Active buildings in the changing policy landscape: conceptual challenges and social scientific perspectives

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

October 2020

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Executive summary

As significant contributors to global CO_2 and other GHG emissions globally, it is recognised that the energy and buildings sectors must find ways to decarbonise in order that climate change targets may be realised. For the energy sector, increasing levels of renewable energy production at all scales presents challenges for national electricity grids in matching supply to demand. Buildings as places of energy consumption and increasingly energy production, may become places for the intelligent storage and consumption of energy, providing grid flexibility through more complete integration into energy systems.

Active buildings present a contemporary conceptualisation for addressing such environmental policy, technical and societal problems, incorporating low carbon building fabric design, renewable energy production and energy storage capacity with intelligent digitalisation. It is directed towards facilitating the scale-up of single buildings to neighbourhoods and beyond. With a number of building certifications, labels and conceptualisations already in existence, active buildings must offer a clear progression and differentiation of those already existing. A key factor under-represented in some existing concepts is understanding of the many diverse and valued roles that building play in society, as material places of commerce, education, healthcare, or home. Buildings, in all forms also have subjective and powerful values and meanings attached to them. For homes, these are formed through a multitude of factors; people's past and anticipated future, life course transitions, social relationships, as well as wider social, economic and political contexts and structures, all of which vary in how they assemble in space and time. Such factors together also hold influence over how people carry out their everyday and energy practices.

As buildings as homes are imagined as playing a dynamic role in future energy infrastructure, understanding the interplay between people, homes and energy and how this may alter as imaginaries are realised is essential to them fulfilling their many requirements. Adopting a social science lens, this paper outlines key international building certification schemes and conceptualisations, including their strengths and weaknesses, that should be drawn on in the formation of active buildings as homes. It also takes account of the changing policy and energy landscapes in the UK and raises critical questions for the conceptualisation of active buildings as active homes.

Introduction

With ever growing awareness that current levels of resource extraction are unsustainable and that greenhouse gas (GHG) emissions are accelerating climatic change (IPCC 2014), addressing the causes of climate change have increased in priority across the globe (UNFCCC 1992; UNEP 2019). Together the energy and building sectors are recognised for their high resource consumption and high CO_2 emissions. In the energy sector, emissions are produced throughout the energy system, during energy resource extraction, energy production and in its consumption (UNEP 2019) with most energy still produced from fossil fuels (International Energy Agency 2019). Global energy demand continues to increase, and since 2010 energy-related emissions have increased by 70% (International Energy Agency 2019). In the building sector, construction consumes an estimated 30% of global resources, 15% of all freshwater withdraws, 25% all of wood harvested, and 40% of all raw materials (UN 2015; Doan et al. 2017; Zhang et al. 2019). In addition, during construction and building occupancy 36% of all energy is consumed and 39% of all energy-related CO_2 emissions are released (UNEP 2019). As global human populations continue to expand, so too does global building stock, leading to increasing energy demand in buildings, most notably during occupation (Nejat 2015; UNEP 2019). Further, greater numbers of residential building stock, compared to non-residential buildings stock, means that energy consumption and CO_2 emissions are greatest in the residential building sector (UN 2017; Schwartz et al. 2018).

The growing international drive towards mitigating climatic change has seen the development of various international and national policy initiatives, these varying in their exact targets and application between different countries. International efforts to decarbonise the energy sector have emphasised the diversification of energy sources by integrating renewable energy into existing energy systems in ways that do not accelerate energy costs for consumers (UN 2015). Decarbonisation of energy systems has resulted in increased decentralisation as renewable energy is produced at a variety of different scales including at a household level. This alters the direction of energy flow, whilst also presenting new roles for energy consumers who produce energy to 'prosumers' (Parag & Sovacool 2016; Thomas et al. 2020). It also alters when energy can be produced, with renewable energy production, depending upon the source (e.g. wind, solar hydropower or biomass), often aligned with natural day/night, climatic or seasonal cycles, which can be out of step with consumer energy demand (Wimmler et al. 2017; Gram-Hanssen et al. 2020; Thomas et al. 2020). In addition, while exact pathways towards decarbonisation remain in flux, many expect significant electrification of both the energy and transport systems (CCC 2019a; Ofgem 2020; Regen 2020). In this instance new patterns of electricity demand will form as well as new potential for grid flexibility (Ofgem 2020). While the exact renewable energy mix may vary between countries, integrating renewables into pre-existing energy grids that have developed over time using fossil fuels presents challenges for national energy grids and energy regulators who hold responsibility for balancing energy within the grid with consumer energy demand (Wimmler et al. 2017; Gram-Hanssen & Darby 2018; Wilson et al. 2018).

Traditionally considered as places of energy demand and consumption, the role of buildings within the energy system is becoming more prominent as they drive the seasonal winter peak in the UK's energy consumption, but increasingly are also spaces of energy production. While early efforts towards reducing energy consumption in buildings focused on increased energy efficiency and demand reduction, now attention is turning to more fully integrate buildings within the energy system as distributed or aggregated energy producers and energy storage sites, thereby creating additional system flexibility for national grids (Hansen & Hauge 2017; Hargreaves & Middlemiss 2020; Thomas et al. 2020). However, to realise such ambition there are a number of problematics that must be addressed. First, existing attempts to increase buildings energy efficiency have yielded mixed results, with many researchers finding a 'performance gap' between predicted efficiency and realised efficiency when the buildings are occupied (Mallory-Hill & Gorgolewski 2017; Cozza et al. 2020; Mitchell & Natarajan 2020). Second, attempts to alter consumer energy demand, through reducing demand or 'shifting' times of demand, most notably via smart meters (Balta-Ozkan et al. 2014; Hansen & Hauge 2017; Tirado Herrero et al. 2018), have been met with some suspicion over data security and privacy concerns (Balta-Ozkan et al. 2014; Fabi et al. 2017). Longitudinal research has also illustrated how interest in devices may wane over time, as they become 'backgrounded' and unused (Hargreaves et al. 2013; Shirani et al. 2020a).

Unifying these different issues is the need to both understand, and integrate more fully into models or conceptualisations, those who will be occupying such buildings. In the first instance, research has highlighted that buildings that are lived in are 'workplaces', 'places of education', 'places of healthcare' and 'homes'. For buildings as homes, understanding how homes are subjectively perceived and valued is vital to understanding how people live within them and how they may perceive changes to the home (Després 1991; Moore 2000; Roberts & Henwood 2019). This includes the introduction of new technologies or fundamental changes in who can access this traditionally private and sacred space (Strengers 2013; Gram Hanssen & Darby 2018). In line with considering subjective meanings of home, is a need to understand building occupiers' expectations of their home, including expectations of autonomy and control over their private space (Cherry et al. 2017; Zhao & Carter 2020). This enables the fulfilment of everyday practices that are informed by interconnected and relative social connections formed within the home, as well as with people, communities, and organisations outside of the home (Shirani et al. 2017; Hargreaves & Middlemiss 2020). Such insights reveal that energy practices are more than simply a tangible end function determined by individual preference (Henwood et al. 2016; Shirani et al. 2017; Ozaki 2018). For example, opening a window while fulfilling a tangible function of increased ventilation, may also fulfil related psychosocial functions around cleanliness, health, or family security (Hansen et al. 2018). Similarly, lighting a fire in the home for warmth can also create a social space where relational connections between members of a household and their extended relations is facilitated and deepened (Rhose et al. 2020). These practices of course take place within and are influenced by material spaces of the home (Roberts & Henwood 2019) and, stepping outside of the home, place-specific energy geographies (Golubchikov & O'Sullivan 2020; Roberts 2020) and social structures (Middlemiss et al. 2019). In constant interplay, and variable through time and over the life-course (Shirani & Henwood 2011; Groves et al. 2016a), the above factors are instrumental to the formation of energy practices.

In order to fully understand how we might address the interplay between building design, renewable energy production, what occupants do, and the wider need to balance national grids, stock should be taken from experiences within existing building interventions developed around the globe. Active buildings represent the latest conceptualisation towards increased 'smartness' of energy efficient buildings and integration of buildings into the energy system. Understanding building occupants' expectations of their homes (Shirani et al. 2020b), in addition to how and why they carry out everyday practices including those which impact energy demand is key to their success. This paper starts by outlining international and UK policy and regulatory drivers towards building decarbonisation before exploring key low carbon building certifications, labels, and conceptualisations. This starts with unpacking Green Buildings and Green Building Rating Systems, followed by Passivhaus and Energy Performance Certificates, then moves to explore Nearly-Zero and Zero buildings. These sections seek to elucidate the strengths and weaknesses each concept, certificate or standard has realised to date. In the remaining sections, focus is placed on contemporary concerns of addressing building occupants' energy needs with balancing national energy grids, whilst also achieving zero or nearly zero CO_2 emissions. This discussion centres on the evolution of smart low carbon buildings and incorporation with smart grids to develop active buildings, neighbourhoods, and cities, highlighting the new flexible role active buildings may offer to grids whilst also maintaining occupier satisfaction. Finally, we raise critical questions for active buildings as homes, highlighting key areas where active buildings can learn from predecessor concepts and increase in relevance in policy and future energy pathways.

1. The changing policy landscapes

The Bruntland Report (1987) provided foundation for international discussions on the effects of climate change and finding solutions towards climate change prevention (Horne & Hays 2008). The report focused attention on the importance of purposeful sustainable development within all aspects of life, including the environment, energy, and buildings. Since then, international climate change obligations have been agreed, commencing with the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and Kyoto Protocol (1997). Most recently the Paris Agreement (2016) requires signatories to reduce greenhouse gas (GHG) emissions in order that global temperature rise is limited to "well below 2°C" above pre-industrial levels and to "pursue efforts towards 1.5°C". In the same year, the United Nations (UN) outlined the 2030 Agenda for sustainable development. These agreements recognise that reducing GHG emissions, and in particular carbon dioxide (CO_2), is key to slowing climate change and reducing its impact. As a large proportion of GHG emissions between 1970-2010 were from the combustion of fossil fuels (Sample & Jenkins 2020), and as nearly 40% of energy related CO_2 emissions is from energy consumed within buildings (UNEP 2019), such agreements hold direct and indirect implications for the both the energy sector and building sector.

In working towards international agreements, many countries, regions and even cities have adopted their own strategies to reduce CO_2 emissions (UNFCCC 2019). These include national-scale legislative and policy commitments, and regional or sector driven strategies. Since 2016 many countries around the globe have declared a 'Climate Change Emergency' and new ambitions to achieve at least 'net-zero emissions by 2050' (UNCC 2019; Climate Emergency Declaration 2020). Further, while exact constitutions of climate change policy and laws vary between different countries depending on their individual legislative processes, as of 2019, 170 countries had implemented climate change policy or climate change-relevant laws (Grantham Research Institute 2019). Climate change is now recognised as being interconnected with different policy areas and accordingly has become integrated within housing and energy policies (amongst others). The most common integration of climate change is into energy policy. In 2017, 88% of countries had integrated these two policy areas, prioritising concerns for electrification, energy efficiency and conservation and renewable energy production (Grantham Research Institute 2017). As a large proportion of energy is consumed in buildings (UNEP 2019), and as increasing numbers of buildings can produce and import energy into the grid (Parag & Sovacool 2016) there is no escaping the interconnection between energy and building policy. Thus, reducing in-building energy demand alongside increasing renewable energy production are considered the key means of reducing building and energy system CO_2 emissions, although in cost-effectiveness terms the balance of benefit obtained from each of the two strategies is likely to alter as buildings become more efficient and improvements in technology progress.

In Europe, EU-wide commitments have been in place since 1990, commencing with an initial agreement to stabilise the GHG emissions of the European community to their 1990 levels by 2000. Over time this initial agreement progressed a climate change policy-framework with more nuanced aims and actions agreed. The policy-framework includes the '2020 Climate and Energy Package'; a 20% reduction in CO_2 emissions, a 20% increase in energy efficiency and 20% of energy for heat, transport and electricity from renewable sources (European Commission 2019a), and the '2030 Climate and

Energy Framework'; at least 40% cuts in GHG emissions (from 1990 levels), at least 27% share for renewable energy, and at least 27% improvement in energy efficiency (European Commission 2019b). Within these frameworks, member states agreed to a proportion of the GHG emission targets set out in EU Climate Change and Energy policy (in addition to signing the Paris Agreement). For example, of the 2020 Package the UK agreed to a 16% reduction in GHG emissions and to meet 15% of its total energy needs from renewable sources (Hammond & Pearson 2013; Hannon et al. 2013). A number of building directives have also been developed towards reduction of energy demand in buildings that link in with the Climate Change Policy Framework. This commenced with the 2002 Energy Performance of Buildings Directive (EPBD) 2002/91/EC which mandated all member states to work towards minimum energy performance standards for all buildings and adopt building energy performance rating methodology and certification known as EPCs. It should be noted that prior to the 2002 directive most EU countries had "some form of requirements for thermal performance of buildings" (BPIE 2011, p. 13) for example the Standard Assessment Procedure (SAP) in the UK (Gov.UK 2014). However, with the exception of the Netherlands and Denmark, none had formal energy performance evaluation monitoring or certification schemes established for buildings (BPIE 2011). In 2010, the Directive was updated (to 2010/31/EU) to state that all new buildings must be 'nearly zero energy' (NZEB) from 2020. In addition, energy used by the buildings "should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (Directive 2010/31/EU, article 2). The latest update of the Directive was issued in 2018 (Directive 2018/844/EU) as part of the 'Clean energy for all Europeans package', placing new emphasis on "electromobility and smart readiness" (Directive 2018/844/EU, article 8). From 2019, a 'Smart Readiness' indicator will be developed that enables the measurement of all buildings capacity to integrate "information and communication technologies and electronic systems to adapt the operation of buildings to the needs of the occupants and the grid" (Directive 2018/844/EU, para 30).

With similar goals to the EU, several other countries have also set strategic goals towards decarbonisation of their building stock. In the U.S., the Department of Energy (DOE) aims to achieve "marketable zero energy homes in 2020 and commercial zero energy buildings in 2025" (Satori et al. 2012, p. 220). Japan has declared all new buildings should be nearly ZEB by 2030 (Liu et al. 2019). Canada plans to develop and adopt increasingly stringent building codes culminating with "a net-zero energy ready model building code by 2030" (Government of Canada 2017). Additionally, in 2019, a United Nations endorsed initiative aiming for all new buildings to be zero carbon by 2030 and existing buildings to be zero carbon by 2050 has been agreed with Kenya, Turkey, the UK and the United Arab Emirates as well as significant sub-national actors (United Nations 2019). Sub-nationally, zero and near-zero building commitments have also been made, for example, by Baden-Wurttemberg in Germany, Nevarre and Catalonia in Spain, Yucatan in Mexico, California in the U.S. and Scotland and Wales in the UK (World Green Building Council undated; Welsh Government 2020).

Contextualising the focus of this paper to the UK, recognition of climate change and the need to reduce CO_2 emissions has likewise seen the formation of both independent climate change legislation and the integration of climate change concerns into other policy areas. In 2019, the Committee on Climate Change (CCC) released 'Net Zero – The UK's contribution to stopping global warming'. The report advised that the UK could achieve more ambitious emission reductions by 2050 using current technical innovations and that doing so was essential to achieving its climate change obligations under the Paris Agreement. Strengthening the position of this report were widespread public protests requesting urgent Government action and declarations of climate change emergency by Scottish and Welsh Governments (Climate Emergency Declaration 2019). Subsequently, the UK Parliament also announced an 'environmental and climate change emergency' (Parliament.UK 2019, para. 3). This was followed by an amendment to the Climate Change Act (2008) by the UK Government, reflecting a new commitment to achieve Net Zero Emissions (or 100% GHG reduction from 1990 levels) by 2050 (Climate Change Act 2008, 2050 Target Amendment).

Prior to this, the UK had addressed climate change within its building and energy policies. The UK Energy Act (2010) has facilitated the implementation of several energy strategies centred around the ‘energy trilemma’, the tripartite concern for security of energy supply, environmental sustainability, and low-cost energy. Such strategies have included the UK Renewable Energy Roadmap (2011); Community Energy Strategy (2014); Clean Growth Strategy (2017); Air quality plan for nitrogen dioxide (NO_2) in UK (2017); and Implementing the end of unabated coal by 2025 (2018). In addition, several schemes were implemented to encourage investment in, and up-take of low-carbon energy technologies and reducing energy consumption. Most notably the Climate Change Levy (2001-15) increased industrial energy efficiencies and the consumption of renewable energy, leading to an estimated carbon emission reduction of 3.5 million tonnes by 2010 (House of Commons Library 2016); and the Renewable Heat Incentive (RHI) and Feed-in-Tariff (FIT) (2011/12) which supplied payment for the generation of renewable energy and in the case of FIT, additional payment was also made for export to the grid. Payments under RHI and FIT were secured for 7 years and 20 years respectively (FIT payments were originally for 25 years). It is estimated that up to 2017 the RHI and FIT saved 23.5 and 1.5 million tonnes of CO_2 emissions respectively (Department of Energy and Climate Change 2015; Department of Business Energy and Industrial Strategy [BEIS] 2018). Finally, the electricity market reform in 2014 introduced Contracts for Difference (CfD) which has also influenced the growth of renewables, with renewable electricity accounting for 47% of all electricity produced in the UK during January-March 2020 (National Statistics 2020). Three rounds of CfD have taken place (2015, 2017 and 2019). In the 2019 round, 6 offshore wind projects secured contracts, representing 95% of the capacity awarded (BEIS 2019), indicating that offshore wind may play an increasing role in UK energy futures.

In terms of its domestic buildings policies, until the Green Deal (2012) which provided loans for domestic energy efficiency improvements, UK policy focused on the improvement of living conditions and reduction in fuel poverty. However, even without a direct climate change focus, these strategies held indirect benefits to climate change, i.e. the Home Energy Efficiency Scheme (1991), focused on the improvement of energy efficiency of homes and in doing so indirectly reduced energy consumption and CO_2 emissions. While the UK was the first to develop a Green Buildings Rating System in 1990 (discussed in the next section), this initially was not aimed at domestic properties. Other policies that directly addressed climate change concerns in buildings (i.e. Zero Carbon Homes Policy 2006) have not gained widespread support and have been discarded. As an EU member state, the UK has complied with EPBD (2002/91/EC), and has used this as a mechanism to improve energy efficiency of existing housing stock, for example, the Energy Efficiency (Private rented property) Regulations (England and Wales) (2014) state that private landlords must ensure their properties achieve EPC of at least E rating prior to leasing (BEIS 2017a). For new buildings, key mechanisms for addressing climate change has been via incremental changes to Building Regulations, that set out standards of building design and construction that must be met in the UK. Most notably ‘Approved Document L’ which addresses energy efficiency and ‘Approved Document F’ which addresses ventilation. In 2019, separately the UK, Scottish and Welsh Governments released consultations proposing changes to Building Regulations, including a proposal that from 2025 all new homes cannot be built with fossil fuel heating systems.

2. Laying the foundation – green buildings

It can be argued that concern for energy efficient buildings has "always existed in a latent form" to varying degrees through time (Ionescu et al. 2015). However, it is not until the 20th century, and in particular from the 1970s oil crisis onwards, that energy efficiency of buildings has gained prominence in public and political spheres (Perez-Lombard et al. 2009; Ionescu et al. 2015). Since then, action to address climatic impacts of the building sector saw the development of Green Buildings (GBs) and associated Green Building Rating Systems (GBRS). GBs, also referred to as Sustainable Buildings and High Performance Buildings (Zuo & Zhao 2014), should minimize building environmental impact; enhance the health conditions of building occupiers; hold economic returns to investors and local community; and have limited negative life cycle impacts during the length of their existence (Zuo & Zhao 2014; Mattoni et al. 2018). GBRS generally consider core criteria: efficient use of energy, water and material; improvement of indoor environmental quality; and minimization of negative impacts on the environment (Zuo and Zhao 2014; Zhang et al. 2018). In addition, as GBs are sustainable *and* high performance one criterion cannot be compromised by the achievement of another, i.e. "energy efficiency cannot come at the cost of reduced indoor environmental quality or comfort level" (Zhang et al. 2018, p. 2235).

In 1990, the Building Research Establishment (BRE), at the time a UK-Government funded research department, launched the first GBRS called the Building Research Establishment Environmental Assessment Methodology (BREEAM). BREEAM provided advice to developers and building owners on how to take into account aspects of sustainable development such as, energy and water consumption, materials and waste, pollution, transport, ecology, health and wellbeing, and management processes (Horne & Hayles 2008; Wu & Pheng Low 2010). Buildings are then rated as 'Pass', 'Good', 'Very Good', 'Excellent' or 'Outstanding' depending on how well they meet BREEAM criteria. Following the launch of BREEAM, it is estimated that between 48 and 600 other GBRS have developed internationally (Doan et al. 2017; Zhang et al. 2019). Some of the most prominent include: Leadership in Energy and Environmental Design (LEED) in the US; Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan; Institute for Transparency of Contracts and Environmental Compatibility Italy (ITACA) in Italy; the Green Star System in Australia and New Zealand; Deutsche Gesellschaft für nachhaltiges Bauen (DGNB) in Germany and Estidama Pearl Rating System (Estidama PBRS) in Abu Dhabi. GBRS were initially applied to non-domestic buildings however many have since adapted to either include domestic buildings within their framework (for example LEED in the US) or have branched domestic specific criteria (BREEAM in the UK).

GBRS were initially developed by national governments, many in conjunction with third parties such as the World Green Building Council. Consequently, most countries have developed an individual rating system, or have adapted existing GBRS to their country context (Panagiotidou & Fuller 2013; Doan et al. 2017). As green buildings are sympathetic to their local contexts for example, working within specific climate conditions, environments, economies and geographies, the same building in two different places may use different GBRS (Panagiotidou & Fuller 2013; Zuo & Zhao 2014). In addition, even within countries GBRS criteria can be weighted differently reflecting regional geographic difference, for example, in Australia the weighting attributed to landscape water efficiency varies between states, higher weighting towards this is evident in states where water scarcity is of greater concern (Zuo & Zhao 2014). Finally, different GBRS can rate the same building differently; BREEAM can rate buildings lower than Green Star and LEED, while LEED can rate the same building lower than other GBRS (c.f. Reed et al. 2009; Wallhagen & Glaumann 2011). Even with variation, most GBRS are similar in more heavily weighting energy related categories, this is evident in BREEAM, LEED, GSAS and Estidama PBRS (Awadh 2017; Doan et al. 2017).

Despite the variety of GBRS around the globe, there has been no empirical analysis of their combined market penetration, therefore, the number of buildings that they have been applied to on a global scale is estimated only (Ade & Rehm 2019a). However, such estimates are relatively low, consequently GBs represent a small proportion of total global building stock (Ding et al. 2018; Zhang et al. 2018). This is attributed to several factors. First, there is widespread perception that GBs are less economically viable than similar 'standard' or non-GBs, due to the additional cost of green materials and equipment (Wu & Liu 2018). Many of the benefits of a GB, such as the satisfaction of building occupants or environmental impacts are difficult to measure economically, meaning in a cost/benefit trade off with a traditional "narrow understanding of economic viability", a GB fairs worse than a similar 'standard' building (Zhang et al. 2018, p. 2234). There is also a mismatch between the distribution of costs and benefits, where building developers bear the financial cost of building a GB, but occupiers benefit from all the operational benefits that a building may offer (Zhang et al. 2018). Finally, research exploring architectural and construction industry perspectives on GBs have noted that a combination of other factors has restricted uptake to date. These include a lack of demand from building developers, due to the lack of financial incentive noted above, the need to follow a more complicated regulatory and recording system than those of standard building regulations, and that GBs remains a non-statutory or voluntary certification (Ding et al. 2018).

Finally, questions remain as to how successful GBs are in achieving their sustainability goals (Amiri et al. 2019). In the first instance, with the exception of LEED since 2016 (Gabe & Christensen 2019), the measuring of a building's performance against any GBRS requires voluntary verification by building owners, which has been only sporadically achieved (Mallory-Hill & Gorgolewski 2017). As such, most GB's are certified based upon their design and construction, not on how they work in later years (Ding et al. 2018). When building performance during occupancy has been assessed, research has demonstrated varying outcomes with a gap between expected and achieved performance (Ade & Rehm 2019b; Amiri et al. 2019), labelled in the literature a 'performance gap' (Mallory-Hill & Gorgolewski 2017; Cozza et al. 2020). Focusing on energy performance, generally speaking GBs tend to achieve better energy performance than similar standard buildings, for example BREEAM certified buildings consume 6-30% less energy than counterpart buildings (Geng et al. 2019) and LEED certified buildings consume between 18-39% less energy (Doan et al. 2017). However, despite this general picture of enhanced energy performance overall, this is not always to the degree modelled in GB design, nor is it consistently achieved (Ade & Rehm 2019b). Geng et al. (2019) carried out a literature review on post-occupancy performance of green buildings focusing on energy use, indoor environment quality and occupant satisfaction in China and the U.S. They found that while green buildings had higher occupant satisfaction than their conventional counterparts and also (albeit with some exceptions) better energy performance, there remained a 'significant gap' between predicted energy consumption compared to operational energy consumption and energy saving. Furthermore, they could not identify a clear relationship between occupational energy use and the green building certification level. However, as with enhanced energy performance, increased occupant satisfaction is also not consistently achieved in LEED buildings, as research by Altomonte & Schiavon (2013), highlight in some cases occupants of LEED buildings can have equal occupant satisfaction to those of non-LEED buildings.

These efforts to design GBs and GBRS represent the beginnings of an international recognition of unsustainable resource consumption within the buildings sector and how this could continue throughout a building's operational lifetime. GBRS were the first global tool for assessing the sustainability of buildings through their life cycle, igniting ambition to achieve certification status by some developers, businesses, and countries. While GBRS are geographically variable, most place priority on occupier experience in their weighting criteria, however, post-construction occupation satisfaction is not consistently monitored. In addition, GBRS also share a commonality in placing priority on energy efficiency criteria, despite this, other building certifications and labels have been developed towards directly addressing energy efficiency of buildings.

3. Energy efficient buildings

The Passivhaus standard was one of the first building design and certification schemes aimed at reducing building occupants' energy consumption. The standard was developed in Germany in the 1990s, with the first Passivhaus being built in 1991 (Sameni et al. 2015). To date, it is estimated that over 65,000 Passivhaus buildings exist globally (Passivhaus Trust undated), and the standard has undoubtedly asserted a wider influence on other low-carbon building designs. The Passivhaus standard focuses on the building envelope, adopting high levels of airtightness to reduce heat losses, making them extremely energy efficient. Passivhaus buildings are also generally equipped to achieve passive solar gain and use mechanical ventilation heat recovery (MVHR) to circulate warm and fresh air throughout the building (Zhao & Carter 2020). While this combination of 'passivce' technologies is not universal and some Passivhaus designs do incorporate gas boilers (and are less efficient than non-gas Passivhaus'), Passivhaus building occupants should still consume less energy than their equivalent in similar non-passive buildings, and therefore also emit less CO_2.

Passivhaus buildings are designed to maintain occupant comfort levels without occupant interaction (i.e. altering of thermostat settings or opening windows) effectively "designing out the role of occupants" (Cherry et al. 2017, p. 43). However, typical passive technologies such as MVHR that are designed to be 'on' constantly contradicts what many people have always been taught: that to save energy appliances and heating systems should be turned 'off' (Ozaki & Shaw 2014). There is a growing body of literature that points out that maintaining comfort requires "a significant level of occupant interaction" (Zhao & Carter 2020 p. 1), and that regardless of decreases in energy efficiency and possible increases to energy bills, building occupants still intervene in their buildings operational functions (c.f. Sherriff et al. 2015; Botti 2017). Indeed, a perceived constraint on a building occupant's freedom and autonomy to intervene in their homes' operational functions can be considered "unreasonable" (Cherry et al. 2017, p.44), resonating with assumptions that a home is a place of (amongst others) comfort and control (Després 1991; Moore 2000; Gram Hanssen & Darby 2018). But also, because how people create their home and live everyday practices is informed by interwoven emotional and social connections and personal beliefs (Shirani et al. 2017; Hess et al. 2018; Ozaki 2018; Lonhurst & Hargreaves 2019; Roberts & Henwood 2019). Accordingly, it is important to pay attention to such commonplace interactions as they are formed through historical narratives and other stories about the dynamics of socio-cultural change (Henwood et al 2016), and past and present experiences combined with expectations of the future (Shirani & Henwood 2011: Goodhew et al. 2017; Ozaki 2018; Shirani et al. 2020b), both of which contribute to the felt dimensions of lived experience and everyday practice. What is considered to be (un) reasonable, and what is felt to be the compelling thing to do in the circumstances (Henwood et al. 2016), are both situated and evolving in space and time (Groves et al. 2016a), and as such are influenced by the materiality of the home, technology and wider social and economic contexts (Ozaki & Shaw 2014; Middlemiss et al. 2019; Roberts & Henwood 2019; Golubchikov & O'Sullivan 2020). As such, opening windows or adjusting thermal temperature is often carried out for more reasons than simply reducing thermal temperatures. Opening windows may also be a part of a household's everyday cleaning practices and concerns for clean air and household health (Hansen et al. 2018); cooking practices (Ozaki 2018); to stem loneliness by listening to birds singing; or part of childcare and safety practices - by listening to their children playing outside (Hansen et al. 2018). Heating regimes likewise can be informed by practices of caring (Shirani et al. 2017) and creating comfort and feelings of belonging, closeness, and family (Henwood et al. 2016; Rhose et al. 2020).

Intervention by occupants, for example turning off MVHR or opening windows, can lead to decreases in the building's energy efficiency as thermal gains that would have otherwise been recycled are released (Nord et al. 2018). Research has pointed out that in some instances occupants had no choice but to intervene in the operational functions of their home, for example, in milder and warmer climates where occupants of Passivhaus have been at risk of overheating (Sameni et al. 2015; Botti 2017; Costanzo et al. 2020). Research by Botti (2017) of social housing Passivhaus occupier experience outlined that a combination of occupants' behaviour, a lack of maintenance, including failure to change or clean ventilation air filters in some homes by social landlords, and malfunction of ventilation equipment in others, meant that occupiers had no choice but to open windows to cool and ventilate their homes over summer. In this instance, as the MVHR were still 'on' to ventilate the air despite not working properly, meaning energy was consumed unnecessarily. However, other studies contradict such outcomes, identifying that not only are many Passivhaus homes more energy efficient than modelled (Mitchell & Natarajan 2020), but that in warmer climates (Fosas et al. 2018), or in summer in the UK (Mitchell & Natarajan 2019), overheating occurred at the same rate as non-Passivhaus homes. Indeed, the extra quality assurance processes that Passivhaus buildings must go through during its design and construction, including evidence from the construction site, means that new Passivhaus buildings are more likely to achieve predicted performance (Mitchell & Natarajan 2020).

Separately, schemes have developed internationally towards the assessment and certification of existing buildings energy efficiency. The International Energy Conservation Code (IECC) provides a framework that can be adopted and modified depending on localised contexts. It is the most widely adopted energy performance standard in the U.S., taken up by 49 states (Golbazi & Aktas 2018) and is also used in other countries such as Mexico and Saudi Arabia (Allouhi et al. 2015). In the U.S., conforming with IECC is only mandatory when the standards are developed within building codes (Allouhi et al. 2015). However, the U.S. also operates the Energy Star energy efficiency rating which is completely voluntary and aims to exceed the energy efficiencies in mandatory building codes. Like Energy Star, are Energuide in Canada, and the National Australian Built Environment Rating System (NABERS) (Semple & Jenkins 2020). These energy efficiency certification schemes typically take account of a building's function and material structure (including energy equipment such as boilers), which are then used to evaluate its energy performance (Li et al. 2019). The buildings are then assigned a certificate that indicates on a scale how energy efficient it is, for example, Energy Star uses a numerical rating scale. The certificates also make recommendations for improvements to buildings efficiency and can provide estimated efficiency ratings should those recommendations be carried out.

In a similar way, in Europe, Energy Performance Certificates (EPCs) are used as an assessment and labelling tool for building energy efficiency. The development of EPCs is attributed to the 2002 Energy Performance Building of Directive (EPBD) in which they were voluntarily adopted and the 2010 EPBD in which they were made mandatory. There were several reasons for the implementation of EPCs in the EU. First they are considered "an integral part of the EPBD, [and] are an important instrument that should contribute to enhance the energy performance of buildings" aiding the effort towards increased building energy efficiency targets (BPIE 2014, p. 10). They also provided a universal and transparent means of assessing the efficiency of existing and new building stock across the EU, highlighting where efforts were being made towards increasing building energy efficiency (Semple & Jenkins 2020). As an information source for building owners and occupiers during sale or rental of buildings, EPCs aimed to act as a market mechanism, creating demand for more energy efficient properties (BPIE 2014). Finally, EPCs have proved to be a valuable tool for other policy assessments and implementations, for example, as a means of spatially assessing places of energy vulnerability and possible fuel poverty (Hills 2012; Gouveia et al. 2019). This application of EPCs while variable in exact use across different countries is fairly consistent (Sempel & Jenkins 2020).

However, whether EPCs have been successful in the achievement of their purpose in the EU is variable. For example, member states have been free to adopt their own energy efficiency methodologies, adapting them to member state specific construction practices and climate conditions (Abela et al. 2016), thus, how each EPC rating is achieved varies across the EU (Sempel & Jenkins 2020). Moreover, jurisdictions vary in their collecting, storing, and sharing of EPC data (BPIE 2014). Outside the EU, as the earlier example of the U.S. demonstrates, multiple energy efficiency assessment schemes may be available, confusing building developers, regulatory organisations and building occupiers alike and diluting the salience of the EPC (Perez-Lombard et al. 2009). Research around Europe of EPC impact on building prices and encouragement of market preference for more energy efficient homes demonstrates mixed results. While some research finds that there is no difference between the sales prices of more energy efficient homes and less energy efficient homes, an increasing literature finds that energy efficiency does command a price premium. Carrying out an international review of homes in Wales, Spain, the U.S., Ireland, Denmark and Sweden, accounting for potential bias in their results around locational effects of house pricing, and of house price on likelihood of higher EPCs, Wilhelmsson's (2019) research found houses with higher EPC ratings can increase in value by up to 13%.

Incorrect EPCs have been issued to buildings because of inconsistency in applying assessment methods and models (Young 2015; Hardy & Glew 2019; Li et al. 2019). This can be because the assumptions of models applied are not reflective of the buildings assessed, leading to inaccuracies in buildings with non-standard floorplans and characteristics (van den Brom et al. 2019), or with heating regimes that differ from the models (Cozza et al. 2020). In the latter point, energy consumption has been typically underestimated for more efficient buildings and over-estimated for less efficient buildings (Cozza et al. 2020). This is similar for assumptions made about GBs where energy efficiency is overstated, and consumption is underestimated (c.f. Ade & Rehm 2019b; Amiri et al. 2019). This has been widely noted within the literature and is a contributing factor to the 'performance gap' emerging between expected modelled energy-related performance of buildings and then their actual performance once built and occupied (Hansen et al. 2018; Ade & Rehm 2019b; Amiri et al. 2019). Research by van den Brom et al. (2019) suggests however that subjective assumptions regarding building characteristics form only half of the performance gap, the other half being attributed to how the buildings are used by occupiers.

Research by Gram-Hanssen and Hansen (2016) found that occupants of older less energy efficient homes in Denmark, whilst still generally consuming more energy than more efficient homes, consumed considerably less than was expected in their EPC assessment. Conversely, those in more energy efficient homes consumed more energy than expected. This difference is largely attributed to 'rebound' and 'preboud' effects (Hansen et al. 2018). Rebound effects can occur when homes are made more energy efficient, through improvements to the building fabric and/or energy system or if people move to a more energy efficient home. In such instances the household's energy consumption can increase even though with more energy efficient homes it would be expected to decrease. A number of reasons have been proposed as contributing to this; one explanation is that the households use the money saved through energy efficiency to pay to consume more energy, this may be because they were previously under-consuming and now can afford to heat their homes as needed, or that the knowledge that they are now more energy efficient can create a more relaxed attitude towards their heating habits (Gram-Hanssen & Hansen 2016; Hansen et al. 2018). In these cases, households may heat their homes to higher temperatures or for longer periods of time to meet their comfort needs.

In addition, heating systems may have altered from one that only heats a room as needed (i.e. stand-alone heaters), to a central-heating system which may warm the whole house. Likewise, a move to a more energy efficient home may also mean a move to a larger home where again, the size of the footprint being heated has increased, and as such more energy is consumed.

Prebound effects can occur when people who live in old and/or energy inefficient properties curtail their energy consumption to make energy and/or cost savings (Hansen et al. 2018; Roberts & Henwood 2019). The study by Hanssen and Hansen (2016) points out that a problem exists for making older homes more efficient based on the energy savings methodology of EPCs, as most likely those in low scoring EPC homes are consuming less energy than expected by the EPC. Thus, increasing their energy efficiency would not lead to economic savings because "you cannot save more than you actually consume" (Gram-Hanssen & Hansen 2016, p. 18). Similar findings have been established in other countries such as Switzerland, the Netherlands, France, Belgium, Germany and the UK (Cozza et al. 2020), and are also similar to those of van den Brom et al. (2019), where occupier energy behaviour is connected to the building character. However, van den Brom et al. (2019) also find that household socio-economic status and composition (number of people living in the household and their ages), in addition to specific personal contexts, beliefs and values, present determining factors in how energy is consumed (see also. Guerra-Santin et al. 2017; Hess et al. 2018).

4. Net-zero buildings

Understandings of what constitutes a zero building vary between different countries. A large body of literature exists attempting to outline and clarify definitions of net-zero buildings as there exists a proliferation of numerous definitions (Torcellini et al. 2006; BPIE, 2011; Williams et al. 2016; D'Agostino & Mazzarella 2019; Liu et al. 2019). As highlighted by Liu et al. 2019, while definitions and applications are not the same, they share anticipated goals of: reduced carbon heavy energy consumption, incorporation of renewable energy and utilising building energy-saving potential. Net Zero Buildings have been described as "Ultra Low Energy Building[s]" (Ionescu et al. 2015, p. 249) where a "low energy building", such as a Passivhaus, is adapted to include energy production (Ionescu et al. 2015; Nord et al. 2018). Net Zero Buildings conceptualisations and definitions can be broadly split depending on their focus – carbon emissions or energy – to be Net Zero Emission Buildings or Net Zero Energy Buildings respectively, however, both are abbreviated to (N)ZEBs. Confusing matters further is that many NZEBs also strive to attain GBRs certification, for example, to be considered NZEB, a building would need to achieve the highest BREEM or LEED certification (Cole & Fedoruk 2015). While conceptualisations vary depending on their main focus, within each NZEB concept are a number of sub-categories defined by the factors used in their measurement, for example, building style and energy efficiency of walls, windows, roofs etc; presence of on-site renewable energy production; autonomy of the building and connection or not to national energy grids, embodied carbon.

Net Zero Emission Buildings can be understood to produce "enough renewable energy to compensate for the building's greenhouse gas emissions over its life span" (Research Centre on Zero Energy Buildings *Undated*). Similar definitions are applied to Zero Emission Houses (ZEH) in Australia; Zero Carbon Building (ZCB) and Zero Carbon Home (ZCH) used in the UK, and Climate Neutral Buildings in Germany (c.f. D'Agostino & Mazzarella 2019). Others such as Zero Net Carbon, Zero Net CO_2 Emissions and Zero Carbon are also used interchangeably internationally. Within these definitions exist sub-categories such as ZEB-Complete and Lifecycle ZEB which hold the same principles as the overall Net Zero Emissions Building but that also account for emissions during the lifespan of the building or the buildings embodied energy (respectively) (Panagiotidou & Fuller 2013; Research Centre on Zero Energy Buildings *Undated*). It should be that the assessment of carbon emissions emitted during a buildings life-cycle is variable, with life-cycles often only considering carbon emissions during a buildings operation time and not typically including resource sourcing, construction, demolition or recycle phases (Liu et al. 2019). Furthermore, assumptions for building operational life cycle varies from 50 and 60 years (Sartori & Hestnes 2007; Schwartz et al. 2018) up to 80 years (Panagiotidou & Fuller 2013).

In addition, the Research Centre on Zero Energy Buildings in Norway has recently conceptualised 4 more sub categories: ZEB-O where the building's renewable energy production compensate for greenhouse gas emissions from operation of the building; ZEB-O ÷ EQ where the building's renewable energy production compensates for greenhouse gas emissions from operation of the building minus the energy use for equipment (plug loads); ZEB-OM where the building's renewable energy production compensate for greenhouse gas emissions from operation and production of its building materials; and ZEB-COM where the building's renewable energy production compensates for greenhouse gas emissions from construction, operation and production of building materials. While Zero Emission Buildings focus is emissions, they also take into account energy source and allow for off-setting to occur, for example if the building needs to draw on energy from the national energy grid, it must then produce more renewable energy than it needs at other times to off-set this.

Net Zero Energy Buildings simply put "is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable energy technology" (Torcellini et al. 2006, p.1). The concept of Zero Energy Buildings has developed from 'Autonomous Buildings', 'Stand-Alone' buildings, or 'Off-grid ZEB', designed to operate off-grid by installing renewable energy production to service the building without need for grid back up (Lu et al. 2019). Zero Energy Buildings are broadly similar in definition to Energy Plus Buildings (+ZEB) (D'Agostino & Mazzarella 2019) where buildings can "export excess energy generated by renewable sources to the grid and achieve an annual positive net balance between demand and supply" (Nord et al. 2018, p. 75). However, as with Zero *Emission* Buildings there exist a variety of definitions, including Nearly Zero Energy Buildings (NZEB); Zero Energy Buildings (ZEB); Energy Plus Building (+ZEB); and Net Zero Energy Building and Zero Net Energy Building (Net ZEB). In France and Denmark these are also recognised as Plus Energy Buildings and Positive Energy Buildings (PEBs) (c.f. Kolokotsa et al. 2011; D'Agostino & Mazzarella 2019).

While in the U.S. NZEB is defined as "an energy efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy" (D'Agostino & Mazzarella 2019, p. 202). Thus, while similar, there are differences between these definitions. Both call for energy efficiency of buildings, but where the EU requires that most energy should be met by renewables, this can be from energy production at the source (building) or another local source. Whereas the U.S. definition is similar to Zero Emission Buildings definitions where trade-off is allowed between renewable energy produced and exported to the grid at source and energy imported from the grid, as long as the former is equal or greater to the latter. The U.S. definition also holds three sub categories to allow for groups of buildings that share energy, namely, a campus (ZEC), a portfolio of buildings owned or leased by the same entity (ZEP), and a community of building sites in a set location (ZECo) (D'Agostino & Mazzarella 2019).

Similar to the U.S. NZEB definition is Net Zero Source Energy Building (NZSoEB). An NZSoEB allows trade-off of energy produced at the source with energy imported from the grid, with one difference, the energy quantified in its calculations are done at the point of production, at the 'source'. Thus, all energy produced is accounted for, including energy that is lost during processes of production, transmission, and distribution, which are not accounted for in the U.S. NZEB definition (Wells et al. 2018). A further similar definition is Net Zero Site Energy Building (NZSiEB) which again allows trade-off between the building and the grid to gain a net-zero balance. However, this definition does not specify the source of energy, therefore energy trading could include carbon heavy sources. Also, it does not specify energy efficiency, therefore, the building could be highly inefficient and consume large levels of energy but can be NZSiEB by producing large amounts of its own energy (Wells et al. 2018). The International Energy Agency definition of Zero Net Energy Buildings (NetZEB) retains focus on renewable energy production by outlining the energy neutrality of the buildings through balancing any energy imported from the grid with renewable energy production. Net ZEB is also used in Canada, with a slight difference in how it is defined, here buildings must be capable of producing the same level of renewable energy as energy it needs to import from the grid, but there is no requirement for the buildings to achieve this capacity.

Again, similar to Zero *Emission* Buildings, there exist subcategories for Zero *Energy* Buildings, these subcategories are defined by the renewable energy source in a zero-energy building. D'Agostino and Mazzarella (2019) define these as: a Photovoltaic Zero Energy Building (PV-ZEB) has low electricity energy demand and a photovoltaic system; Photovoltaic Solar thermal heat pump Zero Energy Building (PV-Solar thermal-heat pump ZEB) a building that considers heat and electricity demand using a PV system in combination with solar thermal collectors, heat pumps and heat storage; Wind Zero Energy Building (Wind-ZEB) simply is a building with a low electricity energy demand and on-site wind turbine; Wind Solar thermal heat pump Zero Energy Building (Wind-Solar thermal-heat pump ZEB) is a building with a low heat and electricity demand and a wind turbine in combination with a solar thermal collector, a heat pump and heat storage (D'Agostino & Mazzarella 2019). Finally, there remains a further definition for Zero Energy Buildings, defined by the cost of energy. Net Zero Energy Cost Buildings (NZEC) is achieved when the "amount of money the owner pays for the energy consumed is balanced by the money the owner receives for the energy delivered to the grid over a year" (D'Agostino & Mazzarella 2019, p. 204).

There are a growing number of zero emission and zero energy buildings around the world. Most have been developed as commercial buildings for example, the Active Office and Active Classroom developed in 2016 and 2018 respectively by SPECIFIC at Swansea University, Wales, are two energy positive buildings achieving positive energy performance in year one and energy neutrality in year two (UK GBC Undated(a)); in addition, the UK GBC lists a further 10 examples of developed or soon to be developed building projects , both commercial and residential that meet ZEB definitions (UK GBC Undated(b)). The Powerhouse Brattørkaia in Norway is the world's northernmost energy-positive building which aims to produce more energy than it consumes over its lifespan, including construction and demolition and including the embodied energy in the materials used to construct the building (Powerhouse 2018). Some have been developed as residential buildings, for example, in Malaysia a zero energy house was built in 2010 as NZEB, and achieved zero energy in 2017 (Lojuntin 2018); in 2015 the Solcer House became the first smart carbon positive energy house in the UK (Solcer 2015), while not used as a residential building currently, the design is due to be implemented in Social Housing developments in Wales in 2020; also, 23 zero energy homes have been built as part of the R-2000 Net Zero Energy Pilot in Canada (Natural Resources Canada 2018). Wells et al. (2018) also note two zero carbon homes in the U.S. (one in New Jersey and one in Vermont) U.S., one in Germany and one in Slovakia (Wells et al. 2018). Finally, Sorensen et al. (2017) present research of five zero carbon demonstrator homes in Arandel, Norway (to be part of a seventeen-house development).

The newness of such developments means measurement of their performance is limited but some earlier developments have yielded data indicating, as with GBs, and EPC's, attaining zero energy or emissions still expects building occupants to alter their existing energy practices in some ways (c.f. Wells et al. 2018; Sorensen et al; 2017). As such questions remain as to how successful such models will be if rolled out more widely. In addition, as the focus of a zero building is to achieve zero emissions/energy at the building scale, there may be adverse implications for national grids they are connected to. As Pean et al. (2017) have demonstrated, such buildings (depending on their energy source) are likely to produce surplus energy at times when energy demand on national grids is low, and consume energy in line with other households (Gram-Hansen et al. 2020), thus contributing to national-scale peak demand (this is unpacked further in next section). Without management of their energy production and consumption that can both satisfy occupant energy needs and reduce pressure, or at least not add to the pressure, on national energy grids implementation of such buildings at scale could compound already existent difficulties in achieving whole-system decarbonisation. Where pledges to achieve net-zero carbon by 2050 have been made, such as in the UK, pathways towards this identify that complete decarbonisation of the energy system is required (c.f. CCC 2019a). Thus, using renewable energy at a building scale to offset carbon heavy energy import from the grid may become less relevant. If a zero-emission energy supply system is achieved then by default all the buildings serviced by that system will also have zero operational emissions. Indeed, research suggests that a more cost-effective route to decarbonisation may involve ensuring buildings are highly energy efficient, but that renewable energy is produced at scale, for example by using offshore wind (Lowe & Oreszczyn 2008). Remaining relevant will be the reduction of embodied carbon (CCC 2019b), and as most energy system decarbonisation pathways include a significant increase in electrification (Ofgem 2020; National Grid ESO 2020; Regen 2020), the ability of buildings to reduce pressure on local electricity grids via energy reduced demand and storage capacity will also be an important consideration (Ofgem 2020; National Grid ESO 2020).

5. Smart buildings

Existing energy systems have evolved over time and are based upon largely uni-directional flows of energy from power stations to buildings for consumption (Parag & Sovacool 2016). Daily, weekly, and seasonal societal energy demand has created distinct patterns of high and low consumption informed by the cumulation and synchronisation of individual everyday practices (Gram-Hanssen et al. 2020). Over time these over-arching demand patterns have been matched with energy production, made easier to manage due to its use of fossil fuels in which energy is naturally stored, ready to be released relatively quickly (Wilson et al. 2018). Decarbonisation alters this arrangement in several ways; widespread decarbonisation and decentralisation of energy networks through increased renewable energy production at all scales, including from 'prosumers' at a household scale, alters one-way energy flows to bi-directional, creating new patterns of energy production (Parag & Sovacool 2016; Thomas et al. 2020). Decarbonisation pathways also indicate higher uptake of electricity for heat as well as non-heat energy demand, thus combining some of the already present, and higher, daily, and seasonal peaks in gas demand with those of electricity (Wilson et al. 2018). In addition, renewable energy production is aligned with natural day/night and climatic cycles, and in the absence of storage, is less able to be 'switched on' rapidly by grid operators during spikes in demand that can be routine and expected (i.e. during mornings and evenings or during winter months) (Wilson et al. 2018; Gram-Hanssen et al. 2020) or that can occur quickly over minutes or hours (Wimmer et al. 2017). With current ability to store renewable energy at scale limited, a potential mismatch is created between times of energy production and times of energy demand. The same supply-demand mismatch exists for households that produce renewable energy, although in this case any surplus energy produced is exported to the grid and any deficit in energy results in import from the grid. In both instances this exacerbates the grid balancing issue of facilitating the correct dynamic relationship between discharge and charge of energy storage, production, and demand.

This energy balance problem is projected to become more challenging as increasing levels of renewable energy are integrated into the grid (Cole & Fedoruk 2015; Thomas et al. 2020). While there is no agreed fixed pathway to net-zero, often future scenarios towards decarbonisation anticipate significant electrification of not just the energy system, including heat demands, but also of transport (c.f. CCC 2019a; Ofgem 2020; Regen 2020), adding a new dynamic to both electricity demand patterns and grid flexibility (Ofgem 2020). In these ways decarbonisation highlights more clearly how energy is interwoven within all aspects of the economy and daily life, and that both the buildings and energy sectors must decarbonise in complementary ways. For buildings, this means zero energy or emission ambitions need strategies that can work with national energy structures and regulations, and likewise for the energy sector, decarbonisation must work with the needs of its end-users, including building occupiers.

Many projected decarbonisation pathways anticipate that a means of achieving net-zero emissions by 2050 while ensuring energy networks maintain capacity to meet energy demand, is to develop "fully integrated digitalized energy systems" (European Technology Innovation Plan [ETIP] 2020, p. 19). This involves the digital integration and communication between energy production, energy storage and energy demand at multiple scales (ETIP 2020; Ofgem 2020) allowing "information technologies and advanced communications to deliver real-time information and enable the near-instantaneous balance of supply and demand" (Dileep 2020, p. 2591). As places of energy demand, production and increasingly projected places of energy storage, homes too form a part of this fully integrated and digitalised future (Spence et al. 2015; Gram-Hanssen & Darby 2018; CCC 2019; ETIP 2020; Ofgem 2020). A step towards achieving this has been the installation of Demand Side Response Systems or Smart devices (i.e. smart meters) within homes (Tirado Herrero et al. 2018; BEIS 2020). These are considered a "central technology in the ICT-energy sphere" (Bastida et al. 2019, p. 455) and to varying degrees, enable intelligent digital energy monitoring and communication between domestic and national energy systems.

In some instances, smart meters can keep occupants "better informed and empowered" in managing their own energy consumption and responding to energy market signals (such as ToU tariffs) (Tirado Herrero et al. 2018, p. 67). In other instances, agents such as Energy Services Companies (ESCOs) or Aggregators (c.f. Hansen & Hauge 2017; Mlecnik et al. 2020) will use smart meters to monitor energy consumption and take actions to increase energy efficiency and reduce energy costs on behalf of the household. In the latter instance, heating systems and appliances are 'backgrounded' through programming and remote control by agents, balancing household energy needs with those of the grid. Finally, sensor and processor learning can be employed to independently control the functions of the home, and over time learn household energy consumption routines and autonomously meets these while communicating with the wider grid to address grid-wide demands (Tirado Herrero et al. 2018; Gram-Hanssen & Darby 2018). In these different ways the building effectively becomes a connected and responsive element of the energy system (Gram-Hanssen & Darby 2018).

In many countries, energy system digitalisation (UN 2018) with smart meter integration is considered important to achieving national and international climate change and decarbonisation goals (World Energy Council 2016; International Renewable Energy Agency [IRENA] 2019; ETIP 2020). By 2017, an estimated 90 million smart meters had been installed globally (IRENA 2019), and with market research estimating that over 16 million smart meters were installed globally between April and September 2019 (Holebrook 2020), it appears roll-out is gaining momentum. In the UK, smart meters are considered a "vital" to the "cost effective delivery of net-zero", "critical" to "modernising the way we all use energy and support the transformation of the retail energy market" (BEIS 2020, p. 5). Under the smart meter regulatory framework, since 2011 energy suppliers in the UK have been obligated to offer smart meter installation to all domestic and small business customers (House of Commons Library 2019) resulting in over 20 million smart meter installations to date (BEIS 2020). Despite significant levels of smart meter installation, they have not been universally accepted by households. Much research has investigated the acceptability of smart meters. In the UK, research has demonstrated that energy customers are resistant to smart technology due to concerns over their reliability, cost, autonomy, privacy and security (Balta-Ozkan et al. 2014; Fabi et al. 2017; Shirani et al. 2020a) as well as ongoing maintenance and upgrades to prevent outdating of the technology (Spence et al. 2015). Consumer concerns have also been noted around potential adverse health risks, installation visits and doorstop selling, ability to switch supplier and the functionality of smart meters in areas with poor mobile network coverage (House of Commons Library 2019).

Within households too, research has highlighted how smart meters can influence social dynamics, for example, in instances where some individuals are purposely excluded or otherwise may have limited interaction with smart technology, while others retain full or nearly full control (Hansen & Hauge 2017; Hargreaves & Middlemiss 2020). Limited interaction may be due to a lack of access, lack of knowledge, or simply a lack of interest, but with the same outcome of decreased control over the home and its smart functions including energy related functions such as temperature and appliance timings (Hansen & Hauge 2017; Hargreaves & Middlemiss 2020; Nicholls et al. 2020). These raise concerns over the risk of such technologies facilitating domestic abuse, for example through locking-out members of the household from their home or services within the home; invasion of privacy through stalking; and remotely altering the environment within the home (Nicholls et al. 2020). Existing research has also indicated scepticism about smart meter technology amongst vulnerable consumers, who already describe having a good understanding of their energy use due to financial necessity and do not see a smart device as being able to provide them with any new information (Shirani et al., 2020a).

In some cases, when smart devices have been installed, similar to some instances of Passivhaus and Zero home occupation, they have not been utilised as expected. A two-year smart grid trial in Denmark demonstrated that smart remote control of various household appliances, heating systems and electric vehicle (EV), received a mixed reception from the households involved. Instead, while some remote control was accepted, in other instances, such as for EV charging, households found ways to over-ride the system, charging their EVs at times that fit in with their other daily practices as opposed to when the system told them to (Hansen & Hauge 2017). This went against the presumption of the smart operator who had assumed households would welcome the remote control and the chance to 'disengage' from their energy system. Research in the UK exploring the impact of time of use (ToU) tariffs on household energy consumption has found that while 13% of UK domestic energy customers use a ToU tariff, only 50% of those customers tailor their energy consumption around the tariff (Ozaki 2018). The research identified that while most people are willing to change household energy practices to match the ToU tariff, they would only do so if it did not interfere with their quality of life (Ozaki 2018). Finally, other research exploring how smart meters might alter occupant energy practices and behaviours, has indicated that over time smart meters become 'backgrounded' (Hargreaves et al. 2013; Skjølsvold et al. 2017), that energy savings are small (Hargreaves et al. 2018; Fredericks et al. 2020; Nicholls et al. 2020), and that past a certain point they do not motivate further energy savings or energy practice change (Hargreaves et al. 2013; Skjølsvold et al. 2017). These examples marry with assertions that household energy consumption is informed by a variety of interconnected "logics, constellations and processes" that make up daily life, where energy consumption decisions are based on more than a simple choice to either consume or not consume energy (Skjølsvold et al. 2017, p. 3). This suggests that even those who engage with the technology will circumvent it or ignore it should it adversely affect their ability to maintain their lives, regardless of increased energy cost (Skjølsvold et al. 2017).

While smart metering is considered a main means of integrating homes within a digitalised energy system, the smart home ontology extends further than energy services. Original imaginings of smart homes were as places where "computing and information technology which anticipates and responds to the needs of the occupants, while working to promote their comfort, convenience, security, entertainment, healthcare, education, and communication through the management of technology within the home and connections to the world beyond" Aldrich (2003, p. 17). Furthermore, they will also "support and augment households' social goals and values" helping to "create and sustain […] household identities" by facilitating participation in "enrichment activities" (Hargreaves et al. 2018, p. 128). Such visions resonate with those of "technological utopian ideals from the past" (Strengers 2013, p. 2), such as, the '1930s homes of tomorrow' (Strengers 2013; Darby 2018) where modernity and efficiency were imagined in the home through technical innovation. As with past technological utopian visions, the "smart utopian" (Strengers 2013) or "domestic-machine utopia" (Darby 2018, p. 141) can be perceived as exclusionary to people outside of dominant visions, such as, elderly, disabled, poor, women or other (non-nuclear) family compositions (Wilson et al. 2015). Or, for example, holding narrow dichotomous expectations of smart users as either logical, reasoned and IT literate (Strengers 2013) or "unable or unwilling to make lifestyle changes" (Gram-Hanssen & Darby 2018, p. 97). These critiques raise concerns that misconceptions of smart customers mean that they can be "deprived of credibility and agency [and] cannot express their ways of knowing and thinking" (Vanolo 2016, p. 29) possibly affecting the ability of smart homes and energy systems in meeting their needs. Similar critique has also been noted with regards to the design and marketing of electric, autonomous vehicles (c.f. Hildebrand & Sheller 2018).

However, given the high numbers of households with smart meters, and recent polls that indicate the majority of those with smart meters would recommend them (House of Commons Library 2019) it appears that acceptance of smart meters is growing. Likewise, the recent uptake of new smart speaker assistants (SSA) such as Amazon Echo and Amazon Alexa, which are voice controlled speakers that respond to verbalised user requests and can link with and coordinate other smart devices in the home, may indicate a quickening towards such 'smart utopian' visions. For example, the first SSA was made available in 2014, by 2018 24% of all U.S. households owned one, and in 2019, 20% of all UK households owned one (Brause & Blank 2019). Regardless of this, the radical shift in both the wider energy system, regulation, and in-building energy consumption that will likely occur with the implementation of smart grids and buildings means that at present their roll-out is limited to individual smart houses (not connected to a smart grid), demonstration projects and pilots (Hansen & Hauge 2017; Hargreaves et al. 2018; Niesten & Alkemade 2016).

6. Scaling-up ambition

The interconnectivity of buildings can allow aggregation of energy demand and storage at a community/neighbourhood scale, reducing consumer energy costs and assist with grid balancing reducing peak energy demand. There are examples of this occurring at small scales, for example, ZECos in the U.S. can balance their energy production and demand between the buildings within the ZECo, only importing energy from the grid when demand cannot be met by their own energy supply (D'Agostino & Mazzarella 2019). Such ambition typically requires both smart energy efficient buildings that can produce, export and store energy, and smart energy grids in addition to a variety of new intermediaries that can facilitate and manage energy trading with such a large-scale distribution of actors (Hansen & Hauge 2017; Mlecnik et al. 2020). In the UK, ambition is growing at sub-national scales and lower to create 'low carbon economies' or 'local energy market places' (c.f. Welsh Government 2019; Local Energy Oxford 2020), where localised multifaceted decarbonisation (buildings and infrastructure, heat and other energy) are viewed as means of securing energy supply, solutions to energy vulnerabilities and as beneficial to the development of sustainable low carbon local economies.

Already existent developments that work towards this scaled-up vision, have developed from GBRS and thus focus more heavily on overall sustainability, for example; BREEAM Communities (Holden et al. 2015), LEED-Neighbourhood Development (Pedro et al. 2018), CASBEE – UD (Pedro et al. 2018), New Urban Districts (DGNB) (Pedro et al. 2018), and Ecourban Communities (Ruano 1999; Griffiths & Sovacool 2019). LEED-ND or BREAM Community neighbourhoods generally place predominant value on environmental and efficiency innovations and outcomes (Holden et al. 2015). This varies depending on where the concept is applied, for example, developments aiming to regenerate urban brownfield sites will typically focus more heavily on capital-gains (Holden et al. 2015). Ecourban Communities have developed from Ecourbanism, "the development of multi-dimensional sustainable human communities within harmonious and balanced built environments" (Ruano 1999). Ecourban communities can be ecodistricts, ecoquarters, ecocities, ecopolises, ecobarrios, One Planet Communities, solar cities, and zero/low-carbon/carbon-positive cities (Holden at al. 2015). Such developments incorporate a "move towards self-reliance with regard to food, energy, water and waste" in addition to incorporating "environmental and energy conservation in building structure" and "active discouragement of the use of private automobiles with encouragement of active and public transportation" (Holden et al. 2015, p. 1149).

The Lammas/Tir-y-Gafel, ecovillage in Pembrokeshire, Wales represents an example of the sustainable or eco concept where residents "live in self-built homes made from natural materials (often locally sourced) with no connection to the national grid (Shirani et al. 2020b, p. 341). The village consists of nine smallholdings with some "active interdependency" or "communality" due to the sharing of a number of resources including hydroelectricity (Shirani et al. p. 341; 344). As an ecovillage demonstrator project, the village aimed to combine low-impact lifestyles, through land-based livelihoods and carbon-neutral housing, which could be replicated as part of Welsh rural sustainable development. Here, complete low-impact lifestyles were adopted by the residents, with a shared goal of "re-assembling […] domestic life" (Vannini & Taggart, cited in Groves et al. 2016b, p. 19) representing an ecologism ontology (Shirani et al. 2020b). This is different to the dominant environmental ontology that underpins many other initiatives, whereby technological solutions are viewed as a means of sustaining existing ways of living while achieving environmental goals. Scaling up, Masdar city, in Abu Dhabi, Arab Emirates, initially envisioned as zero-carbon and zero-waste city, represents a low-carbon ecocity (Griffiths & Sovacool 2019). While the city has downgraded some ambitions due to variable economic crises, changing political contexts and regulatory issues, it retains specific sustainability objectives for reductions in embodied carbon of city and building construction materials and a 40% reduction in the energy consumption of its buildings (both relative to comparable buildings in Abu Dhabi) (Griffiths & Sovacool 2019).

Other developments hold energy and emission management at their core, for example, Positive Energy Network (PEN) (Ionescu et al. 2015), Zero Emission Neighbourhoods (ZEN) (Skaar et al. 2018; ZEN Research Centre 2018), Positive Energy Blocks (PEBs) (European Commission 2019c) and multiple, connected "Grid-Interactive Efficient Buildings" that create "Connected Communities" (Olgyay et al. 2020, p. iv). Such concepts are gaining weight as increasing numbers of cities around the globe establish low carbon development as part of their over-arching development plans. Tan et al. (2017) estimate that 1050 cities in the United States, 40 cities in India, 100 cities in China, and 83 cities in

Japan have identified low carbon development within their development plans. The C40 Cities Climate Leadership Group (C40) is a global network of 96 cities taking action to reduce greenhouse gas (GHG) emissions. Affiliated cities include Sidney, Auckland, Singapore, Yokohama, Delhi, Dubai, Cape Town, Dakar, London, Rio de Janeiro, Toronto, Oslo, Los Angeles, and Mexico City (C40 Cities undated). Of their affiliated cities, 93% priorities actions against climate change at the highest level, 62% had developed a climate change action plan, 50% have a dedicated council or steering committee, and 57% have specific GHG reduction targets for citywide emissions (Tan et al. 2017). In addition, over 100 cities and 77 countries pledged to become net-zero carbon by 2050 in the United Nations Climate Summit 2019 (United Nations 2019). How such pledges are met varies between countries, for instance, Copenhagen is focused on the promotion of renewable energy applications, while London emphasizes energy efficiency programs (Tan et al. 2017).

Zero Emission Neighbourhood (ZEN) has been pioneered by the ZEN Research Centre (2018, p. 5) based in Norway, and who define ZEN as:

> *"a group of interconnected buildings with distributed energy resources such as solar energy systems, electric vehicles, charging stations and heating systems, located within a confined geographical area and with a well-defined physical boundary to the electric and thermal grids. The neighbourhood is not seen as a self-contained entity but is connected to the surrounding mobility and energy infrastructure and will be optimized in relation to larger city and community structures".*

In this definition, not only does ZEN scale-up individual Zero Emission Buildings into geographical clusters of differentially used but interconnected Zero Emission Buildings (Skaar et al. 2018) it also considers the integration of mobility, and wider energy and non-energy infrastructure (Skaar et al. 2018). ZEN is starting to be implemented in Norway, where there are currently 3 demonstration buildings developed and plans for 7 further demonstration areas that range from school and residential care home development, to neighbourhood and city-scale developments (c.f. ZEN 2019). The interconnection of ZEB buildings within a ZEN and further, ZEN within wider city and regional contexts, similar to PEB, necessitates Smart bi-lateral communication capabilities. Thus, there is heavy cross-over between PEB and ZEN with Smart City concepts. However, Smart City concepts while including energy and emission concerns have a broader focus on the overall integration of all aspects of life with, and coordinated by, digital technology (Kylili & Fokaides 2014; Corsini et al. 2019; Nilssen 2019).

The Horizon 2020 Smart Cities & Communities (H2020 SCC) project within the 'secure, clean and efficient energy' category of its Societal Challenges work programme (European Commission 2019c) aims to scale-up Positive Energy Buildings (PEBs) to Positive Energy Districts (PEDs) and Positive Energy Neighbourhoods (PENs). A number of 'lighthouse projects' have been initiated involving 46 cities and over 70 follower cities (EU Smart Cities Information System 2020) aiming to demonstrate measurable benefits in energy and resource efficiency and economic growth. Examples include, the +CityxChange project, based in Limerick, Ireland and Trondheim, Norway. The +CityxChange project aims to develop a framework and tools that can enable a "common energy market supported by a connected community" (EU Smart Cities Information System 2020). The aforementioned ZEB Powerhouse Brattørkaia represents one of the first demonstrators of this project where surplus energy produced by the building is used for charging public electric buses in the city.

While there are several strands of projects under the H2020 SCC umbrella, together the projects work towards connecting economic and environmental goals, creating climate resilience, job creation and economic growth and securing the EU as leaders in renewables (European Commission 2019c). The development of 100 PEDs/PENs by 2025 are key towards this ambition (Urban Europe 2020). The European Commission (2019c) defined PED/PEN as:

> *"several buildings (new, retro-fitted or a combination of both) that actively manage their energy consumption and the energy flow between them and the wider energy system. Positive Energy Blocks [and] Districts have an annual positive energy balance. They make optimal use of elements such as advanced materials, local RES [renewable energy sources], local storage, smart energy grids, demand-response, cutting edge energy management (e.g. electricity, heating and cooling), user interaction [or] involvement and ICT. Positive Energy Blocks [and] Districts are designed to be an integral part of the district [or] city energy system and have a positive impact on it. Their design is intrinsically scalable, and they are well embedded in the spatial, economic, technical, environmental and social context of the project site."*

While the definition does not specify CO_2 emissions, it is implied that zero CO_2 emissions will be achieved in PEDs/PENs because they will have zero energy import (Urban Europe undated). The ambition for PEDs/PENs resonates with both the multiple positive benefits for users or occupiers of smart cities and buildings in Smart Utopian imaginaries, and the holistic, environmentally conscious, place-specific criteria of GBs. For example, in line with smart imaginaries PED/PEN ambition it to lower energy consumption, increase renewable energy production, reduce CO_2 emissions as well as creating a “high quality of life and affordability in the urban environment.” (Urban Europe 2020, p. 5). In line with GBs, PEDs/PENs aim to “realise a holistic implementation process towards […] including technological, spatial, regulatory, financial, legal, ecological, social and economic perspectives in order to provide sustainable urban development” that takes into account place-specific energy geographies (Urban Europe 2020, p. 5). The most recent concept for the scale-up of smart GBs is the idea of ‘active buildings’ (The Active Building Centre Research Programme undated).

7. Active buildings

Use of the word ‘Active’ in relation to energy efficient buildings can be traced to Denmark and France where “active houses” were developed that used solar energy and storage as a means of increasing energy efficiency (Liu et al. 2019). A 6-month pilot ‘Active House’ was also developed in Stockholm, Sweden, as part of a city-wide sustainable transition demonstration project (S3C 2013) that has since seen the development of 154 Active Houses (apartments) (Nilsson et al. 2018). Here the Active House was understood as ‘active’ due to the smart technology used by occupants of the building in line with environmental and time of use (ToU) prompts from the localised smart grid (Nilsson et al. 2018). More generally, the category active building is used to differentiate buildings with ‘active’ technology that produces, uses and exports renewable energy from ‘passive’ buildings such as Passivhaus, which greatly reduce energy consumption and emissions due to ‘in-situ’ energy efficiency properties such as thermal insulation and natural ventilation (Ionescu et al. 2015). In addition, the International Active House Alliance operates as a networking and partner platform for industry, academia and planners. The organisation has three core principles ‘comfort’, ‘energy’ and ‘environment’. It developed an ‘Active House’ label and adopted a holistic approach to develop a healthy and comfortable indoor climate in a way that was “without negative impact on the climate – measured in terms of energy, fresh water consumption and the use of sustainable materials” (Active House undated, para. 3).

In the UK, the Active Building Centre Research Programme presents another contemporary conceptualisation of active buildings, that may present a logical development of GBs, energy efficient and Passivhaus buildings, net-zero buildings and smart buildings, as they directly seek to be energy efficient, energy producers, have zero carbon emissions (including embodied) and provide grid flexibility. Active buildings in this framing are defined as “a building which supports a country’s energy infrastructure” (Nikolaidou et al. 2020) or more broadly:

> *“Active buildings support the wider energy system by intelligently integrating renewable energy technologies for heat, power and transport. Active buildings are designed to be energy efficient, with novel ways of creating, controlling, and releasing energy. Active buildings have the potential to be energy self-sufficient. When connected with other Active buildings in a network, they could have the ability to trade energy.” (Active Building Centre Research Programme undated) and (Elliott et al. 2020)*

> *“An active building is one that interacts with the local and whole-energy system. It, therefore, has intelligence and the facility to modulate load and export energy to networks. In its simplest form, it is either energy neutral or acts to minimise local energy imbalances. In this way, it can reduce stress on the local networks and hence investment costs for the local network operator. In its full form, it can also interact with the GB whole energy system. Using a range of innovative technologies, ABs can offer both flexibility and generation to local and national network operators” (Strbac et al. 2020, p. 1).*

Thus, most similar to PED/PEN, active buildings focus on renewable energy production thereby reducing the amount of energy drawn from the grid, reduced energy consumption and carbon emissions, in addition to the interconnection of multiple active buildings together and with national grids. Active buildings hold the ability to cross-communicate with energy consumers, energy suppliers (including the building’s own energy supply), as well as other active buildings and energy grids. This similarity to PED/PEN in addition to the explicit mention of ‘intelligent integration’ also links active buildings with smart buildings concepts. However, different to PEN/PED, is the explicit ambition for active buildings to scale-up to further support national energy infrastructures by providing flexibility services. A second distinction is that active buildings do not explicitly emphasise the same holistic, place-specific or user/occupier focus as other green buildings and as seen in PED/PEN definitions. Thus, current active building definitions retain a purely technical focus.

In the UK, several new housing developments are hoping to trial the active building concept at neighbourhood-scale. The Nottingham Trent Basin development is a 3-phase project that will eventually consist of 500 homes (Rossiter & Smith 2018). The aim of the development is to economically regenerate a former brownfield site in Nottingham with a new “sustainable neighbourhood” (Rossiter & Smith 2018, p. 25). To meet its energy sustainability goals, the development has designed a community energy system comprising large battery storage, local energy production and smart devices that allow residents to monitor their own energy use and compare to their neighbours (Rossiter & Smith 2018). In addition, the community energy system is managed by an ESCO with all residents holding shares in the company, thus enjoying community pay-back if they export more energy to the national grid than they use (Rossiter & Smith 2018). In time, such a system could “potentially reduce dependence on the National Grid” while its battery storage can help “provide the National Grid with badly needed flexibility and resilience” (Rossiter & Smith 2018, p. 28).

Parc Eirin and Parc Hadau in South Wales are two new neighbourhoods under development consisting of 225 and 35 homes, respectively. The developments have adopted an energy aggregator model whereby energy production by the homes will be managed in line with the energy demand of the homes and the energy demands of the national grid. To understand the energy demands of the home, the aggregator has established an Energy Services Company who will use smart technology along with occupier information and direct feedback to understand how and when certain energy services are needed. Energy produced by the households on the development is pooled together and used to meet the homes energy needs directly or can be stored within individual household batteries or as thermal storage in hot water tanks. In this way the development offers flexibility to the national grid as it can export energy during peak demand (and thus benefit from export high tariff rates) and store energy during low demand, taking pressure off the grid whilst allowing the homes to use their own energy supply.

8. Critical questions for active buildings

A number of building certifications, labels and conceptualisations have developed across the globe over the past 30 years in particular, aiming to reduce the environmental impact of buildings, in their construction and occupation. One of the earlier certification schemes, GBRS focus on a holistic building design approach, minimising overall environmental impact through consideration of all building resources during construction and occupation as well as measuring occupant comfort once built. EPC labels aim to provide a recognisable, measured energy efficiency rating for buildings that allows comparison of different building energy efficiency for policy makers and building occupants. Staying with energy efficiency, Passivhaus buildings offer an extremely energy efficient building structure that through its design, aims to automatically reduce energy consumption, requiring minimal occupant intervention. Zero emission and zero energy buildings take steps towards the integration of renewable energy production with energy efficient building structures, requiring smart technology to monitor and measure their energy export and import, they also represent steps towards the integration of buildings into wider energy systems. This step towards building and energy system integration has been conceptualised as ZEN and PEB, where single ZEBs are multiplied and networked into neighbourhoods, combining their capacity for renewable energy production and energy storage, providing flexibility to localised energy systems.

With such conceptualisations and ambitions already in play, what can active buildings offer? Is there a need for yet another conceptualisation? As this paper and others (c.f. Torcellini et al. 2006; BPIE, 2011; Williams et al. 2016; D'Agostino & Mazzarella 2019; Liu et al. 2019) have noted, internationally there exists a proliferation of building certification schemes, building standards and conceptualisations already in use. Each is variable in its exact aims, and between nations and sub-national regions. This makes evaluation and comparison of each concept and the buildings they are applied to difficult. It can also create confusion and reduction in the salience of each (Perez-Lombard et al. 2009). Attempts have already been made within the literature to consolidate existing concepts, but there remains a large number still in use. For active buildings to contribute meaningfully to this field, it must offer a clear progression and differentiation of those already existing. As a new concept currently in formation, there is opportunity for active buildings to address both the strengths and weaknesses of predecessor concepts (Figures 1 and 2 provide summary of key strengths and weaknesses to be considered by active buildings).

Strengths to draw on:

- Place-specific – flexible to local environmental, socio-cultural, and economic contexts
- Monitoring of building during design, construction, and occupation
- Flexibility
    - Over time as technologies, the energy landscape, environment, and lifestyles change (both at a societal scale and within households over life course)
    - Facilitating different levels of occupier intervention and control, determined by the occupier but whilst maintaining core functions
    - As per Henwood et al. (2016), allowing occupants to adapt their house to 'feel' like home and to carry out non-negotiable everyday practices that enables a 'life worth living' for them and their 'linked lives'
- Secure, Safe and Private

Figure 1. Elements that could strengthen active buildings

Pitfalls to avoid:

- Over complex 'rules' or standards that are not easily applied by industry
- An imbalance in the distribution of costs and benefits
    - Between developers and occupants
    - Between active building occupants and those of non-active buildings
- Place risk of malfunction / incorrect installation with the occupant
- Limited understanding of occupant energy and other daily practices

Figure 2. Elements that could weaken active buildings

In the first instance, there is opportunity to strengthen the significance of active buildings, widening the existing scope of national-scale ambition to reducing CO_2 emissions, to contribute towards wider international climate change goals. For example, making explicit its contribution to purposeful sustainable development, making active buildings relevant both now and in the longer-term. Several of the UN (2015) Sustainable Development Goals are directly relevant to active buildings, for example:

Goal 7 – ensure access to affordable, reliable, sustainable, and modern energy for all.

Goal 9 – build resilient infrastructure.

Goal 11 – make cities and human settlements inclusive, safe, resilient, and sustainable.

Goal 12 – Ensure sustainable consumption and production patterns.

This also neatly connects with UK sub-national policy ambition, such as the ground-breaking Wellbeing of Future Generations Act (Wales) 2015, that advocates decisions are taken now that do not hold adverse effects for the future. In considering longer-term ambitions, active buildings also link well with EU building directives, such as Directive 2018/844/EU which aims to make buildings developed now, ready for future developments by considering electric mobility and smart readiness in building design and upgrade. These ambitions are not new to active buildings, indeed active buildings are already striving towards these goals, by considering the "whole-life sustainability" of the buildings and taking on a "do no harm" (Nikolaidou et al. 2020) or "non-defornocere" ethos (Coley 2019 cited in Nikolaidou et al. 2020). In addition, connecting and facilitating bi-directional communication between energy efficient buildings with energy production technologies, and energy infrastructures via smart digital technology is clearly taking steps towards a new building-energy infrastructure future. However, the connection to such goals could be made more explicit within active building definitions, especially as compared to other similar concepts (PED and PEN) the environmental or place-specific components of active buildings is muted, thus making clear that they offer more than an opportunity to reduce CO_2 emissions could be of benefit.

Second, the multi-faceted potential benefits that active buildings present by integrating a flexible and variable mix of technology to achieve energy efficiency, energy production, storage and discharge (c.f. Strbac et al. 2020), and zero carbon emissions (including embodied). Furthermore, and most notably, 'active management' of these elements can create grid flexibility and occupant satisfaction - this is perhaps the greatest strength of active buildings that differentiates it from predecessor concepts. Active management of its technologies, occupant specifications and grid capacities would alleviate stress from grids at times of peak demand (daily and seasonal), allowing further integration of renewable energy into the energy system and thus decarbonisation overall. Indeed, the active management of active buildings could mean that even if an active building had higher annual energy demand compared to a NZEB counterpart, their CO_2 emissions could be lower if its management is coordinated with the peaks and troughs of grid CO_2 intensities. With a number of decarbonisation pathways highlighting increased electrification of all energy and recognition of the role that homes can play in facilitating grid flexibility (Ofgem 2020; National Grid ESO 2020), the development of active buildings is timely. A further point in terms of the flexibility that active buildings can offer is the development of the Active Building Code which seeks to ensure that the buildings remain flexible to changing contexts over time, including those of their occupants, their technologies and changing energy landscapes (c.f. Nikolaidou et al. 2020).

Third, a commonality between the voluntary certification schemes (GBs and Passivhaus) is that their take-up has been limited in some ways by the additional complexity and cost working to their criteria/standards entails, and the distribution of economic costs and benefits between the building developer and building occupier. Both factors generate a financial cost of applying standards for the building developer, while financial and perhaps other intrinsic benefits (i.e. lower operational costs and high-quality living accommodation) is enjoyed by the occupier (see also. Elliott et al. 2020). As existing certification schemes (including EPC labels) have had only limited impact on building market prices, increases in sale price are not guaranteed and would currently generate a small increase in profit for building developers. Indeed, if sales or rental prices did substantially increase, this could potentially restrict the occupation of those buildings to more wealthy demographics, raising questions around social and energy justice. Conversely, the impact of smart energy technology on building value is unknown and could possibly have opposite impacts as technologies require ongoing maintenance and upgrades that could be costly or difficult to source (i.e. skilled engineers). Sourcing engineers for the maintenance or repair of air source heat pumps (ASHP) in some areas of the UK for example, is already difficult for some (O'Sullivan 2019). Thus, for active buildings to be more readily implemented a balance would need to be struck enabling fair but also attractive to all, distributions of costs and benefits now and in years to come. Work is ongoing in ABC to understand how and where the costs and benefits of active buildings may be distributed during the life-course of an active building, and in varying networked scenarios.

Lastly, existing building certificates and conceptualisations aiming to increase energy efficiency and reduce emissions from buildings have achieved varying results. In the UK, Building Regulations have incrementally increased energy efficiency requirements, for example requiring insulation, double glazed windows, and efficient energy systems (BEIS 2017b). However, this forms only part of the picture and while improved energy efficiency has likely contributed to reduced energy consumption in UK homes since the 1990s (BEIS 2017b), Building Regulations themselves do not go far enough to enable net-zero carbon by 2050. Other, more purposeful interventions have been developed, but many have demonstrated a 'performance gap' (Mallory-Hill & Gorgolewski 2017; Cozza et al. 2020). It is now increasingly recognised that much of this performance gap can be attributed to the design out of building occupants within the various concepts. In some instances, new technologies and building designs are considered too complicated for people to understand and any requirement on them to intervene in the management of said technologies will cause anxiety and under-performance of the design. In this instance, buildings have been designed that do not require, and work better, without occupant intervention. That being said, research has demonstrated that even when people know they should not intervene with the technology, they still do (Sameni et al. 2015; Botti 2017; Mitchell & Natarajan 2019; Costanzo et al. 2020). Alternatively, designs have become increasingly smart, and require, at least initially, occupant input into the management of their energy system, including the ability to act on digital prompts as to when and when not to use energy in their home (Balta-Ozkan et al. 2014; Hansen & Hauge 2017; Tirado Herrero et al. 2018). Research has demonstrated that while people can appreciate and engage with their energy systems using smart technology, the impacts are largely minimal and short-lived (Hargreaves et al. 2013).

These dichotomous perspectives are unified by the need to both understand, and integrate more fully into models or conceptualisations, those who will be living within such buildings. Through the explicit integration of building occupants into an active building concept, their energy needs and associated practices can form a part of the solution to achieving whole system decarbonisation, as opposed to a barrier (see also, Nikolaidou et al. 2020). Furthermore, while much of the literature has pointed to a performance gap in how buildings perform against their energy/emissions targets, perhaps another performance gap exists in how buildings are expected to perform by the occupants, and how they actually do. This alternative perspective may illuminate why people intervene in their new technologies when they should not, or why they disengage with or circumvent other technologies that need their cooperation. To understand such questions, first it must be recognised that an active home is a *home*. More than a material building, or an extension of energy infrastructure, homes are also places of intrinsic meaning and value, representing to some, security or safe haven; privacy; control; reflection of values; relationships and emotional experience (Després 1991). While such meanings and values are subjectively perceived (Després 1991; Moore 2000; Roberts & Henwood 2019) and thus, will affect daily life in different ways for different people, Active homes will likely alter these meanings, through changing existing materialities, by making public existing private space, through adding a new, or at least perceived, security threat, and through altering communication and contestations. Thus, Active homes will also likely alter daily life, but to understand how this will occur or what form such change will take, it is essential that how home as a place in space and time is both understood and lived in by occupants is elucidated.

Drawing on the point above regarding the temporality of home; the way people live in their homes is related to where they are in their life course and the lives linked to the household at different points in time (Shirani et al. 2017; Hargreaves & Middlemiss 2020). For example, a family with small children, a single person household, a household with infirm or chronically ill occupant(s) or a retired person will hold very different daily practices and energy needs. These are informed by personal socio-cultural contexts combined with psychosocial norms and expectations around caring, security, socialisation, and health (amongst others) that are more or less prominent with different households at different stages of their life course (Groves et al. 2016). These personal contexts and linkages within a household also interplay with linked lives or relationships with others outside of the household (Hargreaves & Middlemiss 2020; Shirani et al. 2017), as well as place-specific contexts and energy geographies (Golubchikov & O'Sullivan 2020; Roberts 2020), which are also changeable through time.

Finally, the materiality of the home, the objects within it and energy technologies will interplay with personal subjectivities to influence how comfort (thermal and otherwise) is perceived and achieved (Roberts & Henwood 2019). Together, these multiple links shape how and why people live in certain ways within their home, including how tangible energy and other daily practices fulfil multiple other intangible and somewhat invisible psychosocial functions (Henwood et al, 2016). Thus, active buildings need to understand building occupants' expectations of their homes, in addition to how and why they carry out everyday practices including those which impact energy demand, in order that active buildings can be flexible through time to adapt to peoples ever-changing contexts as well as those of the wider energy system.

Acknowledgements

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.

The EPSRC reference number for this project is EP/V012053/1.

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