Buildings as energy infrastructure, not passive consumers

A white paper on behalf of the Active Building Centre Research Programme

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Contents

Executive summary

It is clear that the energy infrastructure of the UK will be transformed over the next thirty years. The legal requirement to decarbonise and switch to renewables implies, with the possible exception of nuclear, an increasing move from a centralised to a decentralised energy system. In part, this is due to the fact that the energy density of renewables can be lower than that of traditional power stations, which can result in a mass adoption and hence thousands or even millions of suppliers. At the same time, moving from carbon-based fuels to a largely electrical future offers the possibility of large bi-directional flows, which in turn makes it difficult to separate users from suppliers. A simple example being an electric car, which at different times of the day might be a source of propulsion, a store for excess renewable energy or even a supplier of electricity. This new world of bi-directional flows means that the UK will have to re-write the rules on everything from tariff structures to the wiring of cities.

Buildings will have a special role in this future. As a sector, they are the single largest carbon emitter in an industrialised nation and, without their decarbonisation, there can be no decarbonised society. But they are also large and not limited (in general) by questions of mass or mobility. Hence, they can provide large surfaces for PVs and large storage capacity for batteries and hot water or heat in their fabric, among many other opportunities.

In order for buildings to move from passive users of energy (in the form of a final node for energy services), to an active part of the energy infrastructure of the UK (and therefore be able to support bi-directional flows), several technological and human-facing issues need to be solved; with many solutions possibly taking decades to make the journey from idea to mass rollout. Some solutions are however already available, and hence we have the possibility to start building this new generation of what has been termed *active buildings*. However, in order to move from discursive concepts, such as bi-directional flows, to real buildings, we need to provide a definition of what an active building is. A high-level definition might be:

> *a building which supports a country's energy infrastructure or, in more detail, a building which supports the wider energy system by intelligently integrating renewable energy technologies for heat, power and transport.*

Although such a definition is useful at an intellectual level, buildings are physical entities, and commonly expensive ones, so if those financing and constructing them are to be encouraged to create the first generation of active buildings, they need to know what these are and what opportunities they offer.

This practical grittiness, and the need to deliver a final product in a timely fashion, which has characterised the construction industry from at least the time of Vitruvius (2013), is normally handled by way of building regulations or voluntary codes. In the UK context, BREEAM is an example of the latter (Ade & Rehm 2020). Such codes are often long in the making and long in detail. Here, with much of the technology undeveloped and the landscape unknown, but the climate crisis urgent, we have the luxury of neither. In this white paper, we discuss the requirement for an *Active Building Code*. Codes like BREEAM are tautological, in that the definition of a BREEAM-Excellent building is one which scores Excellent within the BREEAM scheme. Here, we follow the same approach:

> *an active building is one which has been scored by the Active Building Code and assigned a rating.*

In creating this code, specific challenges have been identified and either solved or sidestepped for later consideration, in order to ensure the necessary momentum dictated by the climate emergency and the retirement of much of the UK's generating capacity – particularly nuclear.

Challenges include (*suggestions presented in the main text in parenthesis*):

1. How to create a code that is flexible to new technology, yet can be applied to the first wave of active buildings (which are now in design stage)? (*Structure the code in an active way with the expectation that it will change, possibly on an annual basis.*)
2. How to make the code easy to use? (*Provide easy to follow guidance, with rules of thumb for design and free, easy to use tools to help rate the relative merits of a design proposal.*)
3. How to ensure the concept of an active building informs and transforms designs? (*Make the code, guidance and tools applicable at the earliest design stages. This is in line with Passivhaus thinking.*)
4. Do only renewables sited on the building count as part of the active building? Or might district heating be acceptable? And if off-building solutions are to be considered, how far off-building? For example, is a wind turbine in another part of the country acceptable, or even an offsetting scheme on another continent? (*Electrical generation must be on within the curtilage of the development; heat networks are acceptable; offsetting not included.*)
5. Does the code include retrofitting? (*As yet no.*)
6. Does the term active building apply only to a building, or also to a collective of buildings, for example a housing estate? (*Either, but only one or the other, never both, see Section 5.3.*)
7. Should the code be pass/fail, or a more nuanced scale-based system? (*Scale based, like a Display Energy Certificate (DEC).*)
8. What are the key sustainability elements that should be included? For example, does the energy use of the building matter, or is it just its ability to provide off-grid services? (*The code is currently based on; embodied energy, electrical storage, operational energy use, renewable generation, discussion with local energy companies, requirement to monitor performance.*)
9. What forms of energy, or production systems, or storage count? (*Electricity, biomass, batteries, hot water storage, heat networks, solar hot water, PV. Solar, metabolic, and other incidental gains count with respect to reductions in energy needs, but not as generation.*)
10. Beyond hours of electrical storage, how should potential grid services be counted? (*At present, the grid-supporting nature of active buildings is reflected in their ability to offer the surplus electricity they generate and store to the grid, see Section 5.3. The interaction with the grid is not currently real-time, due to the difficulty in capturing such a relationship at an early design stage.*)
11. Is there a requirement to monitor the performance against the key sustainability elements post construction? (*Yes. The code is both an EPC-like and DEC-like object.*)
12. With respect to the building, how is the code integrated into the likely future regulations or ambitions of the industry or government? (*It is likely that things like fabric standards will become more ambitious, and buildings head towards a very low energy future, supported by integrated renewables to make them near zero energy/carbon. Hence, the code encourages a highly performing fabric-first approach.*)
13. How to account for systems which intelligently control the flow of energy into and out of the buildings? (*Ignored at present.*)

14. Is there a minimum performance for a building to be considered an active building? (*At the moment, the question is how well active buildings score within the code, see Section 5.3. This stance could easily be changed.*)

We believe that unless an Active Building Code is developed, the whole active building idea will be seen as ill-defined and unlikely to gather support from the main stakeholders (architects, developers, owners, occupants etc.) The concept may also be at risk due to accusations of tokenism, or of lack of new benefits. Alongside this is the observation that most of the world is facing similar challenges, and hence there is a market advantage and an export opportunity in the UK to lead on active buildings. Therefore, it is our responsibility as part of the Active Building Centre Research Programme to provide a firm foundation for the active building industry through the establishment of a robust definition of an active building. Concurrently, we will define the Active Building Code, a peer-reviewed list of compliance measures by which the future of active building development can be certified and promoted.

Introduction

The building sector is responsible for 40% of final energy consumption[1] and 36% of greenhouse gas (GHG) emissions in Europe, therefore being the largest single contributor to energy consumption and associated GHG emissions (European Commission 2019).

To minimise emissions, the Energy Performance of Buildings Directive (EPBD) (European Commission 2010) states that buildings should have a ‘very high energy performance’ (article 2). In this context, countries have drawn up National Plans for increasing the number of ‘high-performing’ buildings, with the use of energy from renewable sources playing an essential role in achieving independence from fossil fuels. By producing renewable energy, buildings have the potential to actively contribute to the vision for clean energy, with the integration of storage systems and the connectivity to electric vehicles enabling buildings to be more flexible and hence adapt to the needs of the grid through load shifting and peak shavings (Giordano et al. 2011).

In the UK, the Government has an aspiration to at least halve the energy use of new buildings by 2030 (BEIS 2017), and Parliament recently amended the Climate Change Act to require GHG emissions to be brought to net-zero by 2050 (Priestley 2019), following a recommendation from the Committee on Climate Change (CCC 2019). Determining the pathway to delivering high-performing buildings that support the wider energy network and achieve significant GHG emission reductions, is thus even more critical.

With the aim of defining such a pathway, this paper explores the concept of active buildings, 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 either the grid or surrounding buildings (Bankovskis 2017). Such concept was promoted as part of the SPECIFIC project and was subsequently applied to demonstrator buildings such as the Active Classroom and Active Office (Active Building Centre 2018). However, it remains an open question how lessons learned from pioneering experiences can be upscaled to transform the construction and energy sectors in the UK and countries with a similar context, to meet societal and environmental needs over the next few decades. To this end, UK Research and Innovation, as part of the Industrial Strategy Challenge Fund, supported with £11.6 million the establishment of the Active Building Centre Research Programme, an academic consortium of 10 universities to research how this concept can be widely adopted (UK Research and Innovation 2018).

The aim of this white paper is to suggest a way forward for the expansion of the active building concept. This is achieved by looking at a possible quantitative definition of an active building, then capturing this in a voluntary building standard.

[1] 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’ (European Commission 2009).

1. Problem definition

Building design approaches

Several design approaches have been launched over the last few years to improve the performance of buildings, these having been driven by one or more of the following aspects:

- **Energy -** with the excessive use of natural resources being the main motivator, the goal is to minimise energy demand
- **Environmental impact -** with environmental degradation being the main motivator, the goal is to ensure sustainability. This is most 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 buildings: either with or without a connection to an external energy network or grid (Figure 1). On the one hand, there are buildings that meet their energy demand through on-site energy generation only (called autarkic, autonomous or grid-isolated buildings) and, on the other hand, there are buildings that import at least some of the required energy from an energy network (called grid-connected buildings). An *autarkic* building can be viewed as a 'pure' example of a zero-energy building, evoking the ideal of pre-industrial buildings (Williams et al. 2016). However, the vast majority of existing buildings in countries with developed economies are connected to an energy network from which they import their required energy (Figure 1).

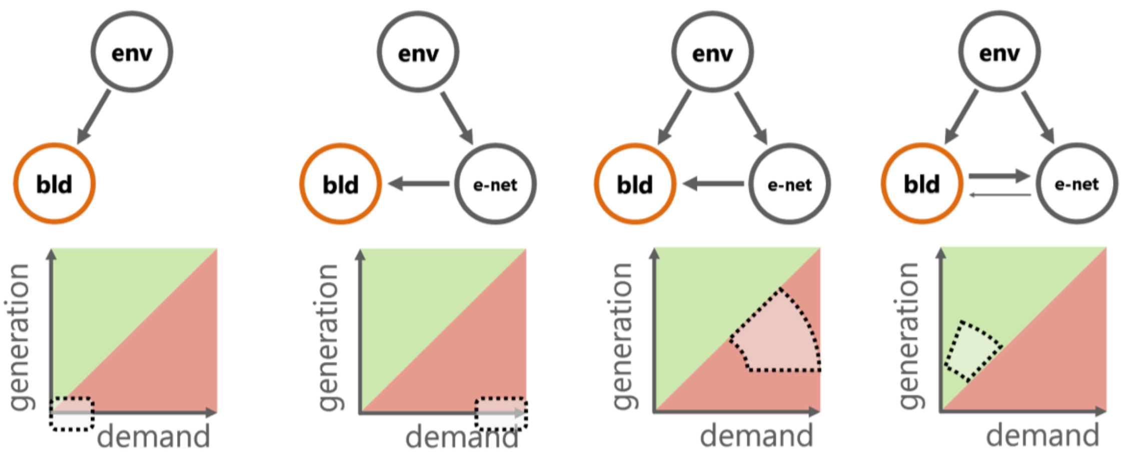

Figure 1: Overview of the relationship between the building (bld), environment (env) and energy networks (e-net), and the corresponding mapping between energy demand and generation of buildings (with a dashed line) over time. The green area indicates net positive buildings. The red area signifies buildings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

There is the aspiration to transition to low-energy and low-carbon buildings, mainly through a tighter control of energy consumption (e.g. increased energy efficiency of the building envelope and services) as well as the inclusion of on-site renewable energy generation and storage systems (e.g. PV systems and batteries). These strategies can also support the implementation of *net-zero* energy buildings; i.e. buildings that produce as much energy as they consume over a defined period of time. This concept can be stretched beyond the needs of buildings to deliver *net positive* (also called *net plus*) energy buildings. Due to the ongoing transformation of the construction and energy sectors that aims to minimise their detrimental impact on the environment, increasing attention has been paid to low and net-zero carbon buildings, this taking into account embodied carbon (RIBA 2019; UKGBC 2019).

Regulations, standards, and definitions

There are numerous building regulations and standards in the world that aim to deal with the energy and environmental performance of buildings (Williams et al. 2016; Liu et al. 2019), as well as dozens of definitions that are suggested or investigated in relevant studies. However, the proposed definitions are not always accompanied by a calculation method, thus hindering their application in real-life problems and the quantification of their benefits to the environment and different stakeholders (Sartori et al. 2012; Parkin et al. 2016).

The wide range of proposals around energy, environmental and cost issues raises the question: why does defining performance targets matter? Torcellini et al. (2006) underline the importance of such a definition using two fundamental arguments. Firstly, establishing performance expectations against which to judge a potential candidate provides stakeholders with a clear goal during the design process, which can be methodically attained. Secondly, it provides designers with a rationale behind setting limits on the design flexibility, quality of construction and operation of the designed building. For example, if net-zero primary energy is required, designers need to maximise the energy generation potential of the building. Parkin et al. (2019) investigated how different definitions related to net-zero energy and carbon constrain the design space for architects. Using a sample of 24 million buildings, they found that using zero carbon as the main performance target, rather than zero energy, led to a much less constrained design space.

The following calculation is but an example that demonstrates just how dramatically the design space is likely to be constrained in the case of aiming for a zero-energy building (judged over the annual cycle). Given: (i) only operational energy has to be considered; (ii) the building is highly energy efficient to Passivhaus levels; and (iii) the building is all electric and powered by PVs. Then (a) energy demand for heating is 15 kWh/m^2 (of treated floor area per annum), hot water demand is about 15.5 kWh/m^2 (based on 25 L/person/day and 3 occupants) and non-regulated demand is about 9.6 kWh/m^2 (based on an average of 1.1 W/m^2), with total demand being 40.1 kWh/m^2 (of treated floor area); (b) renewable energy generation is about 104 kWh/m^2 (of roof area). Hence the maximum number of storeys is 104 kWh/m^2 divided by 40.1 kWh/m^2 ≈ 2.6, that is between 2 and 3. If the building had a higher energy consumption, this number would be even lower.

Unless we are to significantly constrain the design space, this calculation points to the need to create a realistic rating standard which incorporates buildings that are not zero energy, and most likely based on a scale, rather than a simple pass/fail philosophy. Minimising the energy use of the building can provide a useful strategy to support the energy network it is connected to. Storage systems and occupant behaviour can also support the network by offering the opportunity to adapt the energy requested from or exported to the network.

The needs of energy networks

Although there are several energy networks (e.g. electricity, gas, hydrogen), past discussions around grid-servicing buildings have focused almost exclusively on the electricity grid, due to its ubiquity and versatility to meet energy needs in buildings. The UK's electricity network will need to overcome three main challenges: the retirement of existing generators; the rapid installation of new low-carbon and renewable generators; and a significant increase in electricity demand (Allen 2011). A reinforced network is needed to support the connection of new low-carbon and renewable generators. At the same time, electricity demand is expected to increase rapidly and significantly as space heating and road transport are shifted to electricity (DECC 2010; CCC 2019).

Additional solutions are hence necessary to meet the vision of a decarbonised grid, with renewable energy production playing a pivotal role. Solutions must also ensure the stability of the grid in view of the expected high penetration level of renewable energy sources, as this may result in overloaded transformers and consequently in voltage instability or even collapse (Mohammadi & Mehraeen 2016). The stability of the electricity grid may also be affected by the temporal imbalance between peak demand and solar energy production (Lew & Miller 2016) that leads to duck-shaped net-load curves (Figure 2). Such curves demonstrate the need for energy flexibility in order to reduce, shift and flatten energy demand through demand-side management strategies (Figure 3).

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 response to the needs of the grid (Table 1), and hence accelerate the transition to a low-carbon network (Junker et al. 2018). At the same time, by shifting from passive users to active elements of the energy infrastructure, buildings can become part of a decentralised solution for energy supply which has the potential to enhance energy quality and security thanks to the associated improvement in supply and demand matching and the minimisation of energy supply cuts (Kolokotsa 2016). Such a decentralised control of power also offers a faster response to the changing levels of renewable energy generation as well as lower transmission losses (Weckx et al. 2014).

By developing a two-way interaction with the grid which also supports the communication with electric vehicles, buildings can hence contribute to addressing the challenges of the energy network, while meeting their service obligations to their occupants and minimising their carbon footprint (Georgakarakos et al. 2017). Even though buildings are an effective sub-system which is expected to play a critical role in the transition to a smarter network (Sinopoli 2009), their role as active elements of the grid is commonly not considered by the definitions of low-energy and low-carbon buildings, nor is it defined by relevant design standards.

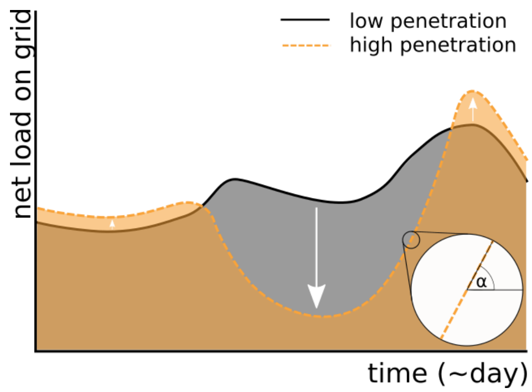

Figure 2: Example load curves illustrating the high penetration of solar energy production without energy storage systems and a low-penetration baseline (based on California ISO 2013). The high-penetration scenario is accompanied by the risk of over-generation and rapid changes in net load (depicted by slope α of the tangent line).

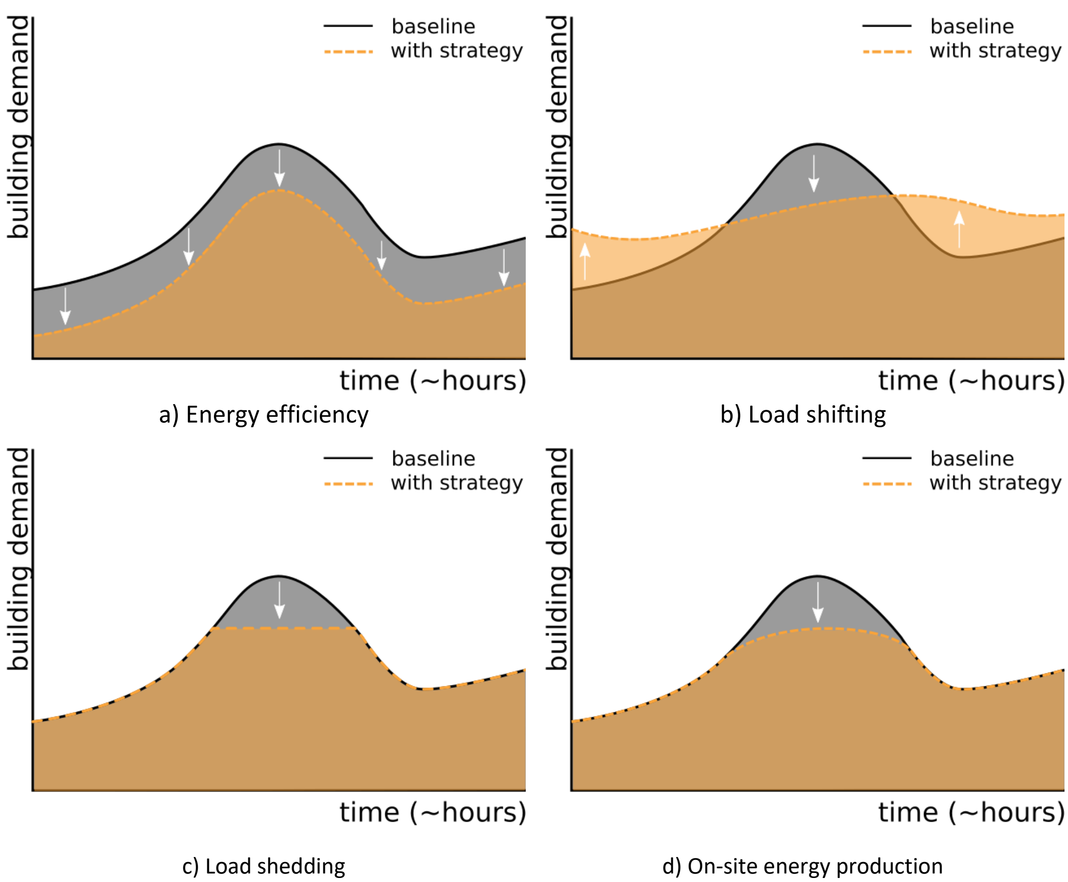

Figure 3: Overview of selected demand side management strategies.

Grid-service	Comment and potential benefits	Potential market size in the US	Strategies at building level: Efficiency	Peak Shaving	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. 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				•	

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 (Neukomm et al. 2019); 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).

2. High-level strategy for the way forward

Buildings and the grid: need and challenges

Integrating renewables into the wider energy network is required for a cleaner and more competitive energy sector across Europe (European Commission 2019). To achieve a low-carbon energy sector, energy generation at building level has been identified as one of the most promising opportunities available to further exploit natural resources such as the sun or wind (De Groote & Fabbri 2016).

Although the EPBD (European Commission 2010) dictates the use of energy from renewable sources (produced either on site or nearby), its share in the final energy consumption of buildings is not explicitly mandated. In an effort to translate the nearly zero energy building (NZEB) definition that is mandated by the EPBD into a numerical target, the Buildings Performance Institute Europe (BPIE) suggests that the minimum share of energy from renewable sources (in final energy consumption) should be 50–90%, this referring to either on-site or off-site renewable energy production (Boermans et al. 2011). BPIE also encourages the future expansion of NZEBs towards energy positive buildings – this however necessitating buildings generating renewable energy on site. That is, in order for a building to be characterised as an energy positive building over a year, its on-site renewable energy production should be higher than the energy it imports from energy networks (GBPN 2013). Achieving this target may, however, be restrictive in terms of the number of storeys (see calculation in Section 3.2), and indeed the great majority of energy positive buildings are reported to be single-storey buildings (Griffith et al. 2007; Garde et al. 2017; Parkin et al. 2019). The type of building (home, school, office etc.) is also important as this defines its energy demand profile (Goldstein et al. 2010; Torcellini & Crawley 2006).

Maximising self-consumption – and thus avoiding drawing energy from the grid – can also reduce the peak demand on the grid (if peaks in generation match peaks in demand), which can help avoid investments in infrastructure. Reductions in peak demand also improve the stability of the grid, if the rates of change in demanded power are kept relatively low (e.g. via integrated energy storage) (Giordano et al. 2011). For the majority of existing buildings (including those that may have renewable energy sources on site e.g. PV panels), energy tends to flow from the grid to the building, which has the effect of increasing the stress on the grid (Razmara et al. 2017). With the extensive electrification of transport and heating being fundamental to achieving a net-zero economy by 2050 (CCC 2019), the use of electric vehicles and heat pumps (both conventional and hybrid) is anticipated to be rapidly expanded, thus further stressing local electrical networks. Having a high PV penetration can also have a deteriorative effect on the grid, with overvoltage[2] being a challenge (Hashemi & Østergaard 2016).

From a grid-level perspective, this can be mitigated by reinforcing the grid, which may however be accompanied by a high cost depending on the existing grid structure (Pudjianto et al. 2013). In the UK, shifting heating from the natural gas grid over to the electrical grid could bring with it significant challenges in energy flexibility (Rowley et al. 2018), making localised flexibility increasingly important. Electrical demand shift (Kohlhepp et al. 2019) in conjunction with local energy generation and storage could help ensure grid stability (Kohlhepp et al. 2019). In addition to avoiding overvoltage, localised

[2] That is, an unacceptable voltage rise in the grid.

flexibility can contribute to mitigating the risks of shortfalls in generation during peak times (Khan et al. 2018)

Buildings can act as localised energy flexibility solutions by storing their self-produced energy and releasing it during peak times of need on the network with the help of commercially-available storage systems (such as batteries), which enable an 'active' demand response (Wang et al. 2013). Note that, such a local strategy for energy storage may be more reliable than a centralised approach, as the latter may trigger a communication failure leaving consumers without power. However, it may also be less cost-effective, as it increases the energy storage capacity that is required for overvoltage prevention. A combination of both local and centralised strategies is reported to be the most robust approach (Weckx et al. 2014).

3. Existing standards and rating systems: what is missing?

Design stage

The Building Regulations Part L (UK Government 2013) defines the design requirements for buildings located in England, which are, however, expected to change given the national net-zero carbon target (MHCLG 2019b). Part L also describes a procedure for predicting the (carbon) performance of buildings during the design process, this being based on a notional building of the same size and shape (as the actual building). This method is, however, often criticised for not discouraging poor design and performance, as it aims for reductions in emissions that are relative to the building's particular shape and size – and not informed by a specific performance target (Passivhaus Trust 2019; LETI 2020). By setting stricter limits on the quality of construction and the operation of buildings, the Passivhaus Standard (Passive House Institute 2018) significantly increases the energy efficiency of buildings (Nikolaidou et al. 2015). Nevertheless, there are still barriers to the broad adoption of the Passivhaus Standard (Mlecnik et al. 2008), which can be attributed to the cost of the certification, but also to the inherent insecurity of its pass or fail philosophy.

After harnessing the energy efficiency potential of buildings, increasing their renewable energy supply is fundamental to ensuring a positive environmental impact, with UKGBC arguing that on-site sources should be prioritised and off-site sources should demonstrate additionality (UKGBC 2019). As mentioned in Section 4.1, energy flexibility is becoming increasingly necessary for both the built environment and energy networks, as it can mitigate the risks of shortfalls in generation during peak times and thus increase energy self-sufficiency for buildings, while reducing the risk of overvoltage and hence improving grid stability. Even though energy flexibility implies support of wider low-carbon energy networks (electrical, heat or indeed low-carbon gas), such support is often not addressed by the definitions of low-energy and low-carbon buildings (described in Section 3), nor is it defined by relevant design standards (Sartori et al. 2012). Taking into consideration the wider network interaction is, however, necessary to ensure buildings will not disproportionally increase requirements on networks by their harvesting of local renewable energy (Voss et al. 2010). At the same time, an interaction with the grid is challenging, as it requires sufficient information on building generation and loads to understand the residual imports from wider energy networks, and whether building exports would help. Detailed generation profiles and the control systems on both the building and grid sides (such as imported and exported peak values, the amount of time when the building is demanding or exporting energy etc.), are unlikely to be certain at the early design stages (Salom et al. 2014) and, in any case, would be expected to shift throughout the building and wider energy networks lifetimes. Finally, design standards do not currently support community-based concepts, which advocate the energy trading between different prosumers (Sousa et al. 2019).

In use stage

Making the regulations more stringent by adopting for instance the design requirements of the Passivhaus Standard, is often suggested in the literature as a means of reducing the performance gap (Tofield 2012). In addition to imposing stricter design requirements, the Passivhaus Standard dictates a stricter quality assurance process, which can ensure a high-quality construction and consequently a low energy demand (Passivhaus Trust 2019). Discrepancies in construction quality is not, however, the only cause of the gap, as even high-quality buildings – including Passivhaus – are reported to be susceptible to factors that remain unknown throughout the building design process and jeopardise satisfactory performance, with the level of occupant interaction with their thermal environment being an example (O'Sullivan et al. 2020). To achieve satisfactory performance, building standards therefore need to provide stakeholders – including occupants – with incentives for well-performing buildings (Klinckenberg & Sunikka 2006), and/or penalties for not meeting performance targets (Roelens & Loncour 2014). There is, however, an absence of such incentives in the majority of the regulations of European countries (Annunziata et al. 2013), as well as of standards such as BREEAM and LEED, which still treat in-use measurement as an optional measure to assess performance. Achieving satisfactory performance should not however detrimentally affect occupant comfort (Elliott et al. 2020).

4. ABCode: a proposition for an Active Building Code

It is clear from the above that we need to move to buildings that have a dynamic relationship with the energy sector – in addition to a better energy and carbon performance. This in turn requires a way of judging the success of buildings in providing this relationship. This lack of a definition of what an active building is, seriously curtails the ability of building scientists and others to do research on such buildings, as the problem space is unbounded, and particularly for teams to compare their results. However, as low carbon networks themselves evolve, and network-supporting technologies are in many cases only in early phases of development and deployment, any defined rating system will need to evolve over time: not only will active buildings need to be active and responsive, but any Active Building Code will need to be active and responsive too.

Hence, we define an active building as one that was rated as 'active' by the Active Building Code (ABCode) at the time the building was designed. This then raises the following question: what must the ABCode include? This Section is an initial proposition, called ABCode1.

Vision and principles

The vision for the ABCode is to streamline the production of active buildings that 'do no harm' according to the *non-defornocere* principle (Coley 2019). Given this, and taking into account the needs of the built environment and the grid as well as the relevant shortcomings of existing design approaches (discussed in Sections 3 and 4), we suggest that active buildings abide by the following *general principles*:

1. **Whole-life sustainability:** active buildings recognise that the fundamental challenge for the construction industry at present is to deliver buildings that satisfy the needs of occupants, but in

a way that is cognisant of the climate emergency. In this context, minimising embodied carbon and operational energy use become key performance targets for active buildings.

2. **Energy network support:** active buildings also recognise the role of buildings in supporting and enhancing the performance of the wider energy networks. This is expressed by the notion of 'buildings as energy infrastructure'; that is, buildings that are able to generate, store and release energy in response to their own demand and the needs of the grid.

Design standard

Active buildings need to provide a clear pathway for impact in the building sector and therefore need to make technical, economical, and environmental sense under the *non-defornocere* vision. Acknowledging that this is an initial proposition, ABCode1 is conceived as a design standard for new buildings, not a post-construction rating system. It focuses on individual buildings or buildings from a development involving a single site.

The following *design principles* are proposed in order to enable the implementation of the two general principles (presented in Section 5.1), these informing how buildings are designed – but also operated, maintained and demolished or recycled:

1. **Fabric-first approach -** reducing operational energy use necessitates a fabric-first approach, including a compulsory air test.

2. **Low whole-life carbon -** reducing embodied carbon is an essential part of curtailing whole-life CO_2 emissions.

3. **Energy efficiency -** this principle expresses the need for optimizing the performance of systems, such as HVAC.

4. **Accountable performance -** this principle expresses the need for reporting energy performance to a central source in order to provide feedback to the design team and others.

5. **Energy capture -** energy capture systems (e.g. PVs, ambient heat) must be prioritised.

6. **Energy flexibility and integration -** possible strategies include passive storage of thermal energy in the building fabric (e.g. thermal mass or phase change materials (PCMs)); active storage of thermal energy through dedicated systems (e.g. water tanks); and electrical energy storage through batteries (connected to electricity generating systems). Energy can be distributed internally or traded externally, and energy storage systems can mediate these interactions to achieve flexibility in matching 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 the grid (e.g. shift energy demand to support wider network infrastructure). Control systems can ensure additional flexibility by supporting demand-response strategies (e.g. delay start on a washing machine). However, at present, it is challenging to measure the benefits of these in a meaningful way. Hence, ABCode1 focuses on the storage of electricity to enable flexibility.

Rating system

The rating system includes the following four *metrics* for quantifying performance: embodied carbon; energy consumption; renewable energy production; and energy flexibility (Table 2). Overall, these four metrics rate active buildings as consumers, producers and traders of energy and carbon. An overall performance value is then computed as the weighted average of all metrics:

$$Overall\ value = w_M \cdot M_i + w_R \cdot R_i + w_P \cdot P_i + w_X \cdot X_i \tag{1}$$

where M_i, R_i, P_i and X_i are integers varying from 1 to 7 to express the labels for each metric varying from A to G (Table 2), and w_M, w_R, w_P and w_X are the respective weights for each metric fluctuating between 0 and 1, subject to $w_M + w_R + w_P + w_X = 1$.

Metric	Embodied carbon [$kgCO_2e/m^2$]	Energy required [$kWh/m^2.y$]	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 active building?
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

Table 2: The suggested rating system for assessing building performance during the design process. In all cases, m2 refers to treated floor area as defined in the Passivhaus Standard. In the ABCode1, an active building 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 (*).

The weighted average is proposed for two reasons. Firstly, it provides an overall label (varying from A to G) that is easy to read. Secondly, weights indicate where effort should be invested in by designers to achieve a better performance. For instance, weights could be used to encourage the adoption of novel strategies, such as those being related to energy network support. The following weights are defined in ABCode1 to reflect the need to reduce operational energy consumption whilst incentivising the adoption of grid-supporting strategies as well as the calculation of embodied carbon: $\{w_M = 0.15;\ w_R = 0.50;\ w_P = 0.15;\ w_X = 0.20\}$.

To give an example, a building may have been designed in a way that results in the following individual labels: $\{M = D;\ R = B; P = C; X = E\}$. This would be translated into $\{M_i = 4;\ R_i = 2; P_i = 3; X_i = 5\}$ and consequently an overall value of $0.15 \cdot 4 + 0.50 \cdot 2 + 0.15 \cdot 3 + 0.20 \cdot 5 = 3.05 \approx 3$ and an overall C label.

It is proposed that labels A– F are accompanied by a contractual obligation to as-built reviews for M and X (i.e. embodied carbon and energy flexibility, respectively) and in-use reviews for R and P (i.e. energy consumption and renewable energy production, respectively), with the latter two being performed by the design team after three years[3] of operation as part of a POE process. It might seem that a more sensible choice of variable naming would have been E for embodied carbon and C for consumption, etc.; however, letters A-G are ruled out as these are used for the performance labels.

In addition to the requirement for a post occupancy evaluation, it is suggested that labels A– F require the scheme to be discussed with the local electricity company before generation or storage is sized by the design team. This is to encourage the team to be aware of any issues with import or export in the local area, or any local issues the building could be beneficial in solving.

The individual values that correspond to labels A– F for each metric are displayed in Table 2. These values have been chosen on the following basis:

- **Embodied carbon (M):** To define the values of embodied carbon against which performance is assessed in ABCode1, 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 ($n = 1{,}190$) referring to different building types (Simonen et al. 2017). To create the rating system, the empirical distribution of the CLF dataset for carbon intensity was divided into equally spaced quantiles based on the suggested number of labels.

- **Energy consumption (R):** There is, likewise, a lack of an adequate number of datasets reporting the total energy consumption of the building stock. The Display Energy Certificates (DECs) database was used ($n = 357{,}392$) (MHCLG 2019a). This contains a mix of commercial buildings, mainly schools ($n = 177{,}223$), offices ($n = 31{,}046$) and university campuses ($n = 26{,}982$). To create the rating system, the overall metered fuel and electricity use of buildings (kWh/m^2.y) was calculated and its lowest half was used in order to incentivise low-energy buildings. Note that energy consumption is independent of renewable generation, although heat pumps (ambient heat) are considered as part of the energy efficiency measures of the building and thus counted in R rather than P. The lack of domestic properties in the data used will hopefully be resolved at a later date.

- **Renewable energy production (P):** In part due to a lack of data providing an alternative, the scale for production is relative to R (i.e. consumption). The advantage of this definition is that it encompasses all possibilities, from no generation (0%) to energy positive buildings (>100% of energy demand). Disadvantages include that the metric for R influences two aspects of the rating system and that, in its current formulation, it does not differentiate building types.

- **Energy flexibility (X):** Despite the numerous ways available to express this, the particular ones in which buildings should provide energy flexibility *in practice* are currently unsupported by empirical evidence. It is hence still an open question what performance aspirations should be defined to account for the needs of both the built environment and energy networks. In this first

[3] This is informed by guides such as the Government Soft Landings (Cabinet Office 2013), which advocates three years of POE to support stakeholders in aligning actual building performance with the targets set during the design process.

iteration, flexibility is defined as the theoretical number of typical hours the building could run autonomously without demanding energy from the network or producing on-site energy (considering all forms of energy consumed in the building). The advantage of this definition is that it is comprehensible and hence suitable for early design stages (as it is not directly linked to the complex needs of the grid). At the same time, it acts as a proxy for the actual flexibility buildings could provide in practice, this reflecting *the way* in which the stored energy is used.

The following complementary mechanisms would be needed to harness the stored energy: *control systems*, including both the hardware (sensors, meters, actuators) and software (strategy, as informed by representatives of the energy networks), and *occupant behaviour*. These aspects are thought of as parts of a unified building-user system that governs the way in which energy is exchanged with the networks. The function of such a system is subject to both improvements in technologies and changes in occupant behaviour lifestyles (O'Sullivan et al. 2020). Until further evidence is collected and shown to be reducible to general recipes, the value of the X metric is merely a summary of the installed capacity, not prescribing particular building-user systems nor metrics that value particular ways of supporting the local energy networks (Figure 3) . As part of the POE process, evidence will be gathered with respect to which control strategy of the energy stored resulted in decreased stress on the local energy network. To avoid penalising buildings that implement storage to help support energy networks, energy losses due to storage are not accounted for in the R metric. 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, i.e. before any dynamical thermal model is created, hence any heat stored in the fabric cannot be accounted for. However, it might be possible to include fabric storage in a simple heuristic manner in the same way that PHPP (PHIS & Feist 2015) considers thermal mass when discussing summertime overheating. In order to avoid double counting, and because the temporal generation of any renewables the building is integrated with might not match the need for autonomy or useful contributions to the local network, only storage is accounted for in X, not potential autonomy given by integrated renewable generation. At present, ABCode1 focuses on short-term storage (hours) rather than the longer seasonal storage (months) given the further lack of evidence and uncertainty to establish general initial guidelines for a variety of new buildings types. Future iterations of the ABCode will further explore the potential of active buildings to deliver flexibility services to the energy network (Elliott et al. 2020).

The energy use (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 truly independent, with P unrelated to R, thereby encouraging maximum generation regardless of the energy consumption of the building. This was not selected as, for most buildings, it is likely that $P < R$, possibly $P \ll R$, and it is likely that descriptive sentences such as "the building generates x% of all the energy it uses" are likely to be much more understandable within a design or public setting, than "the building generates 450 MWh/y". The alternative to make the reported metric simply use minus generation, we feel is not 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. To this extent, 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 allows design focus to be moved between the two in future versions of the code. Finally, it potentially feels expressive of a 'do no harm' philosophy.

As applied in the Appendix, ABCode is based on a single building. It is however likely that many active buildings will be in the form of collectives of buildings, be it housing estates or business campuses, possibly sharing services such as district heating. Within the collective, 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. Hence, we propose that ABCode can be reported at either the single or collective level. However, we propose that it cannot be reported at both levels. 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, the heating scheme only made financial sense because it could sell the 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. This is similar to the approach with electricity and net-zero 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 active buildings, one can imagine a similar approach, with buildings being designed so that PV would be easy to add, or with space for battery storage. We feel though logical, any active-ready status would be too open to simple claims of "ready". Hence, additional work would be needed to put this on a firm footing – for example, what exactly is an active-ready roof. Therefore, such active readiness should be encouraged, but not scored, at least until there is consensus and evidence on the particular features that enable an affordable upgrade to a fully operational active building. Consensus and evidence would similarly be needed on the technology readiness required for the grid to accommodate active buildings (Strbac et al. 2020).

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 thanks to the four individual labels. Thus: a building can either be described as a B, or more fully with its underlying breakdown of metrics, e.g. $B(A, B, D, C)$. This will be particularly useful for those wanting to analyse why a building obtained a particular score, or to compare two or more buildings. Furthermore, for those wanting the full detail, a score could be represented as $B(121, 36.4, 57.1, 6.4)$, i.e. the numerical values used via Table 2 to generate the scores. This would allow a team to see where fine adjustments might be made in the design to improve the score. A useful way of representing the design within the framework of the code would be via a spider diagram with the metric boundaries marked (Figure 4). Given that the ABCode is active 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.

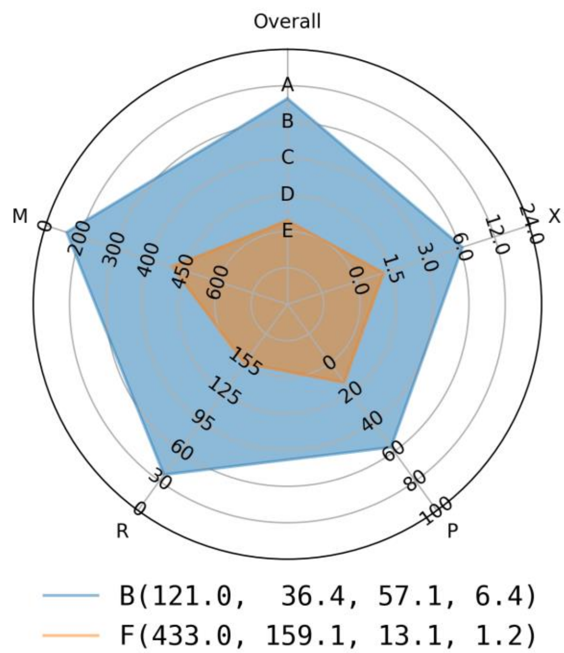

Figure 4: Comparing two buildings using a spider diagram.

In use

ABCode1 has been translated into a spreadsheet tool for designers and researchers to use. This tool is called ZEBRA (i.e. 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). The tool allows for a building (only single buildings are currently accounted for) to be specified at the earliest point, i.e. when knowledge is most likely to influence design. ZEBRA then outputs the scores for the individual metrics M, R, P, X and the overall score.

To ensure that the range of scores is reasonable and broad, a series of buildings were analysed (see Appendix). It appears that the method works, in that it gives a spread of rankings. It is hoped that the active building demonstrators will be analysed (when their data becomes available) to further inform scores.

Future perspectives

Future revisions of the ABCode might consider the following aspects:

- Whole-life performance
- More complex energy network support
- Explicit consideration of occupants and their behaviour 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
- Different scoring for different building types
- Retrofits

Risk of inaction

We believe that the development of an ABCode would help overcome the barriers to active buildings, both the conceptual (what are they?) and the economical (what are the market advantages?). Its initial proposition presented in this paper, highlighted the importance of whole-life sustainability and energy-network support as the general principles of active buildings, which can help unify the fragmented landscape of low energy/ low carbon/ grid-supporting buildings that has arisen the last decade, as well as outline specific areas where further development is needed for their realisation. These are yet to be articulated at scale to all stakeholders (architects, developers, owners, occupants etc.) to fulfil the strategic development for the built environment and the energy infrastructure now and in the next decades. Failure to address would jeopardise the legal requirements of decarbonising our society and would miss the opportunity to capitalize on and lead the emergent markets associated to active buildings, since most of the world faces these challenges as well.

5. Summary and conclusions

Several environmental design approaches have been proposed in recent decades, with net-zero energy/carbon buildings now arising as widely acknowledged aspirations. 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 system, where buildings are not treated as passive consumers of energy, but as active entities that have the potential to support energy. 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 the grid. For example, solar generation without local energy storage can effectively increase, rather than decrease, the variability in energy imports from energy networks.

The development of a design standard, the Active Building Code (ABCode), is proposed to help channel these discussions towards a commonly agreed definition and performance evaluation for active buildings. Considering the needs of the built environment and the grid as well as the relevant shortcomings of existing design approaches, linking the definition of active buildings with the ABCode itself would help ensure they remain true to their two *general principles*: whole-life sustainability and energy network support. A new rating system for assessing building performance with respect to these two principles was suggested in ABCode1, an initial proposition for the ABCode. ABCode1 includes four metrics that assist designers in judging potential candidates against: embodied carbon; energy consumption; renewable energy production; and energy flexibility. The individual values for each metric are combined into a single, aggregate label (varying from A to G). 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.

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.

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The Active Building Centre Research Programme

Funded as part of the UKRI Transforming Construction Challenge, the Active Building Centre Research Programme is delivering an evidence-based transformation of the UK's built environment.

Led by the team at Swansea University, the research programme brings together ten leading universities, businesses and service providers to develop and test innovative technologies and ideas that will ensure buildings of all scale contribute to a more stable power grid.

Our collaborative research framework is delivering valuable insight into novel heat storage, data gathering and analytics, building design and optimisation, software development and human interfacing, social science, and wellbeing.

Active Building Centre Research Programme activities are focused on enabling the construction industry to transform into a net zero emissions building sector within the next 30 years.

Transforming Construction Challenge

The Transforming Construction challenge is part of the Industrial Strategy Challenge Fund and brings together the UK's world-leading research with business to meet the major industrial and societal challenges of our time. It provides funding and support to UK businesses and researchers, aiming to transform productivity in the construction industry through the adoption of innovative technologies and the development of a more highly skilled workforce. part of the government's £4.7 billion increase in research and development over the next 4 years. It plays a central role in the Government's modern Industrial Strategy.

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Appendix

Twenty example buildings were modelled in ZEBRA, with their predicted performance values being subsequently converted into labels according to the rating system introduced in Section 5.3. These modelled buildings represent different building types: apartment (A); detached house (D); (medium-sized) office (O); and school (S). Five design alternatives are modelled for each of these types to reflect prevalent fabric efficiency standards: Building Regulations (1985) (UK Government 1985); Building Regulations Part L (1995) (UK Government 1985); Building Regulations Part L (2006) (UK Government 2006); Fabric Energy Efficiency Standard (FEES) (Zero Carbon Hub 2009); and Passive House Institute Standard (PHIS) (Passive House Institute 2018). Combining the letter that indicates the building type with the year (or abbreviation) that indicates the applied standard forms the ID of each of the models (the first column in Tables 3 and 4). All buildings were assumed to follow the contractual obligation to review ratings once buildings are in operation, hence none of them results in an overall G label.

__Table 3:__ Evaluation of example buildings: key metrics (the apartment refers to a single unit within a four-storey block).

ID	**TFA** [m^2]	**Storeys** [-]	**Heating** [kWh/m^2.y]	**DHW** [kWh/m^2.y]	**Plug-loads** [kWh/m^2.y]	**PV Generation** [kWh/m^2.y]	**Battery** [kWh/m^2.y]	**Consumption** [kWh/h]	**Value M** [kgCO_2e/m^2]	**Value R** [kWh/m^2.y]	**Value P** [%]	**Value X** [h]
A1985	52.5	4	194.0	17.4	9.6	22.5	13.5	1.3	183	221.0	10.2	10.2
A1995	52.6	4	123.2	17.4	9.6	22.5	-	0.9	432	150.2	15.0	-
A2006	52.0	4	62.5	17.5	9.6	22.7	8	0.5	335	89.7	25.3	15.0
AFEES	49.8	4	22.0	14.6	9.6	23.7	10	0.3	538	46.3	51.2	38.0
APHIS	46.3	4	0.0	15.8	9.6	25.5	4	0.1	121	25.4	100.4	29.8
D1985	134.3	2	201.1	13.6	9.6	24.7	-	3.4	250	224.3	11.0	-
D1995	128.8	2	138.6	14.2	9.6	25.7	8	2.4	398	162.4	15.8	3.3
D2006	126.7	2	76.9	14.4	9.6	26.1	10	1.5	590	100.9	25.9	6.8
DFEES	118.2	2	34.4	13.7	9.6	28.0	12	0.8	193	57.8	48.5	15.4
DPHIS	104.7	2	14.1	15.5	9.6	31.6	12	0.5	126	39.3	80.6	25.6
O1985	1500.0	3	203.1	4.9	12.3	20.8	-	37.7	692	220.2	9.5	-
O1995	1500.0	3	142.0	4.9	12.3	20.8	32	27.3	433	159.1	13.1	1.2
O2006	1500.0	3	54.2	4.9	12.3	20.8	40	12.2	438	71.4	29.2	3.3
OFEES	1500.0	3	20.3	3.9	12.3	20.8	40	6.2	121	36.4	57.1	6.4
OPHIS	1500.0	3	8.6	3.9	12.3	20.8	80	4.2	257	24.8	84.1	18.9
S1985	5725.8	1	398.1	24.3	6.2	36.6	320	280.2	599	428.6	8.5	1.1
S1995	5725.8	1	313.7	24.3	6.2	36.6	320	225.0	198	344.3	10.6	1.4
S2006	5725.8	1	115.8	24.3	6.2	36.6	320	95.7	277	146.4	25.0	3.3
SFEES	5725.8	1	60.3	21.6	6.2	36.6	320	57.6	293	88.1	41.6	5.6
SPHIS	5725.8	1	27.8	19.5	6.2	36.6	320	35.0	183	53.5	68.5	9.2

__Table 4:__ Labelling of example buildings.

ID	Building type	Standard	Label M	Label R	Label P	Label X	Overall Label
A1985	Apartment	1985	A	F	F	C	E
A1995	Apartment	1995	D	E	F	F	E
A2006	Apartment	2006	C	C	E	B	C
AFEES	Apartment	FEES	E	B	D	A	C
APHIS	Apartment	PHIS	A	A	A	A	A
D1985	Detached	1985	B	F	F	F	E
D1995	Detached	1995	C	F	F	D	E
D2006	Detached	2006	E	D	E	C	D
DFEES	Detached	FEES	A	B	D	B	B
DPHIS	Detached	PHIS	A	B	B	A	B
O1985	Office	1985	F	F	F	F	F
O1995	Office	1995	D	F	F	F	F
O2006	Office	2006	D	C	E	D	D
OFEES	Office	FEES	A	B	D	C	B
OPHIS	Office	PHIS	B	A	B	B	B
S1985	School	1985	E	F	F	F	F
S1995	School	1995	A	F	F	F	E
S2006	School	2006	B	E	E	D	D
SFEES	School	FEES	B	C	D	D	C
SPHIS	School	PHIS	A	B	C	C	B

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