of SD.

4.2. The Code for Sustainable Homes and the Connection with Part L

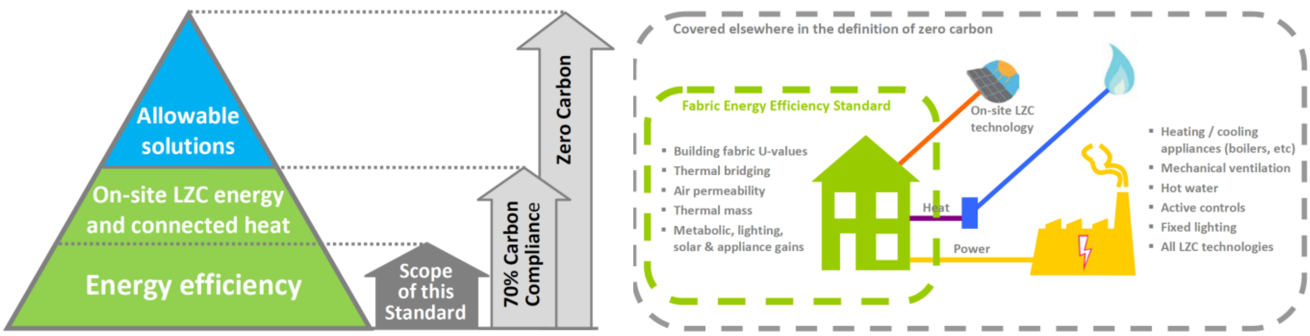
To future-proof the dwelling performance and meet the zero-carbon target, Part L 2006 mandates that energy efficiency requirements of new homes become increasingly stringent in three steps over a period of ten years. Table 4 shows how the incoming Part L updates in 2013 and 2016 are linked with the existing CSH Level 4 and 6, respectively and the tightening of Part L in an effort to achieve zero-carbon new dwellings by 2016. However, it is important to differentiate between energy use (demand-side) and the carbon intensity of energy sources (supply-side). All new homes must receive a Code rating; however, achieving a particular level beyond what is set by the Building Regulations (currently Level 4, as shown in Table 4) is not yet mandatory to give developers the flexibility to determine the most cost-effective level of performance.

Table 4. Tightening of Part L towards achieving zero-carbon homes. Data from [7,8].

Year	2010	2013	2016
Energy efficiency improvement (% over 2006 Part L)	25%	44%	zero-carbon
Equivalent Level in the CSH	Level 3	Level 4	Level 6

Since its introduction in 2006 as a target, there has been uncertainty as to what qualifies as "zero-carbon" (or CSH Level 6), and a widely-acceptable definition is yet to be confirmed. Originally, the CSH stipulated that it encompasses all energy use both regulated and unregulated energy' loads [18,54]. Unregulated loads include what is not currently controlled by the Building Regulations, such as energy from appliances, any electrical equipment, and occupants' activities (e.g., cooking).This posed considerable difficulties in mainstream roll-out and has subsequently been revised to cover, mainly, regulated energy use. Moreover, the current definition of "zero-carbon" excludes embodied carbon; hence, embodied energy and carbon receive little attention and is not covered by the CSH and current UK legislation, such as the 80% carbon emissions reduction target [25,55]. The Zero Carbon Hub (ZCH) has led the revision of the "zero-carbon" definition, proposing a three-level pyramid or hierarchy of measures (Figure 1). This includes [10,21,34,48,56]:

Figure 1. Hierarchical Approach to Zero-Carbon Homes ([21], p.6, p.8). Copyright Zero Carbon Hub 2009.



- *Fabric Energy* Efficiency *Standard (FEES)*, which covers the building envelope and is used to calculate the maximum space heat demand in kWh/m^2 per annum (p.a.) for achieving a zero-carbon. The FEES is a performance standard, allowing for flexibility, as different building solutions can be used to reach the particular levels, which are set to: 39 kW h/m^2 p.a. for apartment blocks and mid terraced houses; and 46 kW h/m^2 p.a. for semi-detached, end-of-terrace and detached houses. Since 2010, achieving CSH Level 4 has incorporated FEES in the "Energy and CO_2 Emissions" category.
- *Carbon Compliance (CC)*, which refers to a minimum of 70% of regulated energy use and carbon savings on-site against Part L 2006 standards through a combination of FEES and LZCs for heating, DHW, fixed lighting, and ventilation, including also direct connection to district heating solutions.
- *Allowable Solutions*, which is a scheme to mitigate the remaining regulated and unregulated carbon emissions with off-site measures, such as exports of heat, insulating existing housing in the vicinity, the use of, or direct investments in, renewable electricity generation situated away from the site via a community energy fund [56].

5. Feasibility Assessment

This section discusses the views and opinions of 14 building practitioners regarding the design approaches that can be currently adopted to future-proof the energy design of domestic buildings, based on the conceptual model presented in Table 2. It should be, however, underlined that transferability relates to the design approaches that inform the decision-making, not the actual building solutions (e.g., choice of materials, structural system, or heating strategy). The analysis of the interviews reveals that there is a strong alignment between context-specific drivers and the identified future-proofed design approaches. It is the specific governance and institutional characteristics that play a key role in design decision-making affecting local planning, housing provision, construction practices, and energy consumption, which means that there is "no-size-fits-all" solution.

Table 5 presents a summary of an assessment of their transferability to mainstream construction practice in the UK. Based on the insights gathered from the interview responses the concept of "transferability" entails three parameters: costs; data; and resource requirements. The research findings are categorised by three levels, namely:

- *"unfeasible"*; *i.e.*, those that cannot be transferred due to high costs, data-intensity and/or specialised resources required to achieve long-term benefits;
- *"reasonably feasible"*; *i.e.*, those that can be transferred with marginal additional costs, data-intensity and/or specialised resources required to offset near-term benefits; and
- *"feasible"*; *i.e.*, those that either already exist in mainstream practice or can be replicated as used in the fieldwork cases without any additional barriers due to costs, data-intensity and/or resources needed. These are the "low-hanging fruits" with often tangible design benefits that lead to cost savings.

Table 5. Transferable design approaches for new housing developments in the UK. (From interview responses).

Future-Proofed Design Approaches	Level of Transferability		
	Feasible	Reasonably Feasible	Unfeasible
X-Axis: Coverage of SD Issues			
X_1: Financial considerations			
X_{1a}: Capital cost assessment	√	–	–
X_{1b}: Cost effectiveness analysis	√	–	–
X_{1c}: Financial incentives	–	√	–
X_2: Environmental considerations Hierarchical approach to low-energy design	√	–	–
X_3: Socio-economic considerations		–	
X_{3a}: Sustainability information and education	√	–	–
X_{3b}: Demand-side management strategies	–	√	–
X_{3c}: Assessment of energy-related social impact	–	–	√
Y-Axis: Adopting Lifecycle Thinking			
Y_1: Operational energy performance			
Y_{1a}: Predictive studies	√	–	–
Y_{1b}: Post-construction audit/post-occupancy evaluation	–	√	–
Y_2: Embodied energy and carbon			
Y_{2a}: Design for “cradle-to-gate”	–	√	–
Y_{2b}: Design for “cradle-to-grave”	–	√	–
Y_{2c}: Design for “cradle-to-cradle”	–	–	√
Y_3: Lifecycle assessment		–	
Y_{3a}: Building material and construction component scale	–	√	–
Y_{3b}: Building scale	–	–	√
Y_{3c}: District scale	–	–	√
Y_4: Lifecycle costing	–	–	√
Z-Axis: Accommodating Risks and Uncertainties			
Z_1: Steady-state modelling	√	–	–
Z_2: Adoption of standards beyond statutory minima	–	√	–
Z_3: Design for adaptive capacity		–	
Z_{3a}: Design for resilience to overheating	√	–	–
Z_{3b}: Design for flexibility	√	–	–
Z_4: Advanced future-oriented analysis			
Z_{4a}: Dynamic building performance evaluation	–	√	–
Z_{4b}: Stochastic modelling of future overheating risk	–	√	–
Z_{4c}: Use of futures techniques	–	–	√

Key √: unfeasible, reasonably feasible, or feasible (based on the category).

Moreover, the empirical findings suggest that exploration of future-proofing is often limited to design approaches that demonstrate minimal consideration of long-term impacts, particularly for mainstream housing developments. This tradition achieves exemplary “green” buildings, focusing on financial considerations with low operational energy using analysis from steady-state models (Interviews 1–14).

5.1. Transferable Design Approaches from the X-Axis: Coverage of Sustainability Issues

Most of the design approaches under this axis represent established practices, which can be replicated easily in new housing developments. These include:

- Capital cost assessment (X_{1a});
- Cost-effectiveness analysis (X_{1b});
- The hierarchical approach to low-energy design (X_2); and
- The provision of sustainability information and education (X_{3a}).

Conventional building design has focused predominantly on financial viability of the preferred building solutions with *capital (upfront) cost assessments* (X_{1a}), using established methods for evaluating the "value for money" or "return on investment". Interviewees 8 to10 refer to *CEA* (X_{1b}) as a tool used by developers and design teams to appraise the cost of a portfolio of building solutions against the generation or saving of carbon emissions. It adopts a common metric (monetary value) and the decision is based on finding the alternative (building solution) with the least cost; however, the project that exhibits the best financial return is not necessarily the best option for the environment.

Moving on to environmental consideration, a common approach expressed by all 14 respondents was the "*hierarchical*" or "*fabric first*" approach (X_2). This refers to applying cost-effective energy efficiency measures to achieve demand reduction first, as the "low-hanging fruit", and, thereafter, use Low or Zero Carbon technologies (LZCs) to cover the residual energy load. Fabric energy efficiency discourages the use of microgeneration technologies as a first priority and, in principle, the greater the energy efficiency, the lower the scale of LZCs that has to be provided (Interviews 3–10). Prioritising energy efficiency improvements seeks to reduce energy demand for heating and cooling through enhancing the thermal performance of the building envelope. In the UK, this hierarchical approach represents an integral part of the Government's current definition and approach to achieve zero-carbon homes by 2016, and the wider strategy for achieving an 80% carbon emissions reduction by 2050 [21,57]. There is, however, a threshold beyond which additional energy efficiency measures are no longer cost-effective and the use of LZCs might be more viable, thus, renewable energy systems and energy efficiency solutions should be designed in combination (Interview 9).

The *provision of sustainability information and education* (X_{3a}) refers to wider city strategies implemented at the local-level affecting the energy design and occupancy phases. Enhancing skills and raising awareness refers to both the industry actors involved (e.g., building professionals, construction workers) and the local residents with the aim of promoting low-carbon lifestyles and drive behavioural change. Examples include (Interviews 1–14):

- Establishing energy service companies and/or multi-utility companies run by local communities, as part of the industry's servitisation process;
- Setting up educational centres providing training and information;
- Running marketing campaigns at city- or project-levels; and
- Launching financial incentives for reducing energy consumption via individual or team (neighbourhood) competitions.

As shown in Table 5, the use of *financial incentives* (X_{1c}) for energy efficiency or LZCs is expected to be adopted more extensively in the UK, in light of the existing policy framework. Examples are the already established Feed-In Tariffs (FIT), Renewable Heat Incentive (RHI) and the recently-launched Green Deal, even though this is for existing properties. All 14 interviewees acknowledged that occupants have a rather limited influence on the selection of building solutions but the energy design should be able to drive their behaviour towards lower consumption patterns. Interviewee 12 stated that "*this is due to the fund relationship between energy systems and the way occupants interact with them*". *Demand-Side Management (DSM) strategies* (X_{3b}) involve the installation of building management systems that display, measure, manage and compare occupants' energy consumption patterns. Examples are:

- Control systems, such as displays and monitoring sensors;
- Individual metering and separate billing of energy uses; *i.e.*, space heating, hot water, electricity; and
- Smart meters.

Interviewees 3 and 4 mentioned that DSM strategies with real-time feedback and dynamic pricing capabilities are expected to be deployed in the UK given that they are readily available in the UK. This is due to the national smart grid functionality being one of the most advanced and proactive in Europe, where smart meters are required to be rolled out across all households by 2019 [58]. Lastly, the 14 respondents agreed that there are currently no established methods for *assessing the social impacts* of the energy-related building solutions (X_{3c}); hence, it is unlikely to expect their use in conventional construction practice.

5.2. Transferable Design Approaches from the Y-Axis: Adopting Lifecycle Thinking

Throughout the interviews, assessment of the operational energy performance emerged as the baseline for adopting lifecycle thinking. It is a key focal point for building performance evaluation, as the operational stage determines substantially the total energy consumption. The use of predictive studies (Y_{1a}) is a design approach that has already been established in mainstream UK practice. These are based on historical data and modelling to project a building's energy performance. Interviewee 4 claims that "*with advances in DSM strategies and use of Soft Landings, Post-Construction Audit (PCA) and Post-Occupancy Evaluation (POE) studies could also become reasonably feasible to transfer to conventional construction*". This can help building professionals to validate the design intent and bridge the gap between design and actual performance (Y_{1b}).

Table 5 reveals that it is reasonably feasible to adopt design approaches that account for embodied energy and carbon. *Embodied energy* (MJ/kg material) constitutes approximately 15%–25% of a building's total lifecycle energy [39,59,60]. *Embodied carbon* (kg CO_2 and/or CO_{2e} per kg or m^3 material) is the resultant emissions from all the energy-related activities during the following phases of the lifecycle [18,22,61]:

1. Construction:
    - "cradle-to-gate" (or "cradle-to-factory-gate"), which includes emissions from mining, raw materials extraction, processing and manufacturing;
    - "cradle-to-site", which adds emissions from the transportation of materials; and
    - "cradle-to-end-of-construction", which adds emissions from assembly on-site and other construction activities.
2. Refurbishment: emissions from maintenance and/or component replacements.
3. Decommissioning: emissions from deconstruction, demolition, and/or disposal.

The respondents acknowledged that progress towards zero-carbon housing will reduce operational carbon; hence, the significance of embodied carbon will increase relative to the total. In addition, improving operational energy performance may involve the use of materials, components, and energy systems that increase embodied carbon. For interviewees 11–14, embodied energy also becomes contentious, when refurbishment, rebuild and/or demolition activities are undertaken as it has implications for the wastage of energy as well as social implications. This is because demolition is considered more energy-intensive compared to refurbishment strategies, as it releases large amounts of embodied energy as waste energy.

The analysis of the responses emphasised that "cradle-to-grave" and "cradle-to-cradle" processes are difficult to quantify. Indeed, recently, embodied carbon databases and standards are usually quoted as "cradle-to-gate" and manufacturers are starting to include "cradle-to-gate" data for their building products through environmental labelling schemes [18,22,60–63]. The "cradle-to-gate" stage contributes around 50% of the total embodied energy and carbon with associated methods and tools offering a simpler and quicker comparison between design options [64]. The majority of the interviewees referred to the Inventory of Carbon and Energy (ICE) database and the BRE Green Guide as an open source carbon accounting tool for assessing the embodied carbon from "cradle-to-grave" (Y_{2b}), thus showing the potential for further promoting its use in UK construction. The interviewees, however, stated that it is currently unfeasible to expect comprehensive application of design approaches for "cradle-to-cradle" (Y_{2c}). This is mainly due a lack of databases and user-friendly assessment methodologies.

It is likely to be unfeasible to replicate the use of *LCA studies* in conventional UK construction. Of the three LCA scales presented in Table 5, *building material and construction component* (Y_{3a}), *building* (Y_{3b}), and *district* (Y_{3c}), the first is the most readily transferable to new domestic buildings, since it is the least costly, time-consuming and data-intensive option (Interviews 1–14). Interviewees 3, 4 and 7 agreed that LCA-based tools are currently available in the UK market; however, there are key barriers that inhibit the application of rigorous LCAs, particularly at the building (Y_{3b}) and district (Y_{3c}) scales. These barriers are also reinforced in existing literature and seminal studies on LCA and include [27,28,30,40,61,65]:

- The need for large datasets;
- Unavailability of the input data needed;
- Complexities or uncertainties regarding the system boundaries, choice of impact categories, and assumptions;

- Complicated calculations and the industry's lack of knowledge of and experience in methodologies and software tools;
- Non-comparable results generated by a range of LCA tools;
- Credibility in interpreting the results;
- High costs of the expertise and time required;
- Clients' resistance and a generally low demand for LCA amongst building designers; and
- The lack of legal requirements and incentives.

The feasibility analysis also suggests that the use of LCA will be adopted widely only when it is required by the local authorities or when developers recognise the benefit of undertaking such studies. As Interviewee 4 explained:

> *In mainstream design teams, each consultant has defined tasks, which follow simple procedures based around intermediate deadlines (planning applications, design stages, etc.), which may not fit well within the wider lifecycle-oriented studies and joined up comprehensive future-proofing approaches.*

To encourage the use of LCA in the UK, the following opportunities were suggested (Interviews 1–14):

- Simplifying input-data collection by determining sources of uncertainties and assumptions, thus decreasing costs and time for the assessment;
- Developing more accurate reference values;
- Developing multiple versions of tools ranging in complexity (and accuracy) so as to be suitable to the needs of a wider spectrum of users, such as: (i) those who drive change (e.g., central or local governments; and (ii) those who should meet the regulatory requirements (e.g., developers, contractors, construction companies, property managers, and suppliers); and
- Combining LCA with LCC tools.

There is the need to mainstream stakeholder-based LCA tools to the UK practice. Such tools enable the generation of information in various formats to build consensus, especially when integrated planning is pursued. At present, this can be reasonably applied at the building material and construction component scale and will help to address the needs of multiple stakeholders in environmental decision-making [66]. In addition, as comprehensive LCAs are burdensome, the simplification of tools to increase their uptake is also suggested; once users become more experienced, more rigorous approaches can be introduced. As none of the interviewees makes detailed use of LCC for the energy design (Y_4) in their everyday practice, it would be unfeasible to propose its widespread adoption in mainstream practice.

5.3. Transferable Design Approaches from the Z-Axis: Accommodating Risks and Uncertainties

Steady-state models, such as the Standard Assessment Procedure (SAP) are common-place in UK mainstream construction (Z_1). SAP is the Government's calculation methodology for assessing the energy and carbon performance demonstrating compliance with Part L and the energy credits of the CSH [67]. A step further towards comprehensive future-proofing is the *adoption of standards beyond statutory minima* (Z_2) that encourage developers and contractors to seek voluntarily to outperform minimum standards and be one step ahead of Building Regulations for the dwelling energy design. This practically means the adoption of CSH certification above Level 4. Interviewee 11 revealed that it is reasonably feasible for conventional practice to go beyond Building Regulations, since:

> *Fabric Energy Efficiency Standard (FEES) helps us to achieve Code Level 4 simply with energy efficiency measures. So we do the best that we can in the fabric and any of the renewable technologies to meet the zero-carbon target can be added on in the future when they become more cost-effective.*

The issue of adaptive capacity (Z_3) was discussed under two main design approaches: *design for resilience to overheating* (Z_{3a}), and *design for flexibility* (Z_{3b}). Designs that are difficult to adapt may lead to buildings that need to undergo costly refurbishments, be demolished, or remain vacant with the associated negative environmental and socio-economic impacts.

To increase resilience, there are established building adaptation strategies, most of them passive design techniques that address summertime overheating and minimise the need for mechanical cooling (Z_{3a}). Although cost-effective and practical to install, they are not yet routinely used in the energy design (Interviews 1–14). These include: solar shading devices (e.g., louvres, blinds, and shutters); thermal mass; insulation; and natural ventilation using the stack effect, incorporating night-time cooling. Mainstreaming these design approaches to the UK practice can help to achieve adaptation and mitigation simultaneously. Nevertheless, interviews 6 and 7 brought up the impact of heavyweight construction on embodied energy. Materials such as brick, concrete or stone, provides high thermal mass leading to thermal comfort without mechanical cooling, compared to lightweight materials, such as timber or plasterboards [68,69]. This results in lower operational energy and running costs but in expense of higher embodied energy. Embodied energy and thermal mass are conflicting properties. Lightweight construction has low embodied carbon but limited thermal mass, thus making the structure vulnerable to the risk of overheating. Conversely, materials with high thermal mass (e.g., brick and concrete) help to reduce variation in the internal temperature profile by providing "inertia" against external temperature fluctuations, but may be higher in embodied carbon [70,71]. At present, innovation in materials science has led to the launch of low embodied carbon alternatives to brick and concrete, such as rammed earth and unfired clay blocks [70]. Interviewee 14 stated, however, that:

> *Adaptation strategies cannot be executed properly until design teams understand the impact of overheating on the energy design and the interaction between occupants, the building fabric, and the indoor and outdoor environments*.

In contrast to resilience, flexibility is the ability to accommodate and successfully adapt to changes in a dynamic environment. Flexibility helps to avoid "lock-in" phenomena that can lead to obsolescence or disruptive refurbishments (Interview 1). According to Interviewee 4:

> *Designing buildings that can be upgraded with minimal disruption reduces the construction energy required and prevents the loss of embodied energy due to demolition or deconstruction.*

Hence, flexibility refers to the extent to which the design is convertible and/or expandable so that it can be reconfigured easily to accommodate change in relation to:

- *Technological innovation* in building materials, components, and energy systems, which includes:
    - Space for energy storage at individual buildings and on-site (especially for solar technologies);
    - Photovoltaic (PV)-ready roof;
    - District heating-ready designs;
    - “Fuel agnostic” district heating networks; and
    - Smart facades via adaptive response systems.
- *Changing needs and behaviours* of both present (“within-use”) and future (“across-use”) occupants’, thus enabling intergenerational and intragenerational equity, which refers to:
    - Home-office for multi-purpose space to accommodate new working and living patterns;
    - “Lifetime Homes” standard; and
    - “Building for Life” standard.

Interviewees 8 and 10 consider the “Lifetime Homes” and “Building for Life” standards as future-proofed design approaches, even though not strictly energy-related. These tools can help to avoid energy-intensive alterations by maximising utility and facilitating the process of upgrade or refurbishment. Lifetime Homes was established in the mid-1990s and contains a set of 16 design criteria for achieving inclusivity, accessibility, adaptability, sustainability, and good value in order to meet the existing and changing needs of households, including elderly or disabled people [72]. Building for Life was established in 2002, and comprises a set of 20 criteria categorised in four themes: environment and community; character; streets, parking and pedestrianisation; and design and construction [73]. This standard also focuses at the neighbourhood level to consider social well-being and quality of life and promotes “best-practice” dwelling design. The interviewees agreed that the transferability of these standards to mainstream construction is feasible, as these methodologies are user-friendly and cost-effective when they are taken into account from the outset (Interviews 1–14).

A key point of discussion was whether steady state models (e.g., SAP) are sufficiently accurate or whether more advanced simulation models would be better able to predict a building’s energy performance. In the face of uncertainty, it is also important to select robust building solutions that remain “fit-for-purpose” under a range of future scenarios (Interview 12). Three types of *advanced future-oriented analysis* were raised during the interviews, namely: *dynamic building performance evaluation* (Z_{4a}), *stochastic modelling of future overheating risk* (Z_{4b}), and *use of futures techniques* (Z_{4c}).

Dynamic building performance evaluation (Z_{4a}) is a more sophisticated approach to future-proof new developments which could be reasonably feasible to transfer. However, as long as SAP remains a steady-state model, it will be difficult to incentivise widespread adoption of dynamic modelling as this increases the costs and expertise required (Interviews 1–7). Dynamic simulation is more complex using numerical methods to model, for instance, the effect of the thermal mass on the total energy performance (Interview 7). Dynamic modelling should be complemented with sensitivity analysis to assess the reliability of design parameters (Interviews 6 and 7). Examples of established dynamic modelling tools for building energy performance are: TAS, EnergyPlus, IES, Ecotect, ESPr, and DOE [74].

As climate change exacerbates the complexities inherent in long-term projections, research has focused on the development of *stochastic weather data representative of future temperatures*, which can then be integrated into building thermal simulations (either steady-state or dynamic) to accommodate uncertainty, especially since no climate model can provide a single definite answer to what the future will be [75]. All 14 interviewees agreed that it is reasonably feasible to use stochastic models for assessing the risk of overheating in new housing developments (Z_{4b}), thus representing a shift from current deterministic models. In contrast to a single forecast, stochastic modelling provides a range of possible outcomes with the associated levels of probability. At present, probabilistic future climate projections can be integrated into building energy performance with the UK Climate Projections (UKCP09) programme. This is the leading provider of probabilistic regional climate data in the UK currently in its fifth edition and based on a methodology developed by the Met Office. The projections are presented in three different future scenarios representing High, Medium and Low GHG emissions for the years 2020, 2050, and 2080, respectively. UKCP09 can be used to simulate how buildings respond to future higher summertime temperatures, thus allowing the uncertainty concerning the future climate to be incorporated into long-term design decision-making [76,77]. UKCP09 provides a range of possible future temperatures, presented in mean seasonal or monthly values, which are then fed into algorithms to create hourly future weather files (reference years). An example of an established algorithm is the PROMETHEUS methodology developed by the University of Exeter [78–80]. The expertise and knowledge gained by using the UKCP09 projections offers great potential to incorporate probabilistic weather files in the overheating analysis. This might require some extra costs or expertise; however, it offers the benefit of a more accurate analysis. Interviewee 6 argues that unless user-friendly; there will be a small uptake for probabilistic climate projections. This is aligned with a report by ZCH stating that improved and simplified calculations for assessing overheating that incorporate the UKCP09 projections should be developed for SAP calculations, which would be adopted more easily by the UK practice [81].

Uncertainty reduces the value of long-term forecasts; although there is no exact duration by when forecasts become unreliable. There is no such thing as "perfect models" and long-term forecasts can be notoriously erroneous [14]. Even if models were perfectly accurate, uncertainty would not disappear, as decisions made today may turn out to be ill-adapted to future circumstances due to extreme events or "unknown unknowns" [82]. Hence, it is erroneous to base decisions on simply extrapolating current outcomes into the long-term future and ways need to be found to accommodate uncertainty [14,83]. *Futures techniques* can be used to identify high-impact and uncertain events by exploring a spectrum of plausible futures for adaptive management [84,85]. The Foresight Horizon Scanning Centre identifies a portfolio of 24 futures techniques [84] and according to Hinnells *et al.* ([71], p. 1008): "*the future is unknowable but can be explored through scenario planning and sensitivity analysis*". Scenario planning, in particular, helps to identify (predictable and/or uncertain) future trends and drivers, bring together different perspectives, challenge current thinking, and aid strategy formulation that will be robust in any future [15]. Nevertheless, the application of futures techniques to new housing developments is currently considered unfeasible, as the analysis of the interview responses reveals that currently tools, such as Scenario Planning, have only been applied to a limited extent in the built environment and energy design. This is because this family of methods have not been developed with sustainability or low-energy construction in mind but have become increasingly dominant in business strategy and long-term planning of products, processes, and industrial sectors [86]. As Interviewee 2 argued, some partial forms of scenario planning and backcasting exercises are carried out in the UK practice particularly during stakeholder workshops, design reviews and public consultations in masterplanning. Their use and value will need to be developed further through application in demonstration projects.

6. Practical Application: Enhancing the Code for Sustainable Homes

This section presents a high-level gap analysis of the CSH with the aim to integrate eight future-proofed design approaches into the "Energy and CO_2 Emissions" category. This seeks to provide useful guidance and promote more widespread future-proofed energy design, drawing on the "feasible" and "reasonably feasible" transferable findings to fill the gaps in the existing assessment criteria, as presented in Table 5. According to the interview responses, these include:

- DSM strategies (X_{3b});
- PCAs and POEs (Y_{1b});
- Embodied energy and carbon considerations from "cradle-to-gate" (Y_{2a}) and/or "cradle-to-grave" (Y_{2b});
- LCA at building material and construction component scale (Y_{3a});
- Design for resilience to overheating (Z_{3a});
- Design for flexibility (Z_{3b});
- Dynamic building performance evaluation (Z_{4a}); and
- Stochastic analysis of future overheating risk (Z_{4b}).

As mentioned in Section 4, the deployment of DSM strategies (X_{3b}) is growing as a means to generate accurate data for effective monitoring. The Code would benefit from the introduction of assessment criteria in relation to the use of displays, individual metering of energy uses, and smart metering, with the latter already mandated by the Government for installation in all homes by 2019. DSM strategies will incentivise the use of actual (instead of predicted) consumption data and improve the accuracy of assessing the payback and performance of the initial building solutions selected.

A shortfall of the CSH, as with most certification schemes, is that ratings are based on the design intent, which does not always match the actual energy performance. Incorporating assessment criteria that encourage monitoring indicators for PCA and POE studies (Y_{1b}) can provide the basis against which actual energy performance can be systematically monitored after construction and during operation; thereby, making the Code more robust to addressing the "performance gap" (Interviews 1–7). This shift could be achieved, for instance, by adopting a three-stage assessment in the Code's methodology (Interview 3): design; post-construction; and operation, with the latter being monitored continuously for systematic feedback on the performance level achieved, for example between two and five years.

There is no clear assessment criterion to account for embodied energy and carbon in the CSH and lifecycle thinking is expressed mainly via the reduction of carbon emissions during the operational stage. This is due to the UK's definition of "zero-carbon" not covering embodied carbon [54,61,87,88]. Nevertheless, environmental labelling of materials is intended for use with whole building assessment tools, such as BREEAM and CSH [89]. In particular, the Code incorporates the BRE Green Guide under the "Materials" (MAT1 mandatory) category, which influences the selection of building solutions from "cradle-to-grave" (Y_{2b}). It is, therefore, suggested that embodied energy and carbon become an additional and explicit assessment criterion under the "Energy and CO_2 emissions" category. This would improve coverage of the full lifecycle energy consumption and, hence, influence the construction, refurbishment, and end-of-life strategies. As detailed embodied carbon considerations from "cradle-to-grave" and "cradle-to-cradle" are difficult to incorporate due to a lack of data, expertise and/or high costs, credits could at least be awarded for:

- Giving preference to low embodied carbon materials and components, especially for the most commonly-used ones (e.g., use of timber instead of concrete, local procurement, or building elements that could be re-used or recycled); and
- Using accredited databases for the embodied energy and carbon of construction materials from "cradle-to-gate" (Y_{2a}), such as the ICE.

Lastly, it would be unfeasible to integrate comprehensive LCA into the CSH. Nevertheless, the tool would benefit from the adoption of LCA criteria for developers and contactors who use even elementary forms of LCA to assess the environmental impact of the most commonly-used materials and construction components should gain extra points in the assessment (Y_{3a}).

A further gap in the Code's assessment criteria is the absence of criteria to encourage incorporating resilience (Z_{3a}) and flexibility (Z_{3b}) into the design. The focus of the CSH is predominantly on mitigation and currently there are no adaptation-related criteria. Interviewee 12 suggested that appropriate performance indicators that account for climate change adaptation in BEAMs need further development. Hence, it is suggested that the CSH should integrate assessment criteria that account for passive design techniques, such as shading strategies, high thermal mass and natural ventilation. The design should also allow for adaptation, conversion and extension to accommodate new technologies when they become cost-effective (e.g., PV-ready roofs, space for energy storage) and occupants' future needs and behaviours. At present, the "Home-Office" criterion represents the Code's only future-proofed criterion, which may encourage internal space flexibility to accommodate change in working and living patterns (Table 3). The tool also applies the Lifetime Homes standard under the "Health and Well Being" category, but not for the energy-related aspects. To further enhance flexibility in the energy design, the CSH could combine the "Home-Office" criterion with energy-related aspects of the Lifetime Homes and Building for Life assessment methodologies [72,73].

The CSH uses SAP; hence, it does not consider fully the dynamic characteristics of buildings. The use of dynamic models, such as IES VE, is suggested by interviewees 6 and 7 because it would assess more comprehensively the total energy performance (Z_{4a}). There is also the potential to standardise stochastic modelling for overheating analysis and encourage its consideration at an early design stage (Interview 5). Hence, criteria to encourage the use of UKCP09 probabilistic weather files to inform overheating analysis (Z_{4b}) could be incorporated into the CSH.

7. Concluding Discussion

This paper has sought to promote future-proofing as a concept to facilitate the selection of robust building solutions that will be "fit-for-purpose" under a diversity of future scenarios, especially in situations of high uncertainty. The objective of this study was to identify transferable approaches to inform the energy design of domestic buildings in the UK and explore their integration into the current regulatory framework and established policy mechanisms in the UK. Hence, these findings are expected to be of direct benefit for practitioners, professional bodies and/or innovation agencies, such as Building Research Establishment (BRE), Chartered Institute of Building Services Engineering (CIBSE), Royal Institute of British Architects (RIBA) or the Technology Strategy Board (TSB). This study has also shown that legislation is the key driver for a change in industry mindsets towards future-proofing with direct implications for those responsible for setting regulatory requirements and policy standards, such as the Department for Communities and Local Government (DCLG) and the Department of Energy and Climate Change (DECC). From a wide range of tools and policy mechanisms the CSH was selected as the best platform on which to integrate the design approaches that are "feasible" and "reasonably feasible", due to its applicability to new domestic buildings and established position in support of the UK's zero-carbon policy agenda.

Overall, the empirical research has shown that with the use of mostly existing and proven design approaches, the energy solutions can be future-proofed to a higher degree than what is currently met in mainstream practice. This can be simply achieved by planning ahead and thinking differently about site and building design. Other measures can be implemented in the future, if and when climate predictions and/or uncertainties materialise. This means that a low-energy design does not necessarily constitute a future-proofed one, but represents a baseline from which to develop further this concept, which is more comprehensive. Future-proofing can be achieved by combining three strands of literature in a novel manner, which include:

- *Coverage of SD issues (X-axis)*: financial considerations; environmental considerations; and socio-economic considerations;
- *Adoption of lifecycle thinking (Y-axis)*: operational energy performance; embodied energy and carbon; and the use of LCA and LCC tools; and
- *Accommodating risks and uncertainties (Z-axis)*: steady-state modelling; adoption of standards beyond statutory minima; design for adaptive capacity where building elements are designed for resilience and flexibility; and advanced future-oriented analysis.

Fourteen interviews conducted with building practitioners revealed that not all of the future-proofed design approaches explored in literature are currently scalable due to the high cost of the studies, inadequate data, lack of experience, and shortage of specialised-resources required for their use. An assessment of what can be practically transferred to new housing developments in the UK was carried out to identify ones that are the "feasible" and/or "reasonably feasible" to transfer. These include:

- "*feasible*": capital cost assessment (X_{1a}); CEA (X_{1b}); hierarchical approach to low-energy design (X_2); sustainability information and education (X_{3a}); predictive studies for operational energy performance (Y_{1a}); steady-state modelling (Z_1); design for resilience to overheating (Z_{3a}); and design for flexibility (Z_{3b}); and
- "*reasonably feasible*": financial incentives (X_{1c}); DSM strategies (X_{3b}); building performance evaluation with PCA and POE studies (Y_{1b}); embodied energy and carbon considerations from "cradle-to-gate" (Y_{2a}) and "cradle-to-grave" (Y_{2b}); LCA at building material and construction

component scale (Y_{3a}); adoption of standards beyond statutory minima (Z_2); dynamic building performance evaluation (Z_{4a}); and stochastic modelling of future overheating risk (Z_{4b}).

Although lifecycle thinking is conceptually simple, it is challenging to be applied more rigorously to conventional practice due to data requirements and high costs. Embodied energy is increasingly considered in design decision-making to foster a whole life approach to carbon emissions assessment. However, assessment methodologies for "cradle-to-grave" (Y_{2b}) and/or "cradle-to-cradle" (Y_{2c}) should become mainstreamed. LCA (Y_{3a}) and LCC (Y_4) studies are expected to be applied mostly at the building material, construction component, or energy systems scale rather than the building or district scales.

There is significant cultural resistance that renders unfeasible the application of: assessment of energy-related social impacts (X_{3a}); design for "cradle-to-cradle" (Y_{2c}); LCA at building (Y_{3b}) and district (Y_{3c}) scales; and use of futures techniques (Z_{4c}). A substantial section of the UK construction industry still barely meets existing regulatory requirements, impeding efforts towards sustainability, in general, and future-proofing, in particular [36,40,41]. A significant culture change in the industry is, therefore, required to shift to considering the whole lifecycle of housing developments through integrated design teams and procurement practices, new skills, and innovation [90]. Given the gap in future-proofed design approaches and to upgrade the role of the CSH tool in support of future-proofed design, the "Energy and CO_2 Emissions" category would benefit from the incorporation of the following assessment criteria:

- DSM strategies (X_{3b});
- PCAs and POEs (Y_{1b});
- Embodied energy and carbon considerations from "cradle-to-gate" (Y_{2a}) and/or "cradle-to-grave" (Y_{2b});
- LCA at building material and construction component scale (Y_{3a});
- Design for resilience to overheating (Z_{3a});
- Design for flexibility (Z_{3b});
- Dynamic building performance evaluation (Z_{4a}); and
- Stochastic analysis of future overheating risk (Z_{4b}).

Although there is ongoing research interest to reconcile climate change adaptation with mitigation strategies [90,91]; in practice, these two terms are not clearly understood or differentiated. At present, the construction industry prioritises mitigation strategies, which are well-established and their cost is substantially less than any adaptation measures. Hence, many buildings are designed to only just meet national guidance on overheating [18]. Since climate change has energy implications for the dwelling fabric performance and occupants' behaviour, the need to design for adaptation today requires thermal modelling using future climate predictions [18]. This is not yet fully acknowledged amongst building professionals and needs to be given greater prominence [5,48,49,76,91].

Further research should focus on developing further specific databases, weighting factors, performance indicators and assessment criteria, if the proposed design approaches are to be integrated fully into the CSH and other BEAMs (simulation tools and/or certification schemes, such as BREEAM. As the use of BEAMs illustrates the choices, aspirations and values of the designers employing them, consideration of the transferable future-proofed design approaches could potentially lead to the development of new or refinement of existing tools, such as carbon calculators, modelling software or assessment methods. Nevertheless, it is important to state that the use of rating tools will not necessarily lead to more future-proofed designs. Building rating tools cover a wide range of sustainability criteria but when a "tick-box" approach is adopted, limited improvement in actual performance may be achieved. The criticism is not necessarily an objection to a set of clear assessment criteria against which to assess performance. Rather, it is about the focus being on satisfying the criteria at the lowest possible costs and not selecting the most sustainable solutions [48,49]. This criticism is also supported by Interviewee 4, who complained that:

> *It is more about the cheapest way of achieving the Code Levels required by the Councils rather than the best way of doing it*.

Interviewee 2, however, concludes that the CSH is probably the most comprehensive assessment method currently used in domestic buildings in England, Wales and Northern Ireland and despite its "tick-box" approach, "*it does pose significant challenges to design teams in terms of reaching the targets*". Future-proofing should be integrated into widely-used tools, such as the CSH, as most commercial developers are unlikely to commission studies and assessments or pay for additional services that are not absolutely required for granting planning permission. In this regard, she asserts that:

> *The CSH is a policy instrument and a nationally-accepted tool, thus integrating future-proofing into its methodology would be of much greater importance than a client-developed or bespoke voluntary industry tool.*

An area for future work would be the identification of barriers behind the currently "unfeasible" future-proofed design approaches (Table 5) and investigation of practical means for mainstreaming and incentivising their uptake. There is also the potential for applying future-proofing to the energy design of other typologies, such as commercial, public, educational, or industrial buildings. In addition, the research, though carried out with a holistic view of sustainability, has concentrated on only one aspect; *i.e.*, energy. A systems approach to sustainability in the built environment requires consideration of, *inter alia*, energy, water, sewage or wastewater, and waste. Apart from new construction, which was the scope of this research, there is significant potential to apply the transferable design approaches to retrofit projects. Arguably, transforming the existing housing stock should be central to any national decarbonisation strategy, as around 75%–85% of buildings in use today are expected to be standing in 2050 and new buildings comprise a relative small share. If the construction industry is to successfully address the ambitious 80% carbon reduction target by 2050, then it will be imperative that actions address existing dwellings. This entails a detailed understanding of how energy retrofit projects work in practice and the barriers to driving low-energy behaviours. There is also significant potential to apply the proposed conceptual model in the emerging context of standardising PCA and POE studies. The examples of Soft Landings and Building Information Modelling (BIM) framework are a starting point in an effort to address the "performance gap" and ensure design quality in mainstream construction.

The above considerations bring up the issue of skills and capabilities in the construction sector and the practitioners' ability to create sustainable, low-energy buildings that account for the long-term. Detailed briefing, integrated design teams and good communication, supported by accurate calculations are essential to facilitate the necessary cultural shifts to meet the transition to future-proofed low-energy design. Some final specific opportunities pertaining to sustainability that could be key aspects for future work and particularly useful to explore include:

- Examining further the relationship between adopting lifecycle thinking (*Y*-axis) and accommodating risks and uncertainties (*Z*-axis). This could entail the combination of futures techniques with LCA tools to explore a spectrum of plausible futures in a more systematic and quantitative way, which might work more effectively than purely qualitative approaches. This could be achieved by incorporating dynamic methods (e.g., sensitivity analysis and scenario forecasting, statistical probability distribution, decision trees, Monte Carlo simulations, and Bayesian statistics) and/or qualitative methods (e.g., data quality indicators) into the LCA methodology;
- Proposing the business case for future-proofing by quantifying the cost of potential future upgrades or demolition. This would show that future-proofed buildings can grant better financing conditions, as they are less risky and have higher value (easier to sell and achieving higher prices);
- Understanding the cost implications of integrating future-proofed design approaches into financial incentives, such as the FIT, RHI, and the Green Deal;
- Suggesting the integration of future-proofed design approaches into other policy instruments, such as Energy Performance Certificates (EPCs) granted for buildings that are sold, built or rented in order to comply with the EPBD.

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Conflicts of Interest

The authors declare no conflicts of interest.

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