Towards Active Buildings: rating grid-servicing buildings

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Abstract

In most industrialized countries, the buildings sector is the largest contributor to energy consumption and associated carbon emissions. These emissions can be reduced by a combination of energy efficiency and the use of building integrated renewables. Additionally, either singularly or as a group, buildings can provide energy network services by timing their use and production of energy. Such grid-aware or grid-responsive buildings have been termed Active Buildings. The recent UK Government investment of £36m in the Active Building Centre is a demonstration that such buildings are of considerable interest. One problem with the concept, however, is that there is no clear definition of Active Buildings, nor a building code to design or research against. Here we develop and test an initial novel code, called ABCode1. It is based on the need to encourage: (i) the minimisation of energy consumption; (ii) building-integrated generation; (iii) the provision of grid services; and (iv) the minimisation of embodied carbon. For grid services, we find that a lack of a precise, quantifiable measure, or definition, of such services means that for the time being, theoretical hours of autonomy of the building is the most reasonable proxy for these services within such a code.

Practical Application: Buildings have a special role in the transition to a sustainable energy infrastructure and a decarbonised society. They can become an active part of energy networks by leveraging strategies and technologies that are already available, but are not yet articulated in an integrated scheme that facilitates their uptake at scale. This work provides a review of the issues and opportunities, and introduces a practical framework aimed at helping designers and researchers study and deliver such buildings, and in particular the buildings that will form the exemplars in the first wave of Active Buildings.

Keywords: Active Buildings, grid-responsive buildings, defornocere, design standards, ABCode1

1 Introduction

The building sector is responsible for 40% of final energy consumption* and 36% of greenhouse gas (GHG) emissions in Europe.[1] With approximately 80% of final energy consumption in buildings being supplied by fossil fuels such as coal, oil and natural gas,[2] the building sector clearly needs to change its relationship with the energy-services sector.

To minimise CO_2 emissions in the EU, the Energy Performance of Buildings Directive (EPBD)[3] states that buildings should have a 'very high energy performance' (page 153/18), with renewable energy playing a fundamental role. By producing renewable energy, buildings have the potential to

* Final energy consumption refers to 'the energy commodities delivered for energy purposes to industry, transport, households, services including public services, agriculture, forestry and fisheries, including the consumption of electricity and heat by the energy branch for electricity and heat production and including losses of electricity and heat in distribution and transmission'.[102]

actively contribute to the vision for clean energy. Going further, thanks to the integration of storage systems and the connectivity to electric vehicles, buildings could be more flexible components of the energy system, adapting to the needs of the electricity grid through load shifting and peak shavings.[4] However, there have been difficulties materialising these aspirations due to ambiguity of definitions,[5,6] and most implementations have neglected the potential buildings have to support the grid.[7]

In the UK, the Government has an aspiration to halve the energy use of new buildings by 2030,[8†] and Parliament now requires net zero GHG emissions by 2050,[9] as advised by the Committee on Climate Change.[10] Determining how to deliver high-performing buildings that support the wider energy network and achieve significant CO_2 emission reductions is thus critical.

To define such a pathway, this paper explores the concept of Active Buildings (ABs), which have been portrayed as 'power stations' thanks to their ability to generate, store and release energy in response to their own demand and the needs of the local grid.[11] Promoted as part of the SPECIFIC project, the concept was subsequently demonstrated in buildings such as the Active Classroom and Active Office.[12] Nowadays, ABs are advertised as buildings that "support the wider energy system by intelligently integrating renewable energy technologies for heat, power and transport".[13] This was not an isolated effort, but part of an emerging field that recognises the potential for buildings to support the energy infrastructure, with similar initiatives in the US under the so-called Grid-interactive Efficient Buildings,[14] among others.

However, it is questionable how lessons learned from pioneering experiences can be upscaled to transform the construction and energy sectors, to meet the societal and environmental agendas. Equally important, any barriers preventing a timely transition must be acknowledged, along with potential solutions. To these ends, the UK Research and Innovation[15] established the Active Building Centre (ABC) consortium.

This paper explores a way forward for the AB concept. Section 2 sets the background to the relationship between buildings and energy networks by reviewing related concepts and discussing how buildings can promote a net positive environmental impact. Section 3 discusses the issues of grid-supporting buildings, and indicates why there has been limited progress to date. Section 4 introduces a novel approach to ABs around an Active Building Code to enable progress while helping gather the evidence required to inform future developments. Formulated as an *active* code itself (one that may change in the future based on such evidence), an initial proposition, called ABCode1, is presented to explore how previous gaps could be bridged in a way relevant to all stakeholders, together with the evaluation of twenty demonstrators. Lastly, Section 6 discusses future perspectives and Section 7 summarises the conclusions of this study.

2 Background to buildings and energy networks

This section presents the background to the relationship between buildings and energy networks. The review focuses on existing building design approaches, definitions and ways in which buildings could support energy networks to enable a more positive environmental impact.

2.1 Building design approaches

Approaches to designing buildings with a net positive environmental impact have been typically concerned with the following aspects:

† Targets vary per constituent country and sector, and progress is routinely monitored.

- **Energy.** The excessive use of natural resources drives the design and the goal is to minimise energy demand.
- **Environmental impact.** Environmental degradation drives the design and the goal is to promote sustainability (commonly expressed via GHG emissions).
- **Cost.** The goal is to ensure that capital investments offer an acceptable return period.

A complementary aspect is how energy is delivered to the building, either with or without a connection to an external energy network (Figure 1). There are buildings that meet their energy demand through on-site energy generation only (autarkic, autonomous or grid-isolated buildings) and others that import at least some of the required energy from an energy network (grid-connected buildings[‡]). *Autarkic* buildings can be viewed as a 'pure' example of zero-energy buildings, evoking the ideal of pre-industrial buildings.[6] This appears to be a viable approach only if the energy demand of the building is controlled carefully and its generation and storage systems are meticulously sized.[16,17] Although advantages include no utility bills and increased levels of resilience in regions with a poor infrastructure, it can lead to over-engineering, hence becoming an unattractive solution financially. Most buildings in countries with developed economies are therefore connected to energy networks (Figure 1).

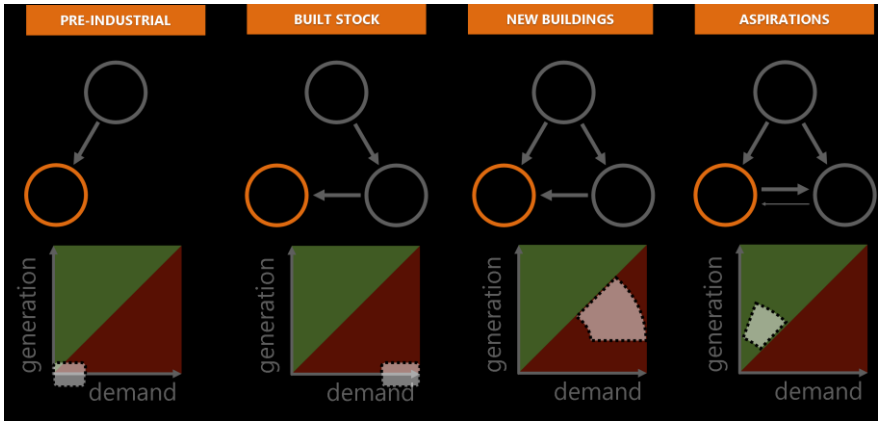


Figure 1: Overview of the relationship between the building (bld), environment (env) and energy networks (e-net) and the corresponding mapping between energy demand and generation of buildings (with a dashed line) over time. The green area indicates net positive buildings. The red area signifies buildings that consume more energy than they produce.

There is an aspiration to transition to low-energy buildings, mainly through a tighter control of energy demand. Taken further, *net zero* energy buildings produce as much energy as they consume and *net positive* (or *net plus*) energy buildings have a net surplus than can be exported to the grid. Currently, the construction and energy sectors pay attention to low, net zero and net positive *carbon* buildings, which address both operational and embodied carbon.[18–20§]

[‡] Use of the word 'grid' varies in the literature, from a generic term that could represent any energy network (for example electrical, gas, district heating) to a specific reference to the power grid (electricity exclusively). Here, we favoured 'energy networks' for the former use and 'grid' for the latter.

[§] To achieve net-zero carbon buildings, emissions must be reduced across the whole life cycle, which means tackling both the emissions caused by a building's operational energy use (operational carbon) and the emissions caused by 'everything else', such as the manufacturing of materials, transportation to site, onsite construction, refurbishment and disposal processes (embodied carbon). As in many contexts, carbon is used as short-hand for 'greenhouse gases', quantified in carbon-dioxide *equivalent* emissions (CO_2e).

2.2 Regulations, standards and definitions

There are numerous building regulations and standards worldwide that aim to deal with the energy and environmental performance of buildings,[6,21] with dozens of definitions being suggested or investigated in relevant studies (see representative examples in Supplemental Material). However, definitions are not necessarily accompanied by a calculation method, therefore hindering their adoption and practical application.[22,23] Examples of commercially successful initiatives include BREEAM (UK, 1990), Passivhaus (Germany, 1991) and LEED (US, 1998).

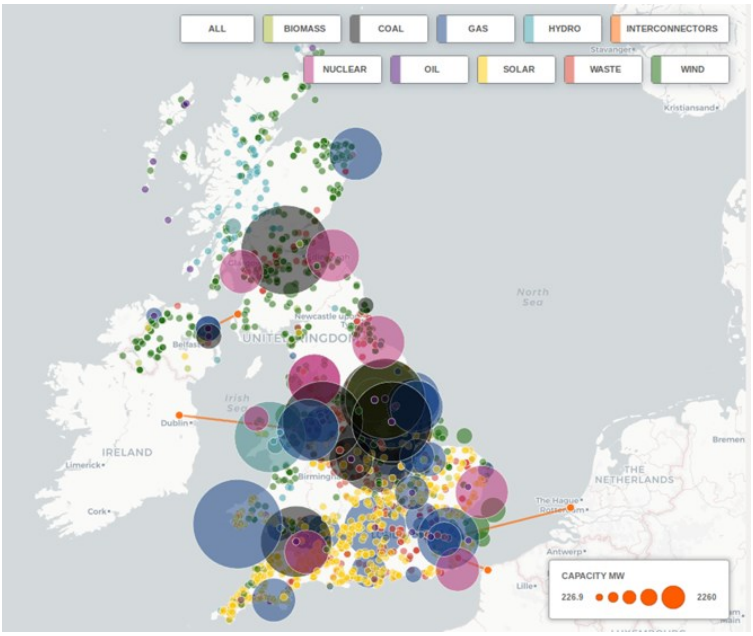
Torcellini et al.[24] draw the attention to why definitions and their performance targets matter by recalling that (i) they help designers make informed design decisions and that (ii) they set a clear goal for stakeholders, which can be methodically attained during the design process. For example, this is the case for the Passivhaus Standard, which sets 15 $kWh \cdot m^{-2} \cdot a^{-1}$ as the maximum allowable value for heating energy demand and 120 $kWh \cdot m^{-2} \cdot a^{-1}$ for primary energy demand. Parkin, Herrera and Coley[5] investigated how different definitions related to net zero energy and carbon constrain the design space for architects, finding that zero-carbon targets offer more design options than zero-energy ones. As an example, a low-energy building with a *total* energy demand of just 40 $kWh \cdot m^{-2} \cdot a^{-1}$ needs to be under 3 storeys if expected to run on PV panels on its own roof. This points to the need to create a realistic rating standard which incorporates buildings that are not necessarily net zero energy, and that is most likely based on a scale, rather than a simple pass/fail philosophy unless we are to overly constrain the design space.

The lack of a uniform definition of high-performing buildings as well as of a global design standard has resulted in an ambiguity in the definition of performance targets, and hence of design spaces. Studies analysing regulatory frameworks and definitions identified this as a source of confusion for stakeholders and an insurmountable issue when attempting to cross-validate results from different rating systems. Sartori, Napolitano and Voss[22] questioned what aspects need to be considered when designing net zero energy buildings (Figure 2). For example, grid interaction is one of these aspects but this is commonly neglected in practice due to challenges such as the spatial variability in the carbon intensity of electricity generation (Figure 3) or its technology-sensitive cost (Figure 4).

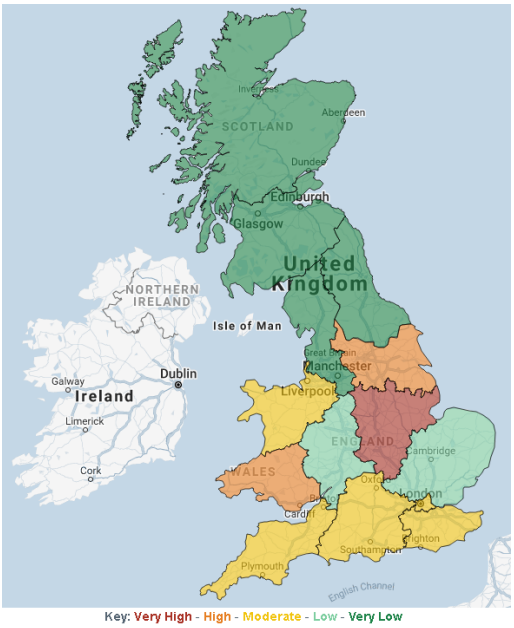
Focusing on metrics, in the UK, whole-life carbon strategies are becoming increasingly important given the Parliament's net-zero emissions target by 2050,[9] similarly to other countries.[20,25,26] Section 2.3 discusses how buildings can also support the decarbonisation of energy networks to promote a net positive environmental impact of both the construction and energy sectors.

SYSTEM'S BOUNDARY	WEIGHTING SYSTEM	BALANCE SYSTEM	TEMPORAL MATCH	MEASUREMENT & VERIFICATION
flows across	normalise units	normalise balance	boosting impact	rating compliance
Physical building(s) & site	**Metrics** $kWh_{(P/F)}$, CO_2e, £, ...	**Balancing period** instant – lifetime	**Load matching** stress on generation	**M & V** is it doable?
Balance what goes in	**Symmetry** bidirectional?	**Type** loads, exports,...	**Grid interaction** stress on imports	**Rating system** compliance tolerance
Boundary comparability	**Accounting** value over time	**Agenda** hard-set requirements	**Whole-systems** transport	**Enabling learning** introspection

Figure 2: Framework for the definition of net-zero energy buildings (diagram based on the work by Sartori et al.[22]).



a) Overview of UK's electricity generation plants.[27] Image under CC BY-NC-ND 4.0 International license, by Rosamund Pearce.



b) Snapshot of the carbon intensity of Great Britain's electricity generation.[28] Estimated values at 2020-03-09 18:30; carbon intensity groups defined by $gCO2 \cdot kWh^{-1}$ as Very High (360+), High (260-359), Moderate (160-259), Low (60-159) and Very Low (0-59)). Basemap by GeoBasis-DE/BKG (©2009), Google, Inst. Geogr. Nacional.

Figure 3: Overview of UK's electricity generation plants and resulting regional carbon intensity.

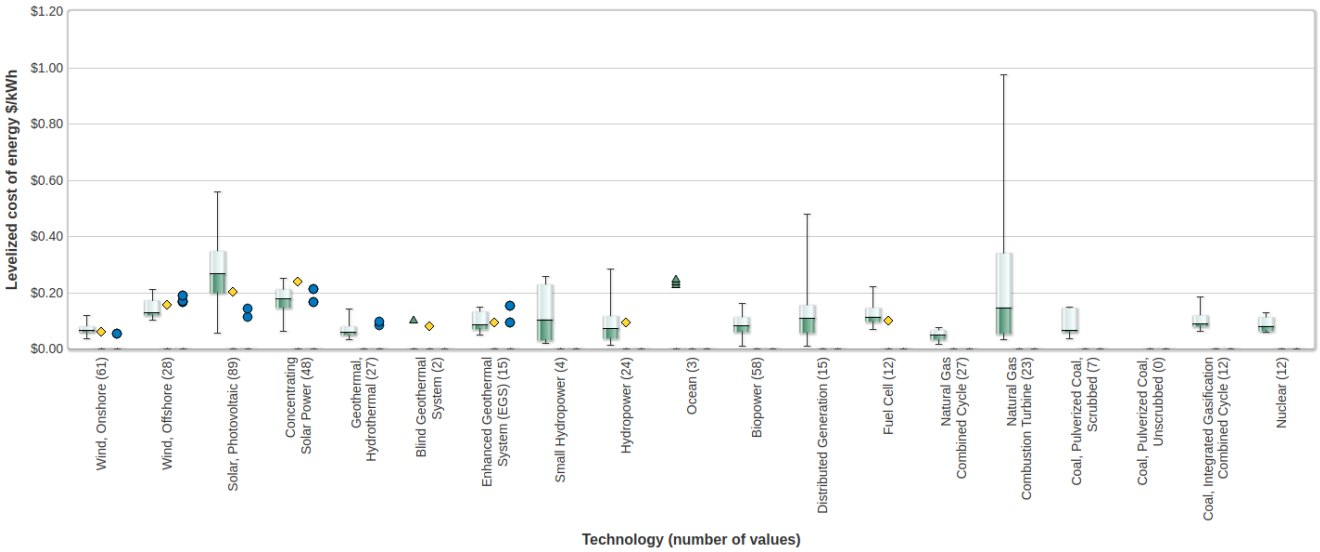


Figure 4: Levelized cost of energy** for renewable sources.[29††]

** The levelized cost of energy (LCOE) is a metric that describes the overall cost of energy generation system over its lifetime (e.g. $ or £) per unit of energy generated (e.g. kWh). If the LCOE is lower than the price of energy purchased from the grid the system is economically advantageous for its owner.

†† Open Energy Information collects data from external publications and reports standardised summaries (see details in source). The number next to each technology in the x-axis indicates the number of reports considered for the estimates.

2.3 The needs of energy networks

Although there are several energy networks (e.g. electricity, gas), past discussions around grid-servicing buildings have focused almost exclusively on the electricity grid arguably due to its ubiquity and versatility to meet energy needs in buildings. As a whole, the UK's electricity network will need to overcome three main challenges to transition to a low-carbon economy: the retirement of existing generators, the rapid installation of new low-carbon and renewable generators, and a significant increase in electricity demand.[30] This is being translated into three core themes: decarbonisation, decentralisation and digitalisation.[31] At the same time, electricity demand is expected to increase further and rapidly as space heating and road transport shift to electricity.[10,32]

New low-carbon and renewable generators are not simply drop-in replacements because many are non-dispatchable by themselves (generation depends on weather conditions rather than the energy demanded) and their characteristics allow for a decentralised implementation in the network.[33] This means that a reinforced and extended network is needed to support the connection of these new generators as well as new operational challenges to balance the network to deliver a consistent energy supply (voltage and frequency)[34] that is still flexible to adapt to changes in demand.[31] The "duck-shaped" net-load curve illustrates the need for flexibility in energy demand to reduce temporal imbalances (Figure 5).[35] Here, buildings could reduce, shift and flatten their energy demand through demand-side management strategies (Figure 6), giving rise to a synergetic relationship with the grid and opening new market opportunities (Table 1).

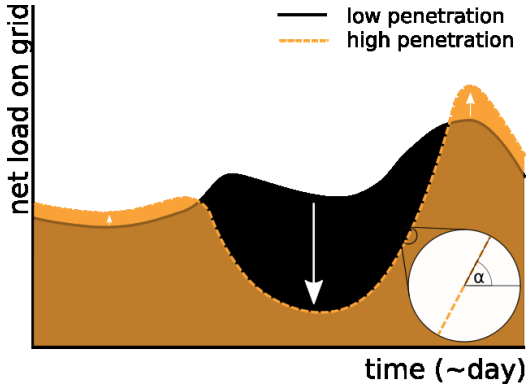


Figure 5: Example load curves illustrating grid instability due to high penetration of solar energy production *without* energy storage systems compared to a low-penetration baseline based on California ISO.[35] The two main issues to the high-penetration scenario are the risk of over-generation and rapid changes in net load (depicted by slope α of the tangent line).

Diamonds indicates US Department of Energy estimates, circles those form National Renewable Energy Laboratory Annual Technology Baseline and triangles indicate point estimates.

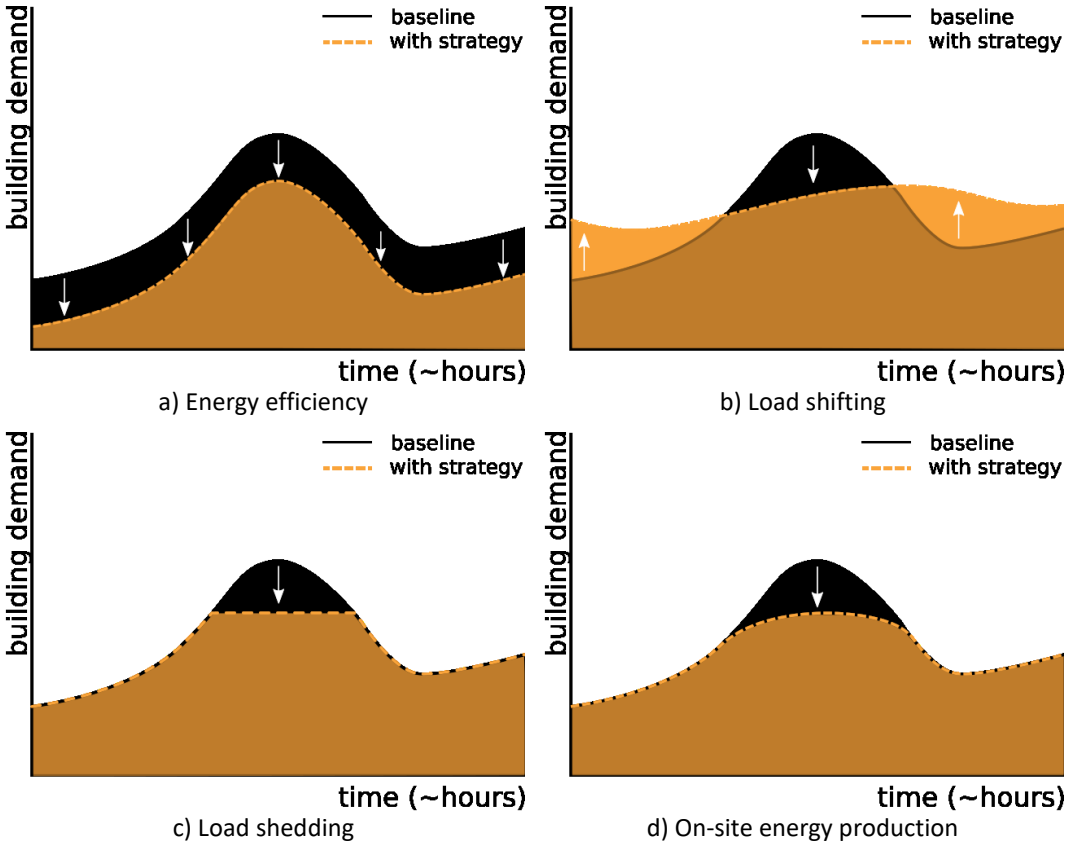


Figure 6: Overview of selected demand-side management strategies and their influence on the final energy demand of the building.

Grid-supporting buildings represent a great opportunity for the flexibility of the network thanks to their potential to store and release their self-produced energy in a timely manner (Table 1), accelerating the transition to a low-carbon grid.[36] Buildings can also decentralise energy supply by shifting from passive users to active parts of the energy infrastructure. This can enhance energy quality and security[37] for example by offering faster responses to the changing levels of renewable generation or reducing transmission losses.[38] By developing a dynamic, two-way interaction with the grid (aspirations in Figure 1) and integrating electric vehicles, buildings can support the energy network while meeting occupant needs and minimising their carbon footprint.[39] Despite their potential and critical role in smart energy networks,[40] their role as active agents in the grid is often overlooked in definitions of low-energy and low-carbon buildings, and undefined in relevant design standards (Sections 2.1 and 2.2).

A key consideration for grid-supporting buildings is how to articulate their potential contributions in the market. Considering the privatized UK market with (1) generators, (2) transmission network, (3) distribution network and (4) consumers, suppliers typically purchase energy in the wholesale market to generators to then sell it in the retail one to consumers.[41] The advent of on-site small-scale distributed generators has been translated in limited retail market access via savings in purchased energy or in payments through specific schemes such as Feed-In Tariffs,[42] but the new possibilities associated with net-zero carbon energy networks have not yet been realised.[43] This has been partly addressed with the transition of the Distribution Network Operators (the owners of the distribution network) to the so-called Distribution System Operators, a name that reflects the new role they can play balancing this part of the grid thanks to innovations such as smart-metering.[41] This opens

the door to new relationships with those consumers that could proactively support the network, which benefits the whole system as the grid features a tight integration of all its elements. However, possibilities have not yet converged to solutions that values and encourages grid-supporting contributions from such consumers (including access to the ancillary services market).[43,44]

Although consumers might be able to offer some grid-supporting services in the context of distribution networks, further potential can be unlocked if several join under the same umbrella in energy aggregators.[45] The benefits include not only the possibility of enhanced management of its members (trading energy internally) or benefitting from the economy of scales (shared generation and storage infrastructure), but also being perceived as virtual power plants by the wider energy network thanks to their overall size. As such, they are better positioned to meet the technical requirements needed for system operators to rely on them as grid-balancing agents in the transmission network.[45,46] This, for instance, is already a route to market in the UK, where the National Grid Energy System Operator welcomes their participation to *some* grid-balancing services as part of its privatised energy system.[34] However, to encourage their participation in the network, further efforts are also needed here in terms of regulatory framework (access to wholesale and ancillary services markets), advanced metering infrastructure (similarly to the decentralisation and digitalisation challenges for system operators) and improvements of generation forecasts (central in distributed low-carbon networks).[31,44,47]

Table 1: Summary of the "Potential Grid Services Provided by Demand-Side Management in Buildings" identified in the US Department of Energy overview on grid-interactive efficient buildings;[14] besides the characteristics of the US grid, potential market size evaluation considers current valuations by their regional transmission organisations and independent systems operators into large (L), moderate (M) and small (S).

Grid-service	**Comment and potential benefits**		**Strategies at building level**				
		Potential market size in the US	Efficiency	Load Shedding	Load Shifting	Load Modulation	Generation
Energy generation	Reduces running costs of existing power plants.	L	•	•			•
Generation capacity	Avoids or reduces investment in new power plants and associated running costs.	L	•	•	•		•
Contingency reserve	Avoids or reduces costs associated with the backup generation to meet demand in case of supply disruptions.	M		•	•		
Frequency regulation	This addresses the need of the grid to operate within statutory frequency limits, which fluctuates with changes in demanded power, among other events. Potential benefits include reductions in cost associated with modulation.	S				•	
Ramping rate	This relates to rapid changes in power demand like that illustrated in Figure 5. Benefits include savings in bringing generators online (start-up) or offline (shutdown) and associated costs.	S				•	•
Non-wires alternatives	This refers to avoided or deferred investments in power infrastructure by recognising least-cost actions may be elsewhere in the demand-supply chain (e.g. influencing power demand needs through better efficiency or load shifting).	M	•	•	•		•
Voltage support	This addresses the need of the grid to operate within statutory voltage limits, which fluctuates with the characteristics of power demand. Supporting voltage regulation could help avoiding capital costs associated with control equipment, maintenance and operation.	S				•	

3 Discussion

This section discusses how buildings could help decarbonise energy networks. It considers how associated challenges may jeopardise benefits for energy networks and the environment and the roles building design standards and their rating systems play in these regards.

3.1 Buildings and energy networks: needs and challenges

Integrating renewables into the wider energy networks is required for a cleaner electricity sector across Europe,[1] with energy generation at building level being one of the most promising opportunities.[48] The EPBD[3] dictates the use of energy from renewable sources, but it does not mandate its share in the final energy consumption. In this regard, the Buildings Performance Institute Europe suggests that the minimum share of energy from renewable sources in final energy consumption should be 50–90%[49] and even encourages energy positive buildings.[50] Achieving the latter may, however, restrict designs to single-storey buildings[51] — indeed most energy positive ones are — even though the building type plays a pivotal role in this regard (for example, warehouses with minimal plug loads compared to hospitals).[52]

To reduce their carbon footprint but also their bills, consumers are often encouraged to participate in the electricity market by becoming 'prosumers': that is, producers and consumers of renewable energy.[53] This is reinforced by the fact that PV systems are already at grid parity[54] in several European countries such as Italy[55] or Germany,[56] while others like the UK are expected to follow next.[57‡‡] Maximising self-consumption can also improve the stability of the grid by flattening the curve of net energy demand, if generation naturally aligns with demand or if energy storage systems mediate interactions.[4] In addition, reductions in peak demand help avoid investments in infrastructure that would have been needed otherwise (the net effect of existing buildings is to increase the stress on the grid).[58] With the extensive electrification of transport and heating being fundamental to achieving a net zero economy by 2050,[10] the use of electric vehicles and heat pumps are anticipated to be rapidly expanded, thus further stressing local electrical networks.

Buildings can provide energy flexibility through distributed online energy storage systems,[59] which could increase the resilience of the network at the expense of a more complex peer-to-peer communication infrastructure. Here, Weckx et al.[38] advocate for a combination of local and centralised strategies to balance the cost-effectiveness of solutions. Energy aggregators are argued to be best placed to provide flexibility and facilitate the uptake of grid-supporting buildings because (1) the economies of scale and scopes makes them cost-effective; (2) they can collect the evidence of how distributed systems work in practice to allow the market converge to superior solutions; (3) they can facilitate at present access to the retail, wholesale and ancillary services markets.[45,60] At the same time, innovations in the way systems operators balance the grid mean that they will be able to *operate* a distributed low-carbon grid thanks to digitalisation, which in the UK is expected to happen by 2025[31] (although the annual carbon intensity may not drop to net-zero until 2030 in the best-case scenario[61]). Hence, the technical barriers for the adoption of grid-supporting buildings are already being removed.

From a building design perspective, these discussions presume data are available to judge how ABs could interact with the local network, but at design stage this is unlikely to be the case.[62–65] Overall, quantifying the impact of building strategies on the energy network is difficult. This is because (i) it depends on the characteristics of the local grid and (ii), there is insufficient evidence given that such strategies have been adopted in pioneering projects in which retailers did not necessarily have a valuation scheme in place. In the US, the Department of Energy is supporting the research of "Grid-interactive Efficient Buildings" to explore opportunities and identify potential market sizes (Table 1 and Supplemental Material).[14,64,66–68] These are but illustrative estimates because the local features of networks, policy, regulations and economic schemes will ultimately influence value streams.

3.2 Existing standards and rating systems: what is missing?

3.2.1 Design stage

A net-zero carbon economy needs buildings with reduced whole-life carbon emissions.[20] Operational carbon is already being influenced by building regulations,[69] which try to reduce the energy demand of at least some energy end-uses. This is typically based on a notional building of the same size and shape as the actual building, an approach criticised for accepting poor design decisions and overall performance, as reductions in emissions are quantified relative to the building's particular shape and size.[70–72] An alternative is given by the Passivhaus Standard, which influences many more building design aspects by establishing absolute performance goals.[73] Yet, the risk entailed by a pass-or-fail certification

‡‡ The total installed cost‡‡ of solar PVs has dropped[103] to approximately £1,000·kW^{-1} and the electricity retail price for the residential sector is expected to range between £0.155·kWh^{-1} and £0.195·kWh^{-1} in the 2020s[104], making grid parity attainable if other influential factors[105] remain the same.

philosophy hinders a broader adoption of the standard,[74] while others like BREEAM or LEED have opted for non-binary rating systems that are more flexible. Moreover, renewable energy generation is fundamental to offset operational carbon while energy networks decarbonise.[19] Taking into consideration the wider network interaction is, however, necessary to ensure buildings play a supportive role according to the state of the grid,[75] this needing information that is unlikely to be known at the early design stages[62] and that is expected to change over time. Unfortunately, design standards do not currently support community-based concepts where prosumers trade energy.[76]

A crucial omission from current building standards is embodied carbon.[§§] However, the landscape is changing rapidly, following improvements in embodied carbon analysis tools and the increasing pressure to pursue net-zero carbon buildings.[20,77,78] Thus, any new building code aiming to drive a move to net-zero carbon buildings — such as the one we propose here (see Section 4) — must include embodied carbon.

3.2.2 In-use stage

At this stage the key variable is energy because it can be measured directly and is the proxy for operational carbon once construction has been completed. The only predictions available at design stage in countries like the UK come from design-based compliance procedures, which do not intend to predict actual in-use energy performance (believing that is the case leads to a prediction gap where in-use buildings perform demonstrably worse than what compliance modelling may imply due to key differences in scope and assumptions).[79–81] Additional efforts are required to estimate in-use energy performance during the design stages to be then followed up by POE to ensure performance targets are met or lessons are being learned for future projects.[82] However these are activities rarely pursued in practice[18,83,84] and, when they are, it is not surprising to discover a significant performance gap.[80]

To achieve net zero operational carbon, the UK House of Commons advocates the use of mandatory operational ratings to promote energy savings.[79] In the UK, the Energy Performance Certificates (EPCs) include the mandatory design compliance ratings that, like the previous, do not intend to estimate in-use performance, this sparking the general criticism of such certificates.[80] On the contrary, the Display Energy Certificates (DECs) do target operational ratings, but they are only a requirement for some public buildings.

Overall, the literature often suggests making the Building Regulations more stringent to improve operational performance.[85] A notorious example is set by the Passivhaus approach given not only its headline requirements but also by its compulsory quality assurance procedure at all stages that minimises potential performance gaps between intended and operational energy use.[85] Considering the influence stakeholders such as building owners and occupants have in operational energy use, even in Passivhaus, standards need to provide incentives for well-performing buildings,[86] and/or penalties for not meeting performance targets.[87] These aspects are however missing in the majority of the building regulations of European countries[88] and building standards such as BREEAM and LEED.

4 ABCode: a proposition for an Active Building Code

As buildings ought to have a more dynamic relationship with the energy sector, a way of evaluating such a relationship is required. The lack of a definition of what an active building is seriously curtails the ability to do research on such buildings, as the problem space is unbounded, and particularly for teams to compare results. However, as low carbon networks evolve and network-supporting technologies mature, any rating system will need to evolve as well: not only will active buildings need to be active

[§§] Some rating systems, such as BREEAM, award credits for life cycle assessment, but this is a relatively minor component.

and responsive, but any active building code will need to be active and responsive too. Hence, we define: *an Active Building is one that was rated as 'active' by the Active Building Code at the time the building was designed and built* (RIBA Stage 6 or similar). This then raises the question: what should the Active Building Code include? This section is an initial proposition, called ABCode1 (Figure 7).

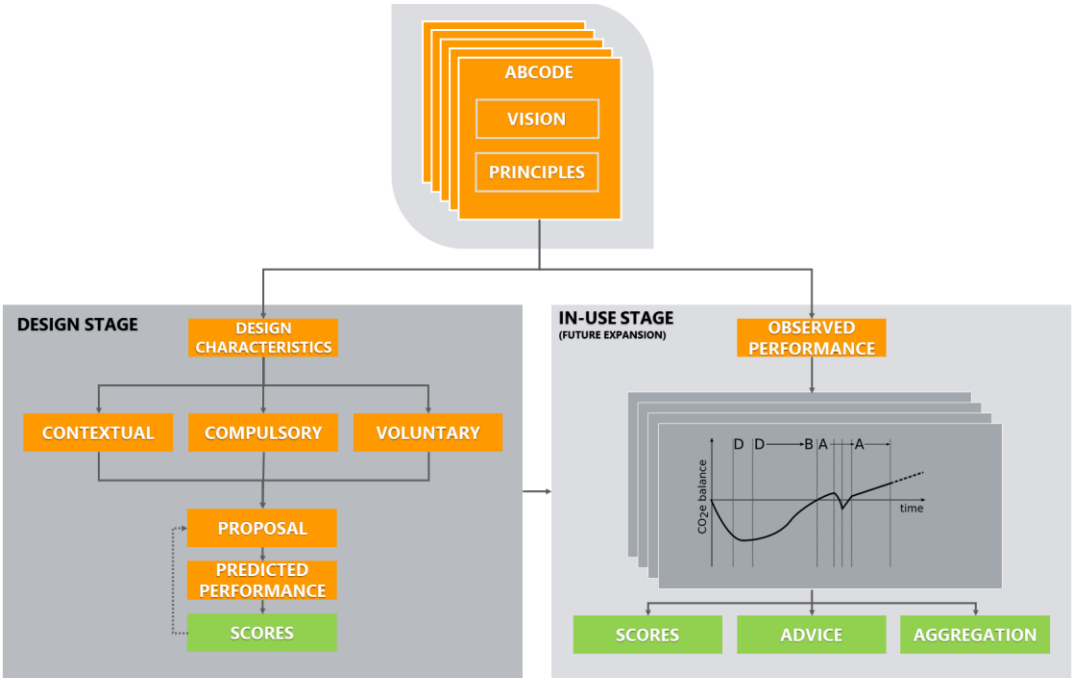


Figure 7: Overview of the Active Building Code. Its first iteration (ABCode1) focuses on the design stage (left).

4.1 Vision and principles

The vision for the ABCode is to deliver at scale buildings that 'do no harm' according to the *non-defornocere* principle.[89] Accordingly, we suggest ABs abide by the following *general principles*:

1. **Whole-life sustainability:** ABs recognise that the fundamental challenge for the construction industry is to deliver buildings that satisfy the needs of occupants in a way that is cognisant of the climate emergency. Given challenges in addressing whole-life sustainability, the performance targets for ABs at present are reducing both operational and embodied carbon (whole-life carbon).
2. **Energy network support:** ABs also recognise that buildings can enhance the performance of wider energy networks, which requires a whole energy systems thinking at different scales. For example, how ABs support the power grid, transport, heat and low-carbon gas networks at building, community and city scales by producing, storing and releasing renewable energy. This is expressed by the notion of 'buildings as energy infrastructure'.

4.2 Design standard

ABs need to provide a clear pathway for impact in the building sector and thus need to make technical, economical, and environmental sense under the *non-defornocere* vision. In this initial proposition, the ABCode1 is a design standard for new buildings, either individual ones or from a development involving a single site and owner for the sake of simplicity. However, the general principle of energy network support may require the aggregation of several ABs in a community (see discussion in Section 4.4).

We propose the following *design principles* to implement the two general principles presented in Section 4.1 and inform how buildings should be designed, operated, maintained and demolished or recycled:

1. **Fabric-first approach.** This is key to reducing operational energy use, including a compulsory infiltration test.
2. **Low whole-life carbon.** Reducing embodied and operational carbon is essential.
3. **Energy efficiency.** Resources must be used rationally.
4. **Accountable performance.** There is a need for reporting energy performance to a central source.
5. **Energy capture.** Renewable energy systems like PVs must be prioritised.
6. **Energy flexibility and integration.** To support energy networks (Figure 6), strategies include passive storage of thermal energy in the building fabric (e.g. thermal mass or phase change materials); active storage of thermal energy (e.g. water tanks); and electrical energy storage (e.g. batteries). Energy can be distributed internally or traded externally, and energy storage systems can mediate these interactions to match supply and demand. Energy flexibility can be exploited to reduce the running costs and carbon footprint of buildings (e.g. reduce peak electrical demand at times where the carbon intensity of the grid is high), but also respond to the needs of energy networks (e.g. shift energy demand to support wider network infrastructure). Control systems can help deliver flexibility by supporting demand-response strategies (e.g. delay start on a washing machine). Given the difficulties in defining it in a meaningful and fair way, ABCode1 focuses on the provision of energy storage as a proxy for energy flexibility.

Design principles can be translated into specific *design characteristics*, which are divided into (Table 2):

- **Compulsory**, if they are imposed on every design (e.g. sub-metering);
- **Contextual**, if they are context-dependent (e.g. renewable energy generation capacity); and
- **Voluntary**, if they are optional (e.g. energy management system (EMS)).

Since accountability is a key principle for ABs, performance must be knowable to assist ABs in reducing a potential performance gap. A built-in monitoring platform should hence be developed to report operational energy use.

Table 2: Examples of the envisaged relationship between design principles and their influence on the suggested rating system. Labels correspond to the metrics of the rating system introduced in Table 3 (*).

Design principle	**Example characteristics**	**Design adoption**	**Influence on the rating system***
Fabric-first approach	Minimal thermal bridges	Voluntary	R
Low whole-life carbon	Use of recycled materials	Contextual	M
Energy efficiency	Best in class systems	Compulsory	R
Accountable performance	Sub-meters	Compulsory	$-$
Energy capture	PV panels	Contextual	P
Energy flexibility	Electrical/thermal storage	Contextual	X
Energy integration	EMS in a smart network	Voluntary	$-$

4.3 Rating system

A barrier to the broad dissemination of buildings that are certified to the Passivhaus Standard is the inherent insecurity of its pass-or-fail philosophy (Section 3.2). Hence, we propose a rating system similar to European energy labelling that considers the general principles of ABs. This is based on four metrics: embodied carbon; energy consumption; renewable energy production; and energy flexibility (Table 3). The intention of the ABCode is to balance permanent design aspects, which set the baseline for environmental performance, with the more ephemeral ones, which depend on the current needs of the energy network and technology available. Overall, these metrics rate ABs as consumers, producers and traders of energy and carbon. An overall performance value is computed as the weighted average of all metrics to express succinctly the relative merits of the design:

$$Overall\ value = w_M \cdot M_i + w_R \cdot R_i + w_P \cdot P_i + w_X \cdot X_i \quad (1)$$

where M_i, R_i, P_i and X_i are integers varying from 1 to 7 to express the labels of each metric (that is, of embodied carbon; energy consumption; renewable energy production; and energy flexibility, respectively) varying from A to G (Table 3), and w_M, w_R, w_P and w_X are the respective weights for each metric fluctuating between 0 and 1, subject to $w_M + w_R + w_P + w_X = 1$.

Table 3: The suggested rating system for assessing building performance during the design process. In all cases, m^2 refers to treated floor area as defined in the Passivhaus Standard. In the ABCode1, an Active Building (AB) is one that meets the specifications in labels A–F at the stage of practical completion (RIBA Stage 6 or similar). Label G captures any other case regardless of the performance attained (*).

Metric	Embodied carbon [$kgCO_2e \cdot m^{-2}$]	Energy required [$kWh \cdot m^{-2} \cdot a^{-1}$]	Renewable energy production [% of R]	Energy flexibility [hours]	Post-Occupancy Evaluation: contractual obligation to in-use review	Obligation to discuss scheme with representatives of local energy networks	Is the building considered an AB?
Label	M	R	P	X	-		
A	≤200	≤30	>100	>24	Yes	Yes	Yes
B	(200,300]	(30,60]	(80,100]	(12,24]	Yes	Yes	Yes
C	(300,400]	(60,95]	(60,80]	(6,12]	Yes	Yes	Yes
D	(400,450]	(95,125]	(40,60]	(3,6]	Yes	Yes	Yes
E	(450,600]	(125,155]	(20,40]	(1.5,3]	Yes	Yes	Yes
F	>600	>155	≤20	≤1.5	Yes	Yes	Yes
G	*	*	*	*	No	No	No

The weighted average is proposed for two reasons. Firstly, it provides an overall label that can be communicated easily (varying from A to G). Secondly, weights indicate where designers should invest effort in to achieve a better performance. For instance, weights could be used to encourage the adoption of novel strategies, such as those related to support energy networks. The following weights are proposed in ABCode1 to reflect the need to reduce operational energy consumption and carbon footprint whilst incentivising strategies to support energy networks: $\{w_M = 0.15;\ w_R = 0.50;\ w_P = 0.15;\ w_X = 0.20\}$. For example, if a building scores $\{M = \mathrm{D};\ R = \mathrm{B}; P = \mathrm{C}; X = \mathrm{E}\}$, this would translate into $\{M_i = 4;\ R_i = 2; P_i = 3; X_i = 5\}$ and consequently into an overall value of $0.15 \cdot 4 + 0.50 \cdot 2 + 0.15 \cdot 3 + 0.20 \cdot 5 = 3.05 \approx 3 \rightarrow \mathrm{C}$. These weights are but an initial proposal indicative of the current need to maximise the energy efficiency potential of buildings to minimise their energy demand, as a first step to achieving a net zero carbon economy.[19] The slightly higher weight of energy

flexibility compared to that of energy production illustrates how energy storage could be promoted over generation to help balance the grid and avoid the duck-shaped profiles depicted in Figure 5.

We propose that labels A–F are accompanied by a contractual obligation to as-built reviews for M and X (embodied carbon and energy flexibility) and in-use reviews for R and X (energy required and renewable energy production), with the latter being performed as part of a POE by the design team within the first three years of operation.[***]

In addition to POE, labels A–F require the design team to discusses with representatives of the local networks before sizing generation and storage systems. This encourages the design team to be aware of the local energy context so that the building design is adapted accordingly.

As a result, it is proposed that *Active Buildings are those meeting the ABCode1 criteria for labels* A–F*, at the time they are designed and built* (RIBA Stage 6 or similar). While the rating F does not affect performance (metrics are open-ended intervals), the ratings A–F and above require contractual obligations and discussions with representatives of the energy networks to encourage better buildings and gather the evidence needed to further develop ABs and their goals in the next years.

The individual values that correspond to labels A–F for each metric are displayed in Table 3, and explained next.

4.3.1 Embodied carbon (M)

ABCode1 considers as embodied carbon emissions all those that occur up to the point of practical completion (life cycle stages A1-A5 in EN15978[90]). Very few datasets report the embodied carbon of buildings and those who do draw values from different assessment methods, preventing cross-comparisons. To define the embodied carbon scale, the dataset of the Carbon Leadership Forum (CLF) was used, as this is an open, peer-reviewed dataset with a reasonably large number of samples ($n = 1{,}190$) with different building types.[91]

First, the empirical distribution of carbon intensity was divided into equally spaced quantiles (as many as there are labels in the scale) and numbers were rounded to the nearest multiple of 50 $kgCO_2e{\cdot}m^{-2}$ for usability. This makes each label equally challenging in practice. The scale is ambitious considering that current standard practices are estimated to entail about 800–1,000 $kgCO_2e{\cdot}m^{-2}$, but necessarily so to advance the delivery of whole-life net zero carbon buildings. Although the representativeness of the dataset for the building stock is unknown, the resulting scale is in agreement with current industry-led initiatives in the UK, and thus considered cognisant of the practical challenges that arise in the design and construction.[71,77,92] Particular ways to achieve a good score are not prescribed, but these will necessarily entail the efficient use of low-impact materials such as recycled or biogenic ones.

4.3.2 Energy required (R)

Energy required (life cycle stage B6 in EN15978) is favoured in ABCode1 to operational carbon intensity to avoid designing energy profligate buildings that passively benefit from an increasingly decarbonised energy network. Datasets reporting the total energy consumption of the building stock feature similar limitations. This is approached through the Display Energy Certificates[93] (DECs) database ($n = 357{,}392$), which contains a mix of commercial buildings: mainly schools ($n = 177{,}223$), offices ($n = 31{,}046$) and university campuses ($n = 26{,}982$). As with embodied carbon, how well this dataset represents the building stock is uncertain. Moreover, the database does not disclose location or year, which obstructs normalising energy consumption for instance based on weather. Although this dataset

[***] This is informed by guides such as the Government Soft Landings,[83] which advocates three years of POE to support stakeholders in aligning actual building performance with the targets set during the design process.

does not include dwellings, 'General Accommodation' buildings were considered as a first approximation.

To create the scale, the overall metered fuel and electricity use of buildings (kWh·m^{-2}·a^{-1}) was calculated, and its lowest half selected to incentivise low-energy buildings. Data was split linearly since this dataset is biased towards older buildings (the UK features one of the oldest building stocks in the world), while ABCode1 focuses on the design of new buildings. Lastly, data was rounded to the nearest multiple of 5 kWh·m^{-2}·a^{-1} for readability. The resulting first two categories of R also happen to reflect the three certification categories promoted in Passivhaus,[†††] which give a notion of how feasible these categories are in practice. Note that energy consumption is independent of renewable generation, although heat pumps (ambient heat) is considered as part of the energy efficiency measures of the building and thus counted in R rather than P.

4.3.3 Renewable energy production (P)

The metric to evaluate generation is derived from others quantifying energy as a proxy not only for carbon but also for the potential to alleviate stress in the local energy network. Aspirations for energy generation (heat and/or electricity) at a building scale vary substantially in the literature. Although domestic buildings have the potential to be net energy positive, this could be more challenging, and often not cost-effective, for other building types. Considering this and the lack of representative empirical datasets to inform values, the resulting scale for production expresses the ratio of the value for metric R (energy required). The advantage is that this definition encompasses all possibilities, from no generation (0%) to energy positive buildings (>100%). This is regardless of the temporal match between generation and consumption, because at present it is assumed that energy will be useful elsewhere in the energy network. Disadvantages include that the metric for R influences two aspects of the rating system and it does not differentiate building types at present.

4.3.4 Energy flexibility (X)

Despite the numerous ways available to express energy flexibility, it is unknown which ones should be used *in practice* given the lack of empirical evidence. It is still unclear what performance aspirations should be defined to account for the needs of the built environment and energy networks, and how they would influence the more permanent aspects of building design.

ABCode1 considers energy flexibility as the number of typical hours the building could run autonomously, theoretically, without demanding energy from the network or producing on-site energy (considering all forms of energy consumed in the building). Label A expresses a higher than 24-hour flexibility and label B signifies a flexibility within $(12{,}24]$, with each label then referring to a range that halves previous values. This has the advantage that it is comprehensible and suitable for early design stages because it is not directly linked to the needs of the local energy networks, which are likely unknown at such stages. Yet, it acts as a proxy for the actual flexibility buildings could demonstrate in practice.

What truly represents energy flexibility is in *the way* the stored energy and the building are used. This could be coordinated by (i) control systems[64] — including both the hardware (sensors, meters, actuators) and software (strategy, as informed by representatives of the energy networks) — and (ii) occupant behaviour. These aspects are envisioned as parts of a unified building-user system that governs the way in which energy is exchanged with the networks, but one that cannot be fully addressed until more information about the practicalities of ABs is gathered. Until then, the value of the X metric

[†††] Note however that the three limits, 60, 45 and 30 kWh·m^{-2}·a^{-1} for Passivhaus Classic, Plus and Premium, respectively are referred to Primary Energy Renewable, a country-specific indicator that describes how much renewable energy needs to be supplied to the grid to satisfy the final energy consumption of a building.

is merely a summary of the installed capacity, not prescribing particular building-user systems, nor metrics that value specific ways of supporting the local energy networks (Figure 6). As part of the POE process, evidence would be gathered to these ends.

The value for X is obtained from the annual energy consumption (from all sources and for all uses, including plug loads and domestic hot water) — hence the use of the term typical hours, as the consumption might be higher than typical in winter for example. As the building might use a variety of energy sources, it would only be theoretically autonomous for the given number of hours. This is in line with ABCode being applicable at an early stage, before any dynamic thermal model is created, hence heat stored in the fabric cannot be accounted for. However, it might be possible to include fabric storage in a simple heuristic manner in much the same way that the Passive House Planning Package (PHPP) considers thermal mass when discussing summertime overheating.[94] To avoid double counting, and because the temporal generation of any renewables at building level might not match the need for autonomy or useful contributions to the local network, only storage is considered in X, regardless of on-site generation.

ABCode1 focuses on short-term storage (hours) rather than the longer seasonal storage (months) given the uncertainty to establish general initial guidelines for a variety of new buildings types and the market readiness of long-term storage solutions at scale. Nevertheless, this aligns with the timescales at which most building-level grid-services are useful to the grid,[14] that is, from minutes to day(s).

4.4 Discussion

Future revisions of the code (ABCode2 etc.) could refine the rating system to reflect the performance achieved by demonstrator buildings, as well as the state-of-the-art in the building sector and energy network. For example, on-site renewable energy production might be useful at present for the UK power grid but, this might no longer be a desirable design strategy once a low-carbon grid is available, nor a crucial metric for the rating system. Since the ABCode is active itself, it could support such a transition, adjusting its design principles and rating system (scales and weights) to reflect the real needs of the built environment and energy networks.

The energy required (R) and the energy production (P) have been kept separate, yet P is expressed as a percentage of R and so they are clearly dependent. Alternatives would be to make them independent, thereby encouraging maximum generation regardless of the energy consumption of the building. This was disregarded, as for most buildings it is likely that $P < R$, possibly $P \ll R$, and it is likely to be more intuitive for the user to quantify energy generation as a percentage of energy use (even if some generated energy is exported). We feel that the alternative to make the reported metric simply *use* minus *generation*, would not be cognisant of the timeline of design, where energy minimisation occurs before considerations of generation, and often by different teams. It also possibly encourages energy profligate buildings. Here, the formulation of P as a percentage of R makes high scores for P unattainable in practice for high values of R and, conversely, the better the score for R the easier it becomes to achieve good P scores. Furthermore, by keeping R and P separate, and applying weights as we do, not only keeps two different aspects of building design (consumption and generation) separate but also the focus can be moved between the two in future versions of the code as needed by the current context.

As applied below, the ABCode is based on a single building. It is however likely that ABs will be developed as collectives of buildings. Within the collective, the buildings might well support each other and provide different active services, either grossly, or temporally, and it might well make sense to maximise these on some buildings and not others (for example PV generation). Hence, we propose that ABCode can be reported at either the single or collective level, but not both at the same time. The

reason for this is that allowing both has the potential to cause confusion, and the selective use of the labels. An example would be a collective that scored B from a mix of A and D buildings. It would be unreasonable for a developer or owner to simultaneously claim the collective was B, and that a particular building was an A, but by omission therefore suggest the D buildings were B.

Another issue is the use of generation or storage systems that cover more than the buildings being scored. For example, a district heating system might have been built to cover the heating needs of a new collective, yet have excess capacity and hence be plumbed into neighbouring pre-existing buildings. This excess might well not be serendipitous, in that, although the only reason for the creation of the district heating scheme was the new collective, it only made financial sense because it could sell excess to the older stock. Because of the temporal nature of demand, it might well be that the district heating system can only supply 50% of the annual demand of the new collective, yet in total it generates several times the annual demand of the new collective. We suggest that all generation of such a district heating scheme is counted as applying to the new collective (for the purpose of rating the collective with the ABCode). This is similar to the approach with electricity and net-zero energy buildings within an annual accountancy framework: all the electricity generated does not need to be used by the building in question, just an amount equal to that which it uses, with export at some times, and import at others.

It is not uncommon for buildings to be designed with an awareness of the future landscape. For example, including space for air conditioning to be added as the climate warms. With respect to ABs, one can imagine a similar approach, with buildings being designed so that PV or batteries would be particular easy to add. We feel though logical, any active-ready status would be too open to simple claims of “ready”. Therefore, such active-readiness should be encouraged, but not scored.

Although most will be interested in the overall score of the building, others will desire a more nuanced analysis. The approach laid out here automatically provides this in the form of the four metrics. For example, a building can either be described as a B, or as a $\mathrm{B}(\mathrm{A}, \mathrm{B}, \mathrm{D}, \mathrm{C})$. This will be particularly useful for those wanting to analyse why a building obtained a particular score, or to compare buildings. For those wanting the full detail, a score could be represented with the numerical values used via Table 3 as $\mathrm{B}(121, 36.4, 57.1, 6.4)$ (Figure 8). Given that the ABCode is dynamic to ensure its guidance and evaluation are consistent with the current landscape, the ratings of a building or a community would be linked to the applicable version of the ABCode at the time of their development, without subsequent iterations threatening the scores obtained in the past. Yet, the monitoring system that helps enable verification, POE and the rating would allow interim calculations of how such buildings would perform in revisions of the code.

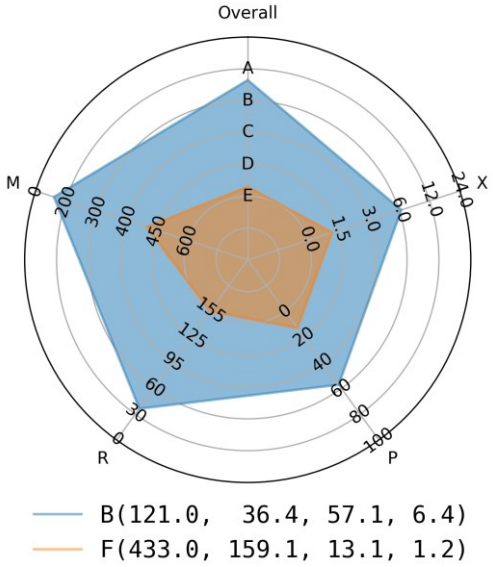


Figure 8: An example comparing two ABCode1 ratings in terms of a spider diagram (cases presented in Section 5 for medium-size offices 'O1995' and 'OFEES' in Tables 4 and 5; n.b. boundaries of each of the four numeric metrics have different units, as per Table 3).

5 ABCode1 in practice

To support designers in assessing the performance of early-stage designs against the ABCode rating system, a monthly energy balance model called ZEBRA was developed (that is, Zero Energy Building Reduced Algorithm, where zero energy just signifies that the reduced algorithm is particularly suited to study buildings with a low energy demand for space conditioning). ZEBRA is a simplified version of PHPP, but a greater fitness for building design explorations, as it minimises the number of inputs at an early stage. The main difference, and limitation, is that ZEBRA does not at present account for auxiliary energy use nor energy losses in storage or other mechanical, electrical and plumbing systems. That would presume detailed knowledge of systems that have not yet been designed, nor influence early stage design as much as building envelope characteristics, but could be included through a safety coefficient based on prior experience in projects with similar systems as an initial estimate if need be.

To demonstrate the applicability of ABCode1, twenty buildings were modelled in ZEBRA, with their predicted performance values converted into labels according to the rating system (Section 4.3). These modelled buildings represent different building types: apartment; detached house; (medium-sized) office; and school. The first two exemplify common domestic archetypes (based on Fosas et al.[95]), and the latter represent common non-domestic building types (based on US building archetypes[96]). Five design alternatives are modelled for each of these types to reflect prevalent fabric efficiency standards:[‡‡‡] Building Regulations 1985,[97] 1995,[98] 2006,[99] Fabric Energy Efficiency Standard (FEES),[100] and Passive House Institute Standard (PHIS).[101] Combining the letter of the building type with the year or standard forms the model ID (Tables 4 and 5). Buildings were assumed to follow the contractual obligations in ABCode1 (Table 3) and hence scores are better than G.

Results demonstrate a wide range of performance for each metric individually as well as overall (Tables 4 and 5). The rating system is able to reflect the diversity of the modelled buildings as, for

[‡‡‡] Note that ventilation rates as well as metabolic and electrical gains remain fixed across all alternatives to draw attention to any differences that are associated with building fabric specifications (see Supplemental Material).

instance, buildings having poor insulation receive an F or E label for metric R (energy required), whereas those having thicker insulation achieve B or A. As the ABCode1 weighting system prioritises the reduction of operational energy consumption, the overall label is biased towards R and hence resilient to poor performance in other metrics (e.g. case ID A-FEES). When the labels for metrics M, P and X are different from that of R, the overall rating can be upgraded or degraded up to one label (e.g. case ID O-2006). With regards to renewable energy production (P), good performance was achieved even in multi-storey buildings (apartments and offices, Table 4), which can be attributed to the normalisation of this metric based on energy requirements. This observation similarly applies to energy flexibility (X), as this also depends on the calculated energy consumption.

Given the current limitations in publicly available datasets, ABCode1 defined a rating system that is agnostic to building type (Section 4.3), but the calculated performance values were found to align with those in the DEC database. Achieving an A label appears to be challenging but attainable.

Table 4: Evaluation of example buildings: key metrics (model inputs are specified in Supplemental Material and IDs are specified in Table 5; the apartment refers to a single unit within a four-storey block).

ID	TFA [m^2]	Storeys [-]	Heating [$kWh \cdot m^{-2} \cdot a^{-1}$]	DHW [$kWh \cdot m^{-2} \cdot a^{-1}$]	Plug-loads [$kWh \cdot m^{-2} \cdot a^{-1}$]	PV Generation [$kWh \cdot m^{-2} \cdot a^{-1}$]	Battery [$kWh \cdot m^{-2} \cdot a^{-1}$]	Consumption [$kWh \cdot a^{-1}$]	Value M [$kgCO_2e \cdot m^{-2}$]	Value R [$kWh \cdot m^{-2} \cdot a^{-1}$]	Value P [%]	Value X [h]
A-1985	52.5	4	194.0	17.4	9.6	22.5	13.5	1.3	183	221.0	10.2	10.2
A-1995	52.6	4	123.2	17.4	9.6	22.5	-	0.9	432	150.2	15.0	-
A-2006	52.0	4	62.5	17.5	9.6	22.7	8	0.5	335	89.7	25.3	15.0
A-FEES	49.8	4	22.0	14.6	9.6	23.7	10	0.3	538	46.3	51.2	38.0
A-PHIS	46.3	4	0.0	15.8	9.6	25.5	4	0.1	121	25.4	100.4	29.8
D-1985	134.3	2	201.1	13.6	9.6	24.7	-	3.4	250	224.3	11.0	-
D-1995	128.8	2	138.6	14.2	9.6	25.7	8	2.4	398	162.4	15.8	3.3
D-2006	126.7	2	76.9	14.4	9.6	26.1	10	1.5	590	100.9	25.9	6.8
D-FEES	118.2	2	34.4	13.7	9.6	28.0	12	0.8	193	57.8	48.5	15.4
D-PHIS	104.7	2	14.1	15.5	9.6	31.6	12	0.5	126	39.3	80.6	25.6
O-1985	1500.0	3	203.1	4.9	12.3	20.8	-	37.7	692	220.2	9.5	-
O-1995	1500.0	3	142.0	4.9	12.3	20.8	32	27.3	433	159.1	13.1	1.2
O-2006	1500.0	3	54.2	4.9	12.3	20.8	40	12.2	438	71.4	29.2	3.3
O-FEES	1500.0	3	20.3	3.9	12.3	20.8	40	6.2	121	36.4	57.1	6.4
O-PHIS	1500.0	3	8.6	3.9	12.3	20.8	80	4.2	257	24.8	84.1	18.9
S-1985	5725.8	1	398.1	24.3	6.2	36.6	320	280.2	599	428.6	8.5	1.1
S-1995	5725.8	1	313.7	24.3	6.2	36.6	320	225.0	198	344.3	10.6	1.4
S-2006	5725.8	1	115.8	24.3	6.2	36.6	320	95.7	277	146.4	25.0	3.3
S-FEES	5725.8	1	60.3	21.6	6.2	36.6	320	57.6	293	88.1	41.6	5.6
S-PHIS	5725.8	1	27.8	19.5	6.2	36.6	320	35.0	183	53.5	68.5	9.2

Table 5: Labelling of example buildings (model inputs are specified in Supplemental Material).

ID	Building type	Standard	Label M	Label R	Label P	Label X	Overall Label
A-1985	Apartment	1985	A	F	F	C	E
A-1995	Apartment	1995	D	E	F	F	E
A-2006	Apartment	2006	C	C	E	B	C
A-FEES	Apartment	FEES	E	B	D	A	C
A-PHIS	Apartment	PHIS	A	A	A	A	A
D-1985	Detached	1985	B	F	F	F	E
D-1995	Detached	1995	C	F	F	D	E
D-2006	Detached	2006	E	D	E	C	D
D-FEES	Detached	FEES	A	B	D	B	B
D-PHIS	Detached	PHIS	A	B	B	A	B
O-1985	Office	1985	F	F	F	F	F
O-1995	Office	1995	D	F	F	F	F
O-2006	Office	2006	D	C	E	D	D
O-FEES	Office	FEES	A	B	D	C	B
O-PHIS	Office	PHIS	B	A	B	B	B
S-1985	School	1985	E	F	F	F	F
S-1995	School	1995	A	F	F	F	E
S-2006	School	2006	B	E	E	D	D
S-FEES	School	FEES	B	C	D	D	C
S-PHIS	School	PHIS	A	B	C	C	B

6 Limitations and future perspectives

Future revisions of the ABCode should consider the following aspects:

- **Whole-life performance.** This is a necessary step towards implementing ABs. Revisions of the ABCode should incorporate the real-world knowledge on how ABs perform as obtained from the monitoring of the performance of demonstrator buildings that are under construction. With accountability being a design principle for ABs, future work should develop the built-in monitoring platform that would capture their operational performance.
- **Energy network support.** A more localised definition of grid-supporting strategies may be necessary in the future, in order to tailor them to foreseeable needs of the local energy network. The assessment of thermal energy storage systems also needs to be improved. Lastly, ABs seek to support any energy networks they are connected to, but at present there is a better understanding and greater focus on how the power grid. Future work should consider the needs of all the networks that play a role in a decarbonised society.
- **Occupant behaviour.** This could be considered as a mechanism to achieve energy flexibility, possibly as part of a unified building-user system that governs how energy is exchanged between the building and the local energy networks.
- **Communities.** Maximising the potential of ABs may require moving from the examined building scale to the aggregation of several ABs in a community and/or city level to ensure cost-effectiveness of solutions. Although an initial proposal to rate communities has been presented, further definition of how this might work in practice is needed considering the implications of different cooperation strategies in multi-owner developments, including scenarios with energy aggregators.

- **Building types.** The possibility of adjusting this rating system to each building type could be investigated as data becomes publicly available.
- **Retrofits.** Future iterations of the ABCode should increase their scope and consider retrofits as well to ensure the transition to a low-carbon economy.
- **Expansion of the testing suite.** The proposed rating system of ABCode1 has been tested against selected design archetypes and it has been shown to perform as expected. Given the size and heterogeneity of the building stock, further work is needed to increase the representativeness of the testing suite whilst reflecting on the lessons learned in each iteration of the ABCode to control potential abuses to the rating system.

Focusing on the development of the rating system for assessing building performance, future revisions should address the following limitations:

- **Energy required ($\boldsymbol{R}$):** Only single buildings or communities can be rated at the moment.
- **Renewable energy production ($\boldsymbol{P}$):** This is based on an annual average.
- **Energy flexibility ($\boldsymbol{X}$):** This is based on the hourly average of metric R, which considers total energy demand (space heating and cooling, domestic hot water, systems, plug loads) against installed storage capacity. This does not make a distinction in the seasonality of the load nor the type of stored energy (thermal, electrical).

7 Conclusions

Building design could play a pivotal role in decarbonisation by supporting the needs of the wider energy infrastructure. The aspirations for a synergetic relationship with the wider energy networks are underpinned by new design goals and, together with the knowledge and technology involved, 'Active Buildings' (ABs) represent promising opportunities for all stakeholders involved. This paper examines what ABs are, what opportunities they present, and how the concept could be adopted in practice and further developed.

A detailed examination of the precedents revealed several building regulations, standards and initiatives worldwide that aim to encourage the design of high-performing buildings as a response to the need for minimising GHG emissions. A number of design approaches have been proposed in recent decades, with net zero energy/carbon buildings now arising as widely acknowledged aspirations for both policy and industry. Nevertheless, pioneering studies and initiatives have started questioning if these are the only ways through which buildings could contribute to the aspired transformation of the construction and energy sectors. Such initiatives advocate an integrated energy-systems thinking, where buildings are not treated as passive consumers of energy, but as active entities that have the potential to support energy networks for both the benefit of the wider energy networks as well as building owners and occupants. Although some strategies (such as renewable energy generation) are already acknowledged in net zero energy/carbon design approaches and relevant building standards, these tend to be collateral benefits, rather than holistic solutions that account for the interaction of buildings with energy networks. For example, solar generation without local energy storage can effectively increase, rather than decrease, the variability in energy imports from energy networks, creating a greater problem rather than a means to support them.

Based on the momentum built by research, policy and industry, and the barriers identified in the literature, the development of a design standard, the Active Building Code (ABCode), is proposed to help channel these discussions towards a commonly agreed definition and evaluation for ABs for the first time. Considering the needs of the built environment and energy networks as well as the relevant shortcomings of existing design approaches, linking the definition of ABs with the ABCode itself would

help ensure they remain true to their two *general principles*: whole-life sustainability and energy network support. Based on these, and in order to help designers judge the relative merits of design alternatives, a new rating system inspired by EU labels was suggested in ABCode1, an initial proposition for the ABCode. This is based around four metrics: embodied carbon, energy consumption, renewable energy production, and energy flexibility. To demonstrate the applicability of such a rating system, ABCode1 was integrated into an energy balance model, ZEBRA, and the predicted ratings of twenty example buildings were examined. Both the calculated values and the resulted labels revealed a wide range of performance (for each metric individually as well as overall), with the rating system hence being able to reflect the diversity of modelled buildings.

Future iterations of the code (ABCode2 etc.) will refine the rating system proposed in this paper to reflect the performance achieved by demonstrator buildings and address current and foreseeable needs and challenges. At the same time, the Active Building definition proposed in the code will help gather the fundamental evidence required to stimulate and inform discussions about how buildings could best support energy networks in practice, and how strategies should influence building design and operation. This aspect is found to be particularly important to help define and measure energy flexibility in a way that is both meaningful for building design and support of energy networks. Thanks to its active philosophy, the ABCode can evolve over time by adjusting its design principles and rating system to reflect the time-varying circumstances of the built environment and energy networks, advancing a timely shift towards a decarbonised society.

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Numbered list of figure legends

1. Figure 1: Overview of the relationship between the building (bld), environment (env) and energy networks (e-net) and the corresponding mapping between energy demand and generation of buildings (with a dashed line) over time. The green area indicates net positive buildings. The red area signifies buildings that consume more energy than they produce.
2. Figure 2: Framework for the definition of net-zero energy buildings (diagram based on the work by Sartori et al.[22]).
3. Figure 3: Overview of UK's electricity generation plants and resulting regional carbon intensity.
4. Figure 4: Levelized cost of energy[††] for renewable sources.[29‡‡]
5. Figure 5: Example load curves illustrating grid instability due to high penetration of solar energy production *without* energy storage systems compared to a low-penetration baseline based on California ISO.[35] The two main issues to the high-penetration scenario are the risk of over-generation and rapid changes in net load (depicted by slope α of the tangent line).
6. Figure 6: Overview of selected demand side management strategies and their influence on the final energy demand of the building.
7. Figure 7: Overview of the Active Building Code. Its first iteration (ABCode1) focuses on the design stage (left).
8. Figure 8: An example comparing two ABCode1 ratings in terms of a spider diagram (cases presented in Section 5 for medium-size offices 'O1995' and 'OFEES' in Tables 4 and 5; n.b. boundaries of each of the four numeric metrics have different units, as per Table 3).