BUILDING TOWARDS NET ZERO CARBON HOMES

THE PRINCE'S FOUNDATION

CLARENCE HOUSE

I am delighted that this year's topic for the *Building a Legacy* report is focussed on building towards net zero carbon homes. This has an impact on how new places are planned, as well as for the design and fabric of the new and existing homes themselves. Given that 70% of all emissions are created by towns and cities, it seems absolutely critical that urban and architectural solutions are built and tested as demonstration projects and then shared and scaled up as quickly as possible. Some solutions may be relatively low-tech and based on historical knowledge, such as using trees for shading and local materials for less embodied carbon. We can learn a lot from studying traditional solutions that used less carbon in their making. However, other solutions will be more innovative and involve technologies that are still under development, like solar tiles and smart communal energy and water systems.

Bearing in mind the speed at which change is needed, it is clearly essential that those landowners, developers, designers and builders who are serious about meeting the net zero carbon challenge should work together to share knowledge and sustainable supply chains to beat the already challenging industry targets. That is why groups like *Building a Legacy* are so important in bringing together the various key players in "making places" in order to benefit from each other's expertise, and to look at how building elements can be sourced and made regionally. Critical to this challenge is the retrofit of existing homes, many of which will have traditional features inside and out, making upgrades more challenging. Again, developing demonstration projects at the scale of the street for different periods of building could be instrumental in convincing homeowners and the various authorities that collective practical action is possible and beneficial.

It is my sincere hope that out of the climate crisis will emerge a more harmonious planning and building practice that is sensitive to the natural environment, healthy for its inhabitants and inherently more beautiful as a result. I wish you all the determination and courage to pioneer the rapid change that is needed.

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THE FUTURE OF OUR HOUSING STOCK

Figure 2: Installing thermal roof insulation

— DR BRENDA BOARDMAN

Two of the major challenges for the UK in 2022 are: how to respond to the climate emergency, and the rapid rises in household fuel bills. There is a link between them: the energy inefficiency of our housing stock. As a result of the increasing cost of energy, the number of households in fuel poverty was set to have more than doubled by October 2022 over the October 2020 level, with fuel bills rising to nearly £3600 this autumn from £1000 two years earlier. Support from the government is planned to cap energy bills at £1300 for 8 million of the poorest households – a 30% increase in their energy costs. For the rest of us the energy cap will be at £2500 a year, so there will still be millions of households faced with extortionate fuel bills from this autumn, struggling to heat their homes and feed themselves. And international gas prices continue to rise – this problem has not been solved. The short-term solution is to subsidise their daily fuel costs, but the permanent response must be to make their homes more energy efficient, so they need to buy less energy. That means capital expenditure on the housing stock. By 2050, there should be no greenhouse gas (GHG) emissions from housing or construction activities. With 40% of the UK's carbon dioxide emissions coming directly or indirectly from buildings (including offices and industry), action on energy efficiency is essential to the UK's contribution to a 1.5C global warming maximum.

So, what must be done, with fuel poverty first? The good news is that the emphasis is gradually switching from installing individual measures to achieving a defined level of energy performance for the whole building, as measured by the energy performance certificate (EPC). Multiple energy efficiency improvements are usually required to upgrade a property and achieve a higher band on the EPC. The focus is on getting homes into the top energy efficiency bands of A - C, in order to reduce the risk of fuel poverty and climate change. Another progressive move is confirmation that the property owner is legally responsible for the energy efficiency of the property, not the tenant. Hence there are now minimum energy efficiency standards for private landlords: no property can be legally rented out if it is F or G-rated. An announcement about the decarbonisation of social housing – owned by housing associations and local authorities – is expected shortly. The rapid rise in energy bills and, thus, increasing numbers of fuel poor households is demonstrating the need for more investment in the energy efficiency of their homes. Otherwise, substantial income support programmes could still be needed into the future. For those on a low income, the government's commitment is to provide each of eight million low-income households with £1200 of financial support at a total cost of £960m. In comparison, the main energy-efficient investment programme, known as the energy company obligation (ECO), takes money from all residential energy bills and spends it on the fuel poor. Ofgem, the energy regulator, has set the scale of the ECO investment at £1 billion per year, which is deemed sufficient to upgrade 112,000 properties at £9,000 each: tackling a tiny proportion of the millions of households likely to be in fuel poverty by October 2022.

The second key issue is the climate change imperative. The built environment is a major consumer of energy, for heating, lighting, and appliances. Of the 40% GHG emissions linked to the building sector, only 13% results from the direct use of fossil fuels (mainly gas) in the home, according to the National Housing Federation. The indirect emissions created by the generation of grid electricity are in addition, while the materials used in a new building, or for maintenance of an existing one, create carbon emissions during their manufacture and transport. This embodied carbon (see below) will be offset if the construction results in a super-energy-efficient building, but if it is just to create a new garage or loft extension the total emissions will increase. Action is needed on all sources of building-related GHG emissions. With new construction, electricity for heating is only a partial solution, especially as electricity is unlikely to be zero carbon before 2035: every new home is therefore adding to our carbon burden daily. To offset these carbon emissions, each new building could have as many photovoltaic panels on the roof as possible. When surplus electricity is contributed to the grid, it will begin to offset the building's additional carbon load. A further consideration for new housing developments and certification schemes (see below) is whether they link into a sustainable transport system. There is no net benefit in building super-efficient homes that foster a car-dependent lifestyle.

What is apparent is that a holistic approach to improving the energy efficiency of the whole housing stock is needed. This is not just a policy on bricks and mortar, it also affects the occupants: many of the fuel poor, often occupying the worst housing, are reluctant to seek help or are hidden, while many individual owners are unsure about how to upgrade the energy efficiency of their homes. For the construction workforce, the challenge is to overcome the focus on the individual skills of particular trades, and to provide the solutions for the property to meet the required standard.

Figures 3-5: One of the first retrofit Certified Passive Houses in the UK, Eco Arc

It would be helpful for homeowners and for the UK's legal commitments on climate change, if the timetable for action on the energy efficiency of all homes was clear and understood. The government's objective is for every home in the UK to be upgraded to a B and C-rating by 2035, so about 60% of all 24 million homes in England will need substantial investment in the next 13 years at a rate of one million homes per annum. For the longer-term climate goals, for instance reaching zero carbon by 2050, all 24 million homes would have to be upgraded again in the next 15 years to get them as close to B and A-rating as possible. This scale of activity is not understood by the general public and is unlikely to be delivered, as now, by finding individual, eligible, fuel-poor properties, and hoping better-off people respond to their newly inflated fuel bills by investing in energy efficiency improvements. For both equity and climate change, a comprehensive strategy, stretching to 2050, would identify the necessary activity for all property owners. Such a comprehensive approach, covering the built environment, indicates a geographical basis, so that the whole country is included and monitored, over time. The most obvious level of governance is those local authorities with housing responsibilities: just over 300 in England alone – these are devolved responsibilities. The local authorities are well-versed in the calibre of their housing stock and have a range of current housing obligations; many still have direct labour departments.

A primary objective of an area-based approach could be to focus initially on those streets where fuel poverty is concentrated. Many of those in the most severe fuel poverty are reluctant to self-identify, even when programmes to assist them exist. If the scheme is based on the street and community level, it should be more likely that neighbours will encourage each other to join in and accept the improvements. Word-of-mouth recommendations, and confirmation that the process of moving towards Net Zero homes is both friendly and beneficial, would be powerful and comforting for residents in the neighbourhood. There are other pragmatic benefits of collective action: for example, for each property, there can be economies of scale, such as requiring just one set of scaffolding for both external wall insulation and photovoltaic panels. There are also savings for the contractors, as they are moving from house to house, rather than travelling considerable distances.

In Northern Ireland, each area of concentrated fuel poverty was quite small, perhaps 125 houses.[1] A rolling programme of contiguous areas was designed so that over a few years, the whole of the local authority was included. Initial scepticism meant that about 50% of households declined assistance at first, so several approaches were needed, together with considerable handholding. This is expensive, confirming that the local authorities may require generous funding from wider sources.

A comprehensive approach is required to improving the energy efficiency of our housing stock. The benefits of reducing climate change, lower fuel bills, and increased energy security means that investment is worthwhile. The result could be reduced fuel poverty, and the legacy of an energy-efficient housing stock for future generations.

Both climate change and fuel poverty are multi-dimensional problems that involve individual solutions and a holistic overview. The benefits from tackling these issues jointly are felt, therefore, by the household and by society.

REACHING NET ZERO REQUIRES A COORDINATED EFFORT

— BEN BOLGAR

Making places to live is one of the most peculiar, interesting, and perhaps frustrating lines of work to be in. It is peculiar in that the most desirable places to live in the UK are mostly well over a hundred years old and some of the least desirable places are less than fifty. It is interesting in that professional town planners and architects, with all their cumulative knowledge and expertise, have largely failed to build successful new settlements at scale. And it is frustrating that with all the endless policies, regulations, and theories we are still struggling to find consensus on how to create more beautiful and environmentally balanced places.

In 2001, the architect Bernard Hunt stated:

> *We have theories, specialisms, regulations, exhortations, demonstration projects. We have planners. We have highway engineers. We have mixed use, mixed tenure, architecture, community architecture, urban design, neighbourhood strategy. But what seems to have happened is that we have simply lost the art of placemaking; or, put another way, we have lost the simple art of placemaking. We are good at putting up buildings, but we are bad at making places.*

Figure 6: The Tower of Babel by Pieter Bruegel the Elder

Making places is clearly a complex system of multiple specialisms, and perhaps this is a field in which the increased complexity and knowledge within each of the specialisms has proved to be an ongoing challenge. Having spent nearly thirty years trying to design places with a host of other experts, local stakeholders, and the wider community, this has very much been my experience. I cannot help but make the comparison to the Tower of Babel[2] narrative where the construction of a ziggurat to the heavens comes to a grinding halt when the common language of the designers and builders is taken away and they can no longer communicate with each other.

What seems to have emerged with the rise of specialisation is not just the loss of a common language in the built environment but also the creation of silos within the regulating and funding bodies concerned. Thus, making it difficult to gain consent and funding for a highly integrated, mixed-income, mixed-use place. That is why twenty years ago The Prince's Foundation pioneered the Enquiry by Design[3] process in order to bring people together from different departments and disciplines to focus on the regeneration or building of a place. In this process, a common language is developed by asking specialists to distil their technical knowledge into short, visual, and simple information with ideas being discussed and drawn in mixed groups on site. It is only once a clear consensus emerges that the specialists are allowed back into their silos to test the solution and feedback any refinements or design changes that are needed. This form of systems thinking[4] is now being more widely recognised[5] as being necessary for driving systemic change for those players involved in making towns and cities.

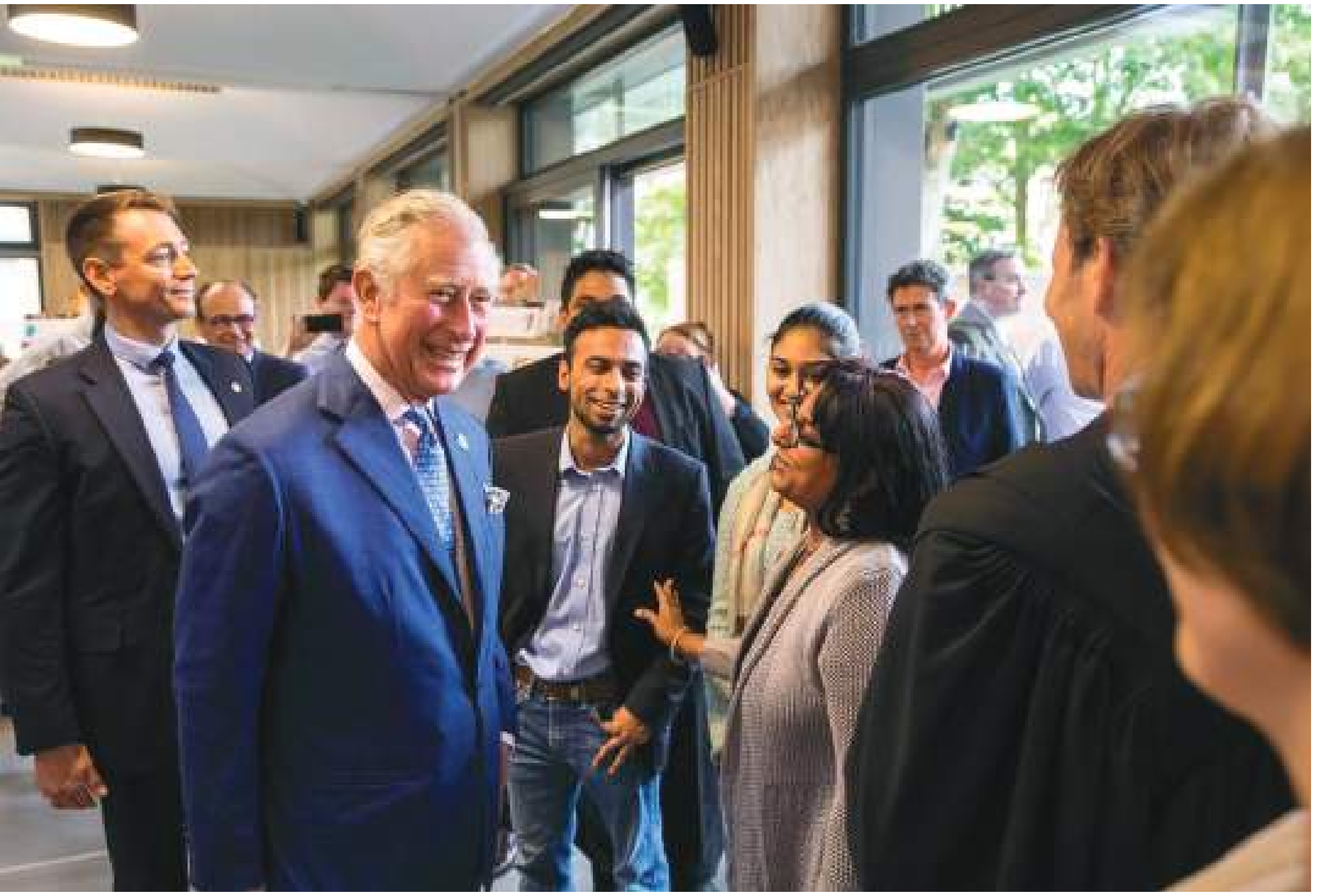

Figure 7: HRH The Prince of Wales visit to Kellogg College , Oxford, May 2017

In terms of holistic thinking The Prince's Foundation is lucky to be guided by its President, The Prince of Wales, who has had continued exposure to the complexity of multiple disciplines throughout his life and particularly through learning from more than 400 charities that he supports. It is largely because of this exposure and his ability to 'join the dots' between the silos that he has been well ahead of the curve in predicting some of the global challenges we now face. Indeed, it is more than fifty years ago that the Prince warned of rising emissions, humans outpacing natural resource, and the accumulation of plastic waste in his first main speech on the environment[6] in 1970. In the same speech, he also spoke about the ecology of natural and human-made environments and the importance of seeing these complex systems and ourselves in harmony with one another:

> *'Conservation' means being aware of the total environment that we live in. It does not mean simply preserving every hedgerow, tree, field or insect in sight, but means thinking rationally and consciously just as much about the urban environment as about the countryside. It should mean for instance that care is taken in housing programmes to see that people are provided with a home and not just a 'house'. All too often the architect seems to forget that a town or a street is made up of individual people and families who happen to have been flung together, and usually the designer is never obliged to inhabit the ecological niche he has created for other people. The word ecology implies the relationship of an organism to its environment and we are just as much an organism as any other animal that is often unfortunate enough to share this earth with us.*
>
> HRH The Prince of Wales

So why is a systems thinking approach, and the focus on placemaking so important for building towards net zero carbon homes? Simply put, we do not believe that these targets can be met by the design of energy efficient homes, or by the design of a mixed-use walkable communities alone. The reality is that the current model of designing and delivering homes in the UK is one of short-term economics where the land is usually purchased at the highest prices and the rest of the build-out period is spent trying to claw back profit from the margins by reducing community amenities and design quality. A different model of stewardship is required[7] that takes a long-term view on investment and builds value over time through the commercial and community infrastructure as well as the quality and energy efficiency of the design.

To explore this issue in more detail, The Prince's Foundation convened representatives from *Building a Legacy* landowners, the Regional and Bespoke Builders Forum, as well as experts in supply chains and finance at Kellogg College, Oxford for a workshop on Delivering Net Zero Carbon Homes in April 2022. There were detailed presentations on the technical work going on to meet zero carbon targets, as well as innovative solutions on energy and supply chains. The case studies and conclusions will be tabled towards the end of this report, but were quite surprising and profound. In essence, the solutions to building towards net zero carbon are not terribly complicated in of themselves, but the barriers to creating systemic change[8] quickly enough are significant due to the disaggregated nature of the various specialists and interest groups.

The conclusions of the event highlighted that there is a great opportunity in coordinating small to medium sized builders in the regions, and aligning them with local supply chains, Legacy landowners and funding partners wanting to take a longer-term view on investment. Expecting the volume industry to change its business model is unlikely in the short term and the

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various components involved with town building are so varied and complex that it would be like completely rewiring an existing circuit. Therefore, the challenge must be to design a new system of relationships and mutual support to move nimbly and efficiently towards a new model and then scale this up in the regions to create a new set of low carbon communities.

Of course, there is also the pressing issue of making existing homes more energy efficient and the current fuel crisis has increased the number of households in the UK in fuel poverty[9] from 4.5 million to 6.5 million, which is nearly a quarter of all households. In Wales, the staggering projection is that 45% of all households could be in fuel poverty by the end of the year. This is having a huge impact on people's quality of life and in many ways should be seen as a national emergency. There is also the issue of creating more airtight homes using synthetic and toxic materials, which again illustrates the danger of silo thinking. So, as we and our partner networks seek to innovate in this field, we should always be mindful of the unintended consequences of a quick-fix solution in one area. Perhaps, we should develop a series of new and retrofit demonstration projects in the regions as a way of coordinating regional networks across many disciplines, and then scaling them up once they have been delivered, tested, and reviewed.

BUILDING THE EVIDENCE BASE

— DR DAVID HOWARD

In December 2020, a report[10] by The Prince's Foundation and partners illustrated that walkable, mixed-use urban neighbourhoods provide a range of benefits for the local economy, and can improve the overall health and well-being of residents and workers. The last *Building a Legacy* report published in 2021, Walkability, Accessibility and Health, presented evidence from a review of 600 peer-reviewed studies which confirmed that the overall positive impacts of higher levels of 'walkability' and wheelchair accessibility, combined with more mixed-use neighbourhoods, delivered better quality of life, notably improved mental and physical health. This current report follows a similar process of rigorous evidence-gathering and review, to consider the pathways to, and impact of, moving towards Net Zero Homes.

Reviews of relevant research literature and peer-reviewed studies were completed by the authors to provide the evidence for this report. A series of keywords were used to conduct a review of peer-reviewed research projects focusing on Net Zero construction, retro-fitting, and sustainable urban living. These themes, outlined further below, are: fuel poverty; household energy efficiency; indoor air quality; embodied energy and the 'hidden' costs of construction, and the role of urban experimentation. Each scoping review was performed using the Scopus and Google Scholar online searches to survey the most relevant literature for the key themes, potential benefits, and potential problems. Reports and papers were accessed via the University of Oxford's Bodleian Libraries resources, if not available by online open access. Of the initial 600 selected research publications, 197 were filtered by relevance to the main themes, and reviewed for this summary of current evidence.

Figure 8: The Prince's Natural House, BRE, Watford

FUEL POVERTY:
UK's growing challenge – affordable fuel for all?

— MICHAEL O'CONNOR

In October 2021, former British Prime Minister, Gordon Brown, issued a dire warning,[11] saying that 3.5 million households faced fuel poverty. A recent Resolution Foundation[12] report warned that the average household energy bill will increase from £1,277 to around £2,000, and that 27% of households in the UK (6.3 million) would spend more than 10% of their income on fuel. The prospect of worsening fuel poverty for many households[13] in the UK during 2022 is now a major social, economic, and political challenge for society. In this context, it is worth revisiting the concept of fuel poverty.

The concept of fuel poverty was first coined in the UK in 1979 after a winter of discontent during which cold weather and an oil shock compounded by strikes meant that fuel was scarce. Two economists, Baron Isherwood and Ruth Hancock, introduced fuel poverty[14] as a term for those "for whom the payment of fuel bills raises difficulties". They defined a household as fuel poor if it spent more than twice the median national expenditure on fuel. Based on the median household expenditure on fuel in the 1990s, Brenda Boardman set the threshold for fuel poverty at 10% of (expected) fuel costs.

The 10% measure is simple to grasp and has been utilised by public health experts to demonstrate a strong link between fuel poverty and measures of public health, such as Excess Winter Mortality[15] among the elderly. It is still the official measure of fuel poverty in Wales, Scotland and Northern Ireland. When the cause of fuel poverty was taken up by the UK government in the late 1990s, the focus was on providing Winter Fuel Payments[16] to pensioners in order to reduce Excess Winter Mortality. In the Warm Homes and Energy Conservation Act (2000)[17] the government committed to eliminating fuel poverty by 2016. The issue, however, remains as challenging as ever, and has been described as a current 'health and social crisis'.[18]

As a result of these challenges, a new definition of fuel poverty was adopted in England and Wales in 2011 following the Hills review.[19] A household is now considered fuel poor if: (i) it has an income less than 60% of the median income for a household of its type (i.e. if it is poor according to the OECD definition[20]), and (ii) has energy needs higher than the median for its household type. This definition seeks to capture the idea that the fuel poor are those who

Figure 9: Smart meter with budget exceeded warning

are both poor and have outsized energy expenditure and is known as the Low Income High Costs (LIHC) definition of fuel poverty.[21]

Studies[22] in the UK[23] have found that the geographical distribution of fuel poverty, and the characteristics of those households in fuel poverty, differ radically depending on which measure of fuel poverty one adopts. Using the 10% indicator, the distribution of fuel poverty is skewed towards homeowners in rural areas, whereas using the LIHC indicator produces a more heterogeneous distribution that includes more urban renters. Other studies have found similar effects[24] in France.

The LIHC indicator is better in several respects insofar as it is more closely targeted and does not rely on a semi-arbitrary threshold that is not based on one used elsewhere (although the 60% figure is somewhat arbitrary, it is the recognised definition for poverty). However, it suffers from its own[25] deficiencies[26]. First, in adopting a relative measure of poverty coupled to a relative measure of fuel costs, it makes fuel poverty ineradicable: there will always be fuel poor people according to this measure. Second, it too fails to fully account for the phenomenon of fuel[27] rationing. Third, it excludes many of those who contribute to Excess Winter Mortality,[28] many of whom are above the 60% poverty line, and so it is less useful from a public health perspective in identifying vulnerable populations.

In an attempt to address some of these problems, the UK government adopted a new fuel poverty indicator[29] in 2020, the so-called Low Income Low Energy Efficiency (LILEE)[30] indicator. According to this new indicator, a household counts as fuel poor if it occupies a property with a fuel poverty energy efficiency rating[31] of band D or below, and spending the amount of money required to heat their home would leave them with an income below the poverty line. This definition is explicitly targeted at identifying those who are liable to poverty because of their energy costs. In doing so, though, it ignores those who live in

Figure 10: Burning gas

ACCORDING TO THIS LILEE INDICATOR, A HOUSEHOLD COUNTS AS FUEL POOR IF IT OCCUPIES A PROPERTY WITH A FUEL POVERTY ENERGY EFFICIENCY RATING OF BAND D OR BELOW, AND SPENDING THE AMOUNT OF MONEY REQUIRED TO HEAT THEIR HOME WOULD LEAVE THEM WITH AN INCOME BELOW THE POVERTY LINE.

relatively efficient homes, but do not keep them at the requisite temperature, possibly because they are poor for other reasons, such as rising energy prices–particularly relevant at the present moment. It also focuses very narrowly on heating to the exclusion of other non-heating energy uses, such as refrigeration, lighting, hot water, and transport costs. This focus on heating to the exclusion of other uses of fuel is a running problem[32] with political rhetoric and policy in the UK.

In addition to these objective indicators, there are also more subjective indicators of fuel poverty that rely on self-reporting. The European Commission[33] has advocated for a definition based on[34] three self-reported indicators[35] including inability to keep a home adequately warm, arrears in utility bills, and the presence of leaks, damp, or rot. Such subjective indicators are better able to include households which may be rationing fuel use, and thus would not show up on objective indicators. They also link fuel poverty to other housing-related health risks, such as mould and damp, thus capturing the broader population of those who are at risk from poor health.[36] But such measures suffer from all the challenges associated with self-reporting.

Several authors argue that we should combine subjective indicators with objective ones,[37] and have proposed a diverse dashboard of indicators for fuel poverty–a so-called 'basket of measures'[38] approach. The advantage of such an approach is that it allows us to identify different populations at risk in different ways from lack of fuel. We can disaggregate energy vulnerability into several different categories and identify different populations vulnerable along a particular axis, or along multiple axes. Categories might include: 'those vulnerable to poverty due to fuel costs', 'those with excessively large fuel costs', and 'those with poor insulation'. These populations may not all meet the definition of poverty as set out by the OECD, so we might call this umbrella[39] concept[40] 'energy[41] vulnerability'[42] rather than fuel poverty.

Which indicator we use will depend on which population we are concerned with. If we are interested in isolating those who, for whatever reason, find it hard to heat their homes then the 10% measure may be a useful one, perhaps combined with a subjective thermal discomfort measure. A useful tool might also be the 'Index of Vulnerable Homes',[43] developed by researchers in Spain to identify homes that are inadequate in terms of the cost of heating and thermal comfort, independent of household income. If we are interested in those who are in poverty due to their fuel costs, we may choose a measure that identifies those who would not be in poverty if their fuel costs were subtracted.[44] The project of developing a more expansive range of indicators has begun in Spain.[45]

Once we have developed a range of indicators, the question is what we do about energy vulnerability. Boardman identified three sets of levers: household income, fuel prices, and household insulation.[46] Thus far, the focus has largely been on interventions targeted at improving household insulation, such as retrofitting, although the UK government also continues to support Winter Fuel Payments.[47] This agenda dovetails with climate concerns, since retrofitting also reduces emissions. But while retrofitting is a crucial element of any programme to tackle energy vulnerability, fuel-side, or income-side interventions[48] could profitably be re-visited. Now may be the moment to look for solutions that pay attention to the full range of energy vulnerability, and the underlying need to provide affordable fuel for all.

ENERGY EFFICIENCY AND INDOOR AIR QUALITY: healthy homes or 'toxic boxes'?

— CHLOE CURTIS

Figure 11: Kleines Haus, Luftpolsterfolie

Creating healthy and comfortable indoor environments is of global concern. In the UK, we spend about 90% of our time in closed indoor environments,[49] the majority at home. Following months of soaring energy prices,[50] with increasing numbers of families placed into fuel poverty and struggling to heat homes over the winter months, the UK and large swathes of the world have experienced record breaking high summer temperatures[51] due to climate change. The importance of reducing our energy consumption for climate health and cost of living, while providing buildings that successfully protect its occupants from extreme weather events, has never felt more imperative.

Since 2006, the England and Wales Building Regulations, Part L, placed an increased demand for energy conservation[52] of buildings, focusing on making them more airtight to reduce fuel and power use. Recent updates to this legislation, since the introduction of The Future Homes Standard,[53] will require new build homes to be future-proofed with low carbon heating and world-leading levels of energy efficiency from 2025. Data from 2021[54] show that the median energy efficiency score for dwellings in England and Wales are in band D, and therefore new legislation aims to improve this rating on the A-G scale.

More broadly across Europe, the first version of the Energy Performance of Buildings Directive (EPBD)[55] was published in 2002, with a revised version in 2010[56] stipulating that all new buildings constructed in European Union (EU) member states should be 'nearly zero-energy buildings' by 2020. The proposed latest recast of the EPBD from 2021[57] set out new definitions of 'nearly zero-energy buildings' compared to 'zero-emission buildings', with a priority placed[58] on the deep renovation[59] of all existing building stock. Similar to UK priorities, the realisation of these objectives has placed emphasis on airtight building envelopes for energy efficiency constructed using plastics, sealants and insulation together with the latest window technologies and heat recovery ventilation systems. With buildings being one of the largest sources of energy consumption across Europe, accounting for 40% of energy consumption and 36% of greenhouse gas emissions[60] in EU member states, these regulations have therefore tended to focus on improving energy efficiency for the subsequent impacts on climate change and air quality of outdoor environments.

Nevertheless, most illnesses related to environmental exposures stem from indoor air.[61] Building materials, furnishings, and activities all produce emissions that contribute to indoor air quality. In lower and middle-income countries, at least 2 million deaths a year[62] are attributed to the unvented burning of biomass for cooking in homes. The result of poor indoor air quality is also a main cause of sick building syndrome,[63] which can include allergies, wheezing and airway infections.

One of the most common[64] contaminants of indoor air is volatile organic compounds (VOCs), which are emitted by materials we use to build and maintain our homes. They can be absorbed into the body via the air we breathe and can transfer through our skin. They can cause headaches, eye and respiratory irritations, and are associated[65] with long-term health effects such as allergies and asthma. The types of materials used in buildings have increased from roughly 50 to 55,000[66] over the last century, with only about 3% of these materials having been tested for their toxicity on humans. This represents thousands of new sources of potential pollutants for harmful indoor air. In Melbourne, Australia,[67] the median level of VOCs across 40 dwellings was greater than those measured outdoors. According to the United States Environmental Protection Agency (EPA), the average level of VOCs[68] in homes is five times higher than outdoors. In Beijing, despite rates of smoking and outdoor pollution having decreased, there has been a 56% increase in lung cancer. It is suggested[69] that exposure to formaldehyde, one of the most common VOCs, in remodelled dwellings could be the main cause of this increase.

> IN MELBOURNE, AUSTRALIA, THE MEDIAN LEVEL OF VOCS ACROSS 40 DWELLINGS WAS GREATER THAN THOSE MEASURED OUTDOORS.

Microbial pollution, including bacteria and fungi from damp and mould, is another key factor that impacts indoor air pollution. This can develop[70] when there is deficient building maintenance, defects that lead to water ingress, and a lack of effective ventilation, which all result in an increase in moisture. This can have serious implications for health, with a strong link[71] between dampness in buildings, mould growth, and associated respiratory diseases. For example, in Sweden[72] it was found that 80% of 605 single-family houses did not fulfil the minimum ventilation rate requirement, which is suggested to have severely contributed to an increased rate of asthma and rhinitis.

It is not only outdoor pollutants that are of concern. Indoor air quality is paramount to human health as well. So, is the current focus on making buildings more airtight to conserve energy creating healthier homes or is it entrapping us in toxic boxes? By aiming to conserve energy are we unintentionally creating worse indoor environments for human health?

When assessing the impacts of making buildings more airtight, and in turn more energy efficient, two areas of concern and investigation are commonly referenced; firstly, the types of building materials that are used, and secondly, the methods of ventilation. A study conducted in Sweden[73] pre-schools found better indoor air quality in those that had been constructed or significantly renovated with environmentally friendly materials. Similarly, two studies in Korea found a reduction in the severity of atopic dermatitis when environmentally conscious materials were used including lacquering made from tree sap[74] and environmentally friendly paint[75] instead of conventional wallpaper. Findings from the UAE,[76] Japan,[77] China[78] and Finland[79] suggest that newly remodelled buildings using conventional or unregulated materials exceeded national or WHO standards of indoor air quality, including VOC levels.

It should be noted, however, that VOC emissions are highest immediately after construction or renovation of buildings. For example, several hours after renovation activities, such as paint stripping, VOC levels may be 100-1000 times[80] higher background outdoor levels. Over time VOC concentration reduces. While better indoor air quality was found in Swedish pre-schools[81] constructed with environmentally friendly materials, with lower initial VOC concentrations, comparable emissions were observed after one year of occupancy between all preschools. Therefore, comparing the indoor air quality of newly constructed or renovated buildings with existing buildings is arguably a skewed data point and understanding how indoor air quality will change over time is important. In order to minimise the impacts building materials have on human health, it is suggested that excessive renovation should be avoided[82] and, wherever possible, alternative regulated and sustainable materials with lower emissions should be used.

Another way to improve indoor air pollution, is to ensure good air exchange rate with effective and safe ventilation. Ventilation serves multiple purposes[83]; removing or diluting indoor air pollutants, including VOCs and excess moisture, establishing a balance of fresh air and regulating the indoor thermal environment for the comfort of occupants. The majority of homes[84] are currently controlled by natural ventilation methods, such as the opening and closing of windows, and the use of trickle ventilators in any double or triple glazing

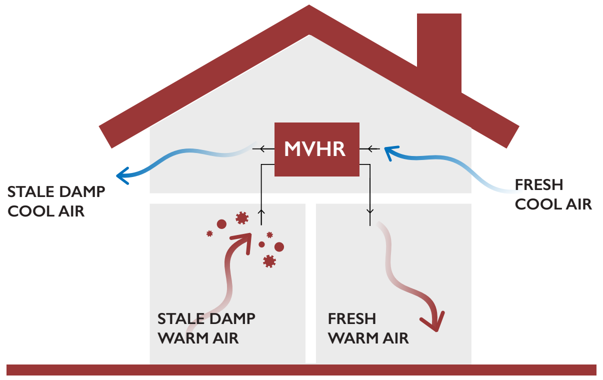

Figure 12: Mechanical Ventilation Heat Recovery (MVHR)

units. These methods can be counter-productive in terms of achieving greater energy efficiency, as they can be a source of heat loss. There are several other mechanical ventilation systems, however, that offer greater energy efficiency, including the mechanical ventilation heat recovery (MVHR) system which extracts warm, damp air from a home and draws in fresh air from the outside. The latest 2022 update[85] of the England and Wales Building Regulations, Part F, requires different ventilation systems dependent on the airtightness of a building, enforcing the importance of 'building tight – ventilating right'.[86]

Perhaps the most iconic building development associated with improving airtightness and energy efficiency is the Passivhaus, or Passive House. While they have an energy consumption that is extraordinarily low compared to conventional buildings, a study conducted in Scotland[87] across five certified passive houses found that imbalanced MVHR systems were present in 80%, contributing to overheating, with temperatures exceeding 30°C, and higher levels of indoor emissions. Similar findings[88] were reported in other UK Passivhaus dwellings. A study[89] comparing mechanically ventilated and naturally ventilated social housing in the UK found significant indoor air quality issues and thermal comfort in both, showing no overall improvements with more energy efficient systems and occupants reporting the air quality as 'stuffier' in more energy efficient homes. One of the reasons suggested for these results was the lack of knowledge of use and maintenance of the mechanical ventilation system. These studies highlight that MVHR is a relatively new technology for domestic dwellings and consequently there have been issues with design, installation, commissioning, and occupant use that have led to these systems not operating as intended. The use of low emission materials[90] would alleviate the need for a higher air exchange rate. The types of materials used to make a building airtight, and the level of energy efficiency achieved, therefore work closely in partnership with the requirements of a ventilation system and should complement each other.

Despite numerous studies evaluating indoor air quality of energy efficient buildings, conclusive evidence about its impact on human health is often speculative. Instead, regulations of sustainable design[91] have focused primarily on resource conservation, energy evaluation and outdoor air quality. One of the main challenges is the lack of appropriate measures. A focus on indoor air quality is largely missing[92] from the UK's environmental rating, the Building Research Establishment Environmental Assessment Method (BREEAM), with its assessments for eco-houses addressing only one of 23 indoor air quality issues.[93] A building can achieve the highest BREEAM rating without addressing any indoor air quality criteria. It is also argued[94] that the Passivhaus standard do not provide comprehensive and standardised strategies for indoor air quality and the protection of human health. Different assessments provide guidelines that vary, often without justification or verification,[95] meaning indoor air quality and subsequent impacts on human health remain a precarious and unregulated field. Emission labelling systems[96] for building materials are also not always available. While some European countries have introduced rating systems, they are not consistent and are voluntary schemes. The lack of consensus[97] across these measures means there are issues with legal responsibilities for monitoring and reporting.

When indoor air quality is assessed, it is often done in a way that does not take into account 'real life scenarios';[98] measurements are taken without occupants, when trickle ventilations are unblocked,

Figure 13: The Prince's Natural House, BRE, Watford

and doors open. Measures that focus on determining total emissions have also been developed for ambient and industrial air and may not be appropriate[99] for home dwellings. Instead, measures of exposure are important to determine impact of indoor air quality. Measurements of indoor air quality and human health also lack a holistic approach, with research siloed[100] by a lack of collaborative research. A broader understanding of indoor environments,[101] rather than just indoor air quality, that take into account factors such as lighting, interior systems, building operation, and occupant experience are needed to account for overall health.

Airtight homes are highly likely to have poor indoor air quality[102] if the correct materials and ventilation systems are not used. Current legislation is heavily weighted to energy conservation goals, with indoor air quality and impacts on human health of secondary concern. Priority is placed on buildings as energy efficient entities, with little regard for understanding how they become healthy and comfortable homes for occupants. While there are remaining challenges, current studies and research provide initial suggestions for how we can address these issues more comprehensively.

ACHIEVING NET ZERO HOUSEHOLD ENERGY USE

— LUCY MAIN

In the UK, domestic buildings account for around a third[103] of the energy budget. One fifth were built pre-1919, giving us some of the oldest housing stock in the world. Accordingly, retrofitting this stock, which forms 80% of the homes needed for 2050,[104] is one of the most cost-effective ways to reduce energy consumption. Modelling[105] suggests that using efficiency measures to achieve a 25% reduction in energy use by 2035 would save households an annual average of £270 and create over 60,000 new jobs. There may also be tangible benefits to occupant health: the NHS could save an estimated 42p for every £1 spent on effectively retrofitting fuel poor homes.

But what, specifically, constitutes a net zero energy building (NZEB)? Since 2021, an EU directive[106] has required all new buildings to be 'nearly zero energy'. Renewable energy should 'to a very significant extent' cover the 'very low amount of energy required' by the new build; in practice,[107] the performance threshold is determined by Member States, accounting for their specific climate and housing stock. The US Department of Energy (DOE) stipulates that an NZEB is 'an energy-efficient building where, on a source energy basis,[108] the actual annual delivered energy is less than or equal to the on-site renewable exported energy'. However, publications often use an 'on-site' basis,[109] simplifying calculations by ignoring the generation mix and supply chain consumption.

Many domestic energy saving strategies are passive. The passive house (PH) standard, most applicable[110] to colder climates where space heating dominates consumption, targets 15 kWh/m^2 annual heating load intensity. This is achieved with improved insulation and reduction in thermal bridging, eliminating the need for conventional heating. Such airtightness demands mechanical ventilation with heat recovery to retain heat while providing fresh air for occupants. Retrofitting[111] buildings to the PH standard often necessitates high up-front costs, although they may pay for themselves in the long-term, and can risk occupant health and structural integrity when significant building envelope changes create inadvertent moisture and ventilation problems.

Retrofits seldom reach new-build standards, as existing characteristics – including shape, orientation, heritage status and neighbouring structures – can limit the viability of certain efficiency measures. Nevertheless, successful PH retrofits[112] exist of pre-1900 cottages and Brooklyn brownstones. A case study[113] of fifty Canadian homes found that deep envelope retrofits and heat pumps could reduce community energy consumption by 69%, with net-negative homes compensated for by net-exporting neighbours. However, retrofitting requires extensive analysis to choose bespoke, cost-effective measures and can suffer when tradespeople lack knowledge and resources. Storage technology is also currently insufficient to make off-grid NZEBs realistic, but future PHs with renewable resources may be able to store energy in times of excess to meet future shortfalls, or even enable homeowners to sell to the grid when demand is high.

MODELLING SUGGESTS THAT USING EFFICIENCY MEASURES TO ACHIEVE A 25% REDUCTION IN ENERGY USE BY 2035 WOULD SAVE HOUSEHOLDS AN ANNUAL AVERAGE OF £270 AND CREATE OVER 60,000 NEW JOBS

In climates where cooling dictates energy use, passive design instead emphasises[114] building shape, shading, window-to-wall ratio, and site layout. These considerations are vital, as solar radiation can increase energy consumption by up to a quarter. The best strategies vary between locations, but a study[115] found that typical annual energy use could be halved in the Middle East and North Africa region. Photovoltaic (PV) systems are increasingly competitive in hot climates and provide a sustainable way to compensate for cooling demands, although, in areas with higher population densities and more multi-residential buildings, there is inevitably less space for PVs and natural light is restricted by neighbouring structures. However, a 'double-skin green façade'[116] of indigenous plants on multi-storey dwellings could reduce cooling-related energy consumption by three quarters, whilst improving humidity, air quality, biodiversity, noise insulation and reducing CO2 levels.

Another source of inspiration is vernacular architecture: traditional passive measures were modelled[117] to reduce the annual energy demand of an average Mauritian house from 24 to 14 kWh/m^2. Similar strategies in Cuban architecture[118] – wind permeable fibres, shade from foliage and pitched rooves for diffuse daylight, rainwater collection and convective ventilation – provide comfort when both temperature and humidity are high. Adobe was once widely used as a construction material in Saudi Arabia. It is durable, locally available, inexpensive and less

Figure 14: Wooden Ornate Windows, Mashrabiya

carbon intensive than reinforced concrete. One model[119] suggested that it could reduce annual electricity use by 6%, whilst mashrabiya (Islamic oriel windows providing natural ventilation and diffuse natural light) resulted in a 4% reduction.

Controlling for the many variables that affect household performance is a major challenge to NZEB construction. Simulations[120] indicate that energy consumption can vary by around 15% with weather. Moreover, anthropogenic climate change means measures must be robust enough to provide enough energy and maintain efficiency under more extreme weather conditions and at higher average temperatures. This is particularly relevant to semi-arid regions, where cooling demand could increase by over 10% by the end of the century.

Occupant behaviour is crucial to NZEB success, as homes are more than just a building envelope. Energy consumption can increase by over 100% with wasteful behaviour, potentially undermining gains made elsewhere. Another great advantage of making our homes less wasteful is the 'freeing up' of emissions for sectors that are harder to decarbonise, such as transport. Occupants need information to get the most out of high-efficiency systems, particularly where smart technologies demand familiarity with user interfaces or necessitate certain behavioural changes.

Half of surveyed residents[121] in highly insulated Norwegian houses reported that bedroom temperatures were too high, with many opening windows to improve comfort at night. By creating a uniform temperature profile, the PH design inadvertently encouraged behaviour that compromised its effectiveness. Fortunately, a review[122] of energy consumption in over 2000 newly built PHs found that they generally suffered a smaller 'performance gap' than non-PH houses, despite wide variation in occupants' space heating behaviours. Overall, they achieved the PH standard with an average annual space heat energy consumption of 14.6 kWh/m².

A study[123] has identified seventeen energy-saving actions (ranging from retrofitting to more efficient driving) and used empirical studies to account for 'plasticity' – the proportion of the population who could be induced to change their behaviour. It demonstrated that 20% of US direct household emissions could be saved after a decade by national implementation of these actions, more than the total emissions of France. This is testament to the active role occupants can play in saving household energy in their everyday lives; when coupled with passive measures, this offers a vision of a future where every home is an NZEB.

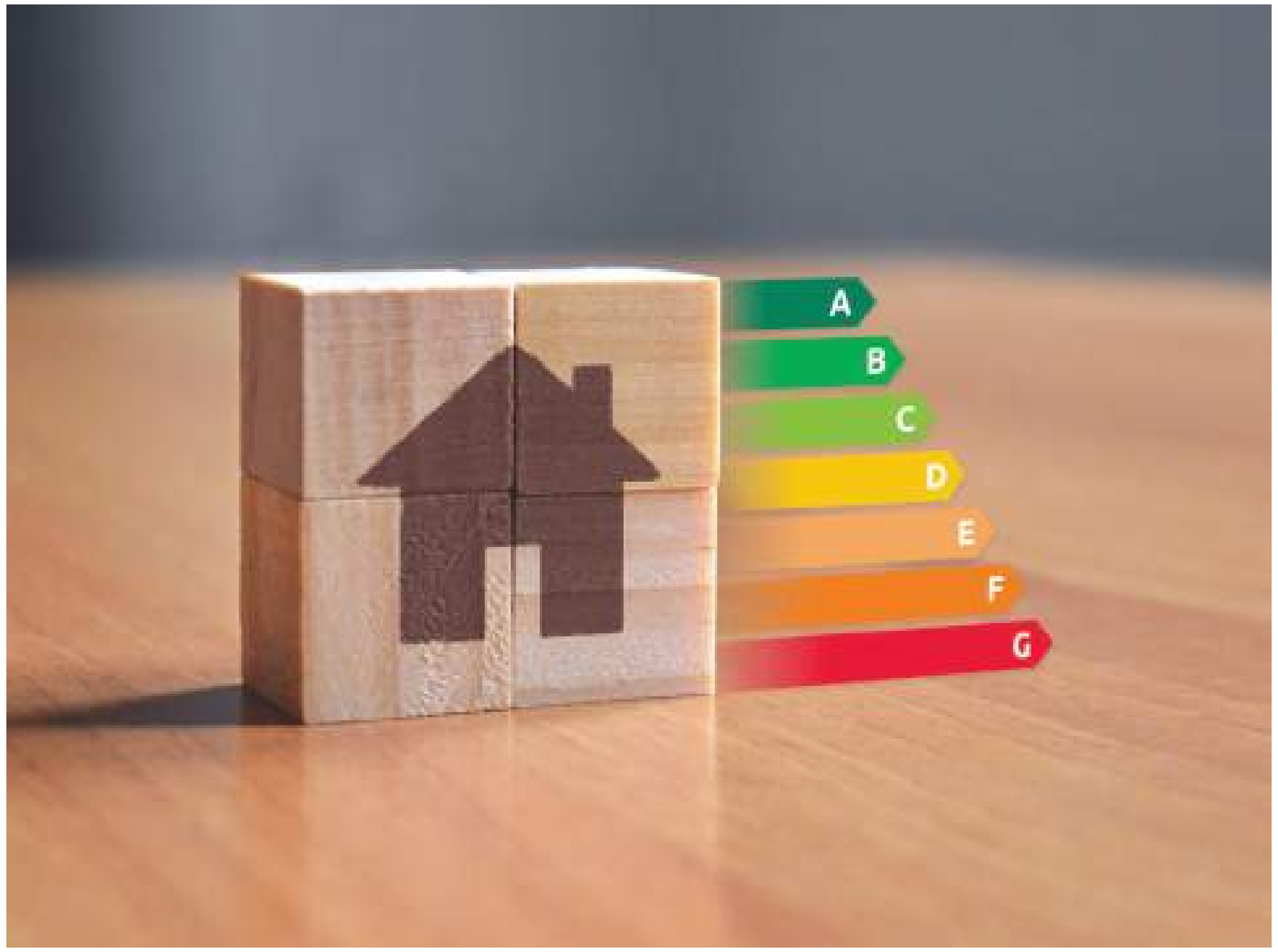

Figure 15: Energy Performance Certificate

THE HIDDEN COSTS OF CONSTRUCTION

— ELEANOR COSFORD

The building sector is responsible for around 40% of global energy use,[124] which contributes over one third of global CO2 emissions. Heading towards climate goals in future years, considering the embodied energy of buildings is increasingly important if we want to accurately assess environmental impact of buildings.

A building's life cycle energy is composed of its embodied energy[125] and its operational energy. The operational energy of a building is the energy used daily for things like cooling and heating. Embodied energy is the energy associated with a material's life cycle, often including but not limited to production of building materials, and replacement of building parts. In recent years there has been lots of research into technologies which have led to reductions in operational energy use.[126] There has not yet been much research into reducing embodied energy. As a result, embodied energy is only now becoming relatively more important to consider when designing a building.

As there is no consistent methodology for measuring the embodied energy of a building, findings are often hard to compare. Based on a recent study,[127] 98% of embodied energy values considered a building's production stage, with 71% also taking replacement of building parts into account. After this, boundaries differ significantly with some other methods accounting for construction energy and others accounting for demolition energy. Clearly, a universal methodology with defined system boundaries which clarify what is included in measurements, would help allow embodied energy to be compared more easily and accurately.

A material's embodied carbon depends on the energy mix of the nation[128] where the raw materials are sourced, and where the desired material is produced. A material could have the same embodied energy across many countries, but if the processing takes place in a country with a higher proportion of green energy sources in its energy mix, the embodied carbon is likely to be less. Therefore, considering where a material comes from before buying it can minimise environmental impact.

The use of recycled materials in new buildings can reduce embodied carbon. For example, runway material[129] from closed airports can be used for aggregate in building foundations and slabs. Since trees sequester carbon in their growth cycle, using wood as a construction material can have a carbon negative footprint, if it is locally grown sustainably and processed using renewable energy. Concrete can also sequester carbon from the atmosphere, since carbon dioxide in the air can react with the material during its life cycle, resulting in a process called carbonation. Studies show[130] that the amount of carbon captured by concrete is greater during its secondary life, when it is likely to be used for more temporary structures, than during its primary life, though during its second life it is generally lower quality. However, cement (a key component of concrete) is globally responsible for more carbon emissions[131] than any country other than US or China.

Using more locally sourced materials can reduce carbon footprints, hence reducing embodied carbon, since transport emissions will be reduced. This can be done without needing to change any building designs or construction materials, making it relatively convenient. In addition to this, if a building needs to be replaced or knocked down, instead of just demolishing the entire thing, the central core can be saved[132] in certain cases, which can save thousands of tons of material in some buildings.

To reduce a building's operational carbon emissions, it almost always requires additional embodied carbon as the building is constructed. It is crucial to consider the environmental impact of materials used in any future green or sustainable building rating and assess the carbon neutrality of a building across its entire life cycle, to accurately determine the total impact of a building.

For conventional single-family homes embodied energy can contribute 50% of the life cycle energy use[133] and for low energy/net zero homes this can be up to 100%. Reducing embodied energy within homes will have a significant impact on the life cycle energy[134] used by a house. For instance, using timber[135] instead of concrete or steel can reduce embodied energy and adjusting concrete composition by substituting clinker with mineral additions can reduce CO2 emissions.

Alternatively, a Passive House is a building standard which aims to minimise operational energy use. Although Passive Houses generally require more energy to build than conventional houses, the design can reduce life cycle energy by approximately 30%.[136] Passive houses generally have thick insulation, external and internal, up to 40cm thick,[137] made from materials with low embodied energy such as wood or mineral wool. This insulation also helps to protect the building from additional thermal stresses. A study[138] of a Passive House in a sub-tropical climate showed that increasing mineral wool insulation thickness from 2cm to 20cm only increases the total embodied energy of this Passive House by 0.5%, whilst dramatically decreasing the energy required for heating and cooling. This makes the house significantly more efficient therefore saving energy in the long term. Passive Houses can also use high performance low emissivity windows to prevent thermal losses and reduce peak cooling and heating loads. Overall, Passive House design can reduce operational energy demand by up to 90%[139] showing that a higher embodied energy of a building can lead to significant reductions elsewhere.[140]

To conclude, embodied energy is something that still seems to be brushed to the side in research, with life cycle energy costs rarely included in building evaluation. Establishing a consistent, universal methodology and system boundaries for measuring it is likely to make comparison significantly easier; this is key for progress and reducing the overall long-term impact of buildings. Furthermore, to head towards climate neutrality and as buildings become more efficient in the way they operate, embodied energy in homes is something that needs to be reduced as it still contributes greatly to life cycle energy use. We should also aim to reduce embodied carbon however we can, even though this may be more costly up front. Whether that be by using different materials, using more local sources or being aware of the energy mixes in the places that materials are being sourced from.

ALTHOUGH PASSIVE HOUSES GENERALLY REQUIRE MORE ENERGY TO BUILD THAN CONVENTIONAL HOUSES, THE DESIGN CAN REDUCE LIFE CYCLE ENERGY BY APPROXIMATELY 30%.

Figure 16: The Prince's Terrace, Adelaide

Figure 17: The first 6 star green building in Australia, The Prince's Terrace, Adelaide

TRENDS IN URBAN EXPERIMENTATION: sustainability infrastructure and green certification schemes

— JUAN VALENCIA

At the recent COP26, pledges were made to achieve significant actions to limit temperature rises to 1.5ºC, which brought the built environment into central focus. This is because urban infrastructure and buildings are responsible for up to 80% of emissions in some cities,[141] and 28% of the energy-related greenhouse gas emissions globally,[142] highlighting the need to transition away from fossil fuels and adopt green building solutions as part of the climate action. The International Energy Agency (IEA) has identified the building sector as one of the most cost-effective sectors for reducing energy consumption,[143] with estimated possible energy savings of 1.509 Mt of oil equivalent by 2050. Moreover, by reducing an overall energy demand and improving energy efficiency, building infrastructure can significantly reduce CO2 emissions, corresponding to a possible mitigation of 12.6 Gt of CO2 emissions by 2050.[144] This section evaluates the responses of the construction industry by considering the rise of urban experiments. Urban experimentation has focused in recent years on mitigating environmental challenges at different scales, from singular buildings to housing districts. Researchers and practitioners are now moving past isolated experiments to consider how more long-term and varied modes of experimentation can stimulate broader urban transformation,[145] emphasising the need for understanding the durability of experiments within the broader urban context. The latter part of this section demonstrates the need to adopt efficient assessment tools and methods, such as green certification schemes and post-occupancy testing, to ensure durability.

Urban infrastructure and buildings have direct and indirect impacts on the environment. During construction, occupancy, renovation, repurposing, and demolition, buildings use energy, water, and raw materials. Additionally, they generate waste and emit potentially harmful atmospheric emissions. Together, buildings and construction account for 36% of global energy use and 39% of energy-related CO2 emissions.[146] Reducing environmental impacts associated with construction processes and ensuring efficiency of buildings to reduce energy use is crucial to meet global climate agreements.[147] To portray the different approaches that mitigate the environmental impact of urban infrastructure, urban experiments can be evaluated at a variety of scales.

At the individual house scale, urban experiments have focused on energy usage and efficiency of houses. In Chile, energy demand in buildings is responsible

Figure 18: Experimental testing and occupancy, The Prince's Natural House, BRE, Watford

THE INTERNATIONAL ENERGY AGENCY (IEA) HAS IDENTIFIED THE BUILDING SECTOR AS ONE OF THE MOST COST-EFFECTIVE SECTORS FOR REDUCING ENERGY CONSUMPTION, WITH ESTIMATED POSSIBLE ENERGY SAVINGS OF 1.509 MT OF OIL EQUIVALENT BY 2050 for 25% of all greenhouse gas (GHG) emissions,[148] with the highest emissions due to gas and biomass consumption for heating. It has been recognised that insulation in existing houses is insufficient or, and in most cases, non-existent.[149] Improving the thermal performance of houses could substantially improve thermal comfort and health, as well as reduce energy consumption and associated greenhouse gas (GHG) emissions. As in other countries, the great challenge in reducing energy demand in Chile's housing sector is rooted in the thermal retrofitting[150] of existing housing. Many existing houses were constructed before the development and introduction of thermal regulations; thus, these houses represent most of the total energy consumption across the residential sector. Research evaluating the performance of energy-efficient housing is vital to support to progress towards a low-carbon housing sector[151] in Chile. Passivhaus has been widely promoted as an approach for low-energy housing.[152] Although originally developed in Europe, the approach is suitable in different climates, suggesting its suitability in Chile. Comparing the performance of different energy-efficient housing solutions in Chile shows that, in most cases, the traditional housing required 10% more energy than a house built with the Passivhaus standard in hot climates and 90% in cold climates.[153] However, by thermally retrofitting traditional houses in hot climates, it is possible to reduce energy demands and achieve thermal performances that meets Passivhaus standards.

At a larger housing district scale, studies have documented the emergence of urban experiments focused on key urban infrastructure networks: energy, transport, the built environment, water, and sanitation. For example, Bangalore is a rapidly growing city that has undergone a profound social and economic transformation in the last two decades. This has had a strong impact on its urban fabric, as new infrastructure is developing on the edge of the city to serve the needs of an emerging industry and middle-class population. These new gated communities are putting pressure on the city's resources, in relation to the supply of energy, but particularly with respect to water. Towards Zero Carbon Development (T-Zed) emerged as a project that seeks to provide an alternative for higher-income classes in Bangalore, taking the form of a gated community on the outskirts of the city. This development, managed by a private developer, Biodiversity Conservation India Limited (BCIL), incorporates numerous social and technical innovations with the intention of reducing the carbon emissions, decreasing the embodied energy of the building, and managing pressure on city's resources.[154]


Figure 19: Residential area and public green space, Milan

T-Zed provides an alternative, greener, market for high-income professionals that attempts to deal with water scarcity, but also contributes to an emergent low carbon urbanism trend in the construction industry. The success of this project, incorporating sustainable ideas about housing and Western appliances at this scale, provides advice to the Indian government on the potential for energy conservation in buildings at a national scale. In this way, the presence of T-Zed within the urban landscape of Bangalore is serving to transform and reconfigure urban infrastructure systems more broadly, by encouraging discourses of responsibility and carbon control.

While urban experiments such as T-Zed, constitute an alternative to conventional forms of building development, they fall some distance from solving fundamental problems of sustainability and infrastructure provision. Green building standards, certifications, and rating systems emerged as tools to assess the impact of new buildings on the natural and social environment. These certifications are intended to outline and establish building standards to ensure they offer socio-economic and environmental benefits. With the launch of the Building Research Establishment's Environmental Assessment Method (BREEAM) in 1990, the first green building rating system in the world, was followed by Leadership in Energy and Environmental Design (LEED) in 2000. Green building certifications are on the rise[155] as market conditions change and the demand for greener products continues to increase. Most certification programmes assess infrastructure and buildings based on multi-attribute programmes, including parameters such as energy use, recycled content, and air and water emissions from manufacturing, disposal, and use. Others focus on a single attribute, such as water, energy, or chemical emissions. More importantly, all certification schemes share common approaches and goals[156] including the environmental evaluation and market recognition of low environmental impact buildings. In the face of global warming, most certifications attribute 51% of the final score to the environmental dimension,[157] making green and sustainable buildings the main focus.

As urban experiments aim to address social, economic, and environmental problems, the current trends[158] in the construction sector and certification schemes are shifting from focusing only on the energy performance of the buildings towards a more holistic approach that encompasses the whole building lifecycle, including sociological aspects, such as impacts on human health. Urban experiments aim to optimise functionality, reduce emissions, and increase

Figure 20: Nordhavn, Copenhagen

NORDHAVN, KNOWN AS THE LARGEST METROPOLITAN DEVELOPMENT PROJECT IN NORTHERN EUROPE, SERVES AS AN EXAMPLE OF A POE AT THE URBAN DISTRICT SCALE.

efficiency of systems but do not necessarily enhance social sustainability aspects such as quality of life, or physical, social, and cultural well-being. Hence, there is a need for certification schemes to include a thorough sociological examination of the effects of experiments in their assessments. The most well-known certification schemes include Leadership in Energy and Environmental Design (LEED), Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) and Building Research Establishment Environment Assessment Methodology (BREEAM), holding the largest market share (80.6%).[159] These commercial certification schemes analyse a variety of parameters including site, energy, water, indoor environmental quality (IEQ), material, waste, and pollution. Only the IEQ parameter partly considers health and well-being, demonstrating how most certification schemes fail to emphasise the health and well-being of the building's occupants. Certain certification schemes have been developed to focus solely on topics related to health impacts like Living Building Challenge, created by the International Living Future Institute in 2006, useful to identify the health parameters that should be addressed in depth throughout certification assessments.

A post-occupancy evaluation (POE) methodology[160] provides a useful lens through which to examine new and existing buildings and provide stakeholders with information about performance and effectiveness of the occupied design environments. A POE aims to fundamentally understand building performance and its socio-economic, environmental, and cultural implications. POEs can go beyond energy efficiency,[161] to evaluate other intangible issues such as productivity, identity, atmosphere, and community, and measure the client satisfaction and functionality. The main benefit of POEs is that they allow the provision of information for continuous improvement to make any adjustments that suit the needs of the occupants better. The data for POEs may be gathered from audits of resource consumption, on-site observations, surveys, or questionnaires. The certification Leadership in Energy and Environmental Design (LEED) evaluates POE to a certain extent through the Occupant Comfort Survey within the category Indoor Environmental Quality. The survey intends to evaluate the user's comfort in topics of acoustics, building cleanliness, indoor air quality, lighting, and thermal comfort. The methodology suggests survey evaluation to rate satisfaction with a seven-point scale, ranging from +3 very satisfied to -3 very dissatisfied. To increase reliability, it is recommended to carry out the evaluation every two years, and to have anonymous responses from over the 30% of the building occupants, to generate a document with a corrective action plan. The corrective plan is meant to be focused in the areas with a dissatisfaction rate above 20%.

Nordhavn,[162] known as the largest metropolitan development project in northern Europe, serves as an example of a POE at the urban district scale. Currently under development in Copenhagen, this project encourages bi-yearly neighbourhood meetings to inform and engage involvement from residents, occupants, and associations, providing information about occupant's concerns and improvements. This led to the creation of Hamburg Square in the Aarhus Street neighbourhood, originally planned without greenery, but due to the people interest, the landscape design plan changed to incorporate increased green features. The use of a POE approach throughout the building of Nordhavn encouraged stakeholders to think holistically about commonly overlooked issues from individual buildings to entire municipalities.[163] Nordhavn's ambitious initiatives have gained worldwide momentum, even hosting the C40 summit[164] on sustainable development, attended by mayors from 40 of the world's largest cities with the shared goal to improve sustainable urban planning and to identify long-term solutions to common problems such as traffic management. In the face of unprecedented global change, regular monitoring and adjusting of green development projects is crucial.

Experimentation has been heralded as a means to trial, learn from, and manage socio-technical innovations and urban transformations in cities to address local sustainability challenges.[165] In conclusion, this report portrayed the rise of sustainable urban experiments, by evaluating two case studies in different countries at different scales. These case studies also demonstrate the sustainability trends in urban experimentation, as most experimental approaches to urban change focus on reducing emissions and optimising environmental benefits. The importance of post-occupancy testing and expanding assessment parameters in green certification schemes was also emphasised, to illustrate what future urban experiments should consider.

CASE STUDY 1

Elite NuGEN – The MMC Approach

— DAVID CRADDOCK

What is MMC?

MMC stands for Modern Methods of Construction. Is it a product, a process, or a system? In our opinion its all of these but most importantly it's a Mindset. We need to change our approach to MMC and embrace all that it has to offer using as many forms as possible in our buildings taking them from the foundations to in house management systems.

HERE ARE A FEW EXAMPLES

- FULLY INSULATED, AND RECYCLABLE, FACTORY MADE GROUND BEAMS (SEE FIGURE 28).
- INTERLOCKING WOODEN BATHROOM WALL TILES MADE FROM 7 LAYERS OF MARINE GRADE PLY (SEE FIGURE 26).
- PRE-MANUFACTURED PAINTED DOOR SETS INCLUDING LININGS, ARCHITRAVE, HINGES, LOCKS AND HANDLES (SEE FIGURE 27).
- SPRAY PLASTER FOR A FAST SMOOTH DRY FINISH USING PRE-MIXED PLASTER SO NO WATER NEEDED WITH NO MESS ON SITE.
- CLOSED PANEL TIMBER FRAMES THAT ARE FULLY INSULATED WITH VAPOR BARRIER AND SERVICE VOID INSTALLED IN THE FACTORY (SEE FIGURE 24).


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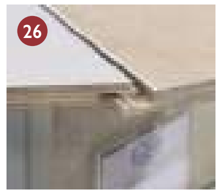
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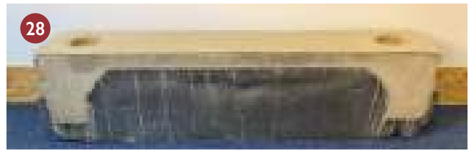
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Energy Creation and Technologies Used

We believe that every house should be a self-generating energy source (see figure 21) that creates as much energy as possible that's needed to run the house. This energy is stored in an intelligent battery pack and used to power Infra-Red panels that are mounted on the ceiling along with a Fractional intelligent Hot Water cylinder (see figure 22 of a Battery Storage and Inverter). Both systems learn your occupancy/usage and adapt accordingly to reduce the energy consumption. This means that the houses use 63% less energy, produce 65% less CO2 and cost 65% less to run than those with an Air Source Heat Pump with traditional radiators and a normal hot water tank.

New Innovations to reduce Energy use and Resource Consumption

We need to be constantly looking at introducing new ways to manage waste and energy in the home. For example, we should be using the energy used to heat hot water twice eg when showering we could use a hot water recovery system (figure 25) that pre-heats the cold water using the hot water, resulting in less hot water usage. We use a micro domestic greywater re-use system (see figure 23) to reduce water consumption by 30-35%. We take the rainwater harvested from the drive and hard landscape areas and use it for washing machines and top up the in-house greywater recycling system.

Challenges in Building Low Carbon Low Operating Cost Housing

The challenges are many and complex but the lack of understanding and appreciation as to what a difference MMC can make, along with a whole house approach, has to change. There is a large amount of industry inertia about the perceived cost to change but the reality is the cost not to change is greater. Presently there is huge confusion as to how we measure and demonstrate what is an energy efficient house, the regulations and methods of rating them are confusing, complex, clunky and due to new technologies and systems coming into use, very out-dated. New Building Regulations, Parts F,L,O,S will put greater emphasis on building performance and integrated technology along with Part Z which is about Whole Life Carbon Emissions. This means every building will have to be individually assessed to show what carbon emissions have been created from product origination through to end of life, this is a hugely complex process.

ABOUT ELITE NUGEN:

Elite NuGEN produces creative, desirable homes in the South of England and who specialises in utilising as many forms of MMC and offsite manufactured systems as possible in its buildings. These along with the use of Photovoltaic Panels, battery storage packs, Infra-red heating and Intelligent Hot water tanks make them some of the lowest cost houses to run in the country. A winner of numerous awards, including ones at the prestigious British Homes Awards and What House Awards for Best Sustainable Development of the Year 2021-22. More recently, Elite NuGEN's partnership with VELUX resulted in a housebuilder product of the year award at the Housebuilder 2022 Awards.

Most importantly what does this mean for the Homeowner?

The reason we do what we do is because we care passionately about the quality of life for all our home buyers and by reducing energy consumption and emissions, we give them lower bills with as lower impact on the environment as we possibly can. So by using the MMC approach we have M&E (mechanical and electrical) systems that require no maintenance or moving parts, we reduce carbon emissions before during and after construction with houses that use less energy and cost less to run.

All of this culminates in homeowners that are living in homes that they can afford and that they can be proud of!

CASE STUDY 2

The Duchy of Cornwall – Landscape-led Masterplan for South East Faversham

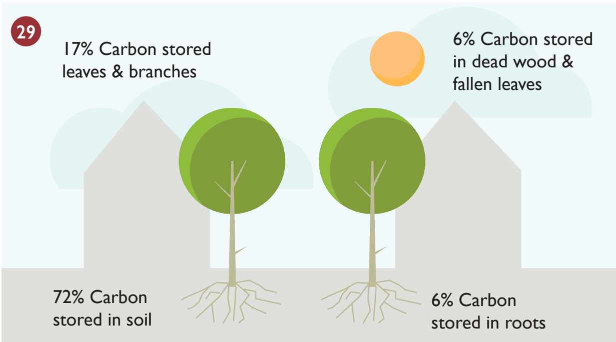
— PETER LACEY

Sustainable Infrastructure for a 2,500-home Community

In accordance with Swale Borough Council's draft Local Plan and guided by public consultations, the Duchy of Cornwall is taking an altogether more holistic approach to sustainable development in South East Faversham. This includes landscape led solutions to the provision of infrastructure and services as part of a wider masterplan for a thriving new community that delivers Net Zero Carbon development, healthy soils, net biodiversity gains and water neutrality.

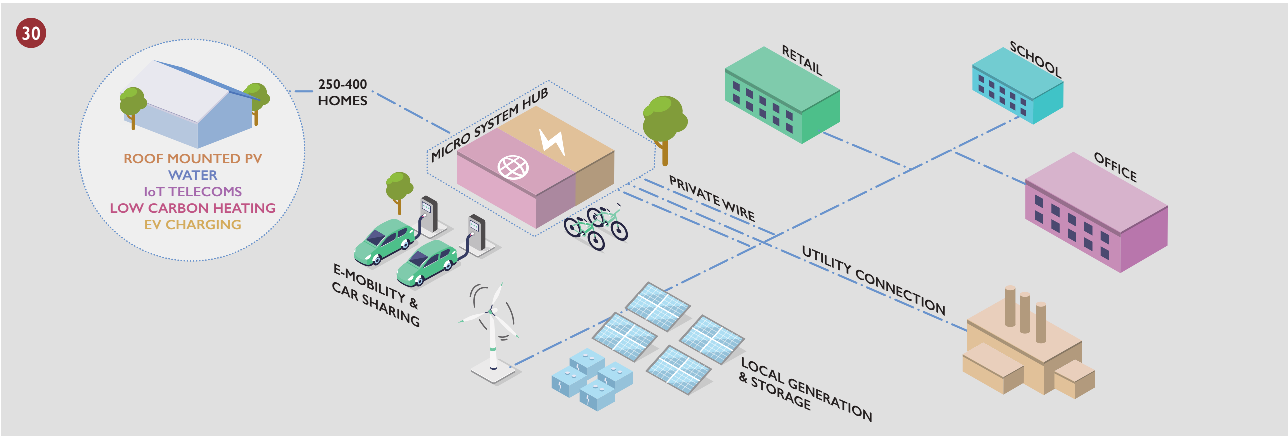
Landscape and Water

The landscape-led masterplan has been designed around soil, water, and the centuries-old, local pattern of human relationship with the land. Avenues, orchards, allotments, meadows and treelined streets will link the homes together in a shaded, green framework



(see figure 29). Tree roots will be free from tree pits to connect through a continuous microbially rich soil, thus improving the health of the trees to full maturity, increasing biodiversity, air quality and shading and cooling during the summer months.

Service media will generally follow a 'negative grid' being distributed through parking courts as opposed to



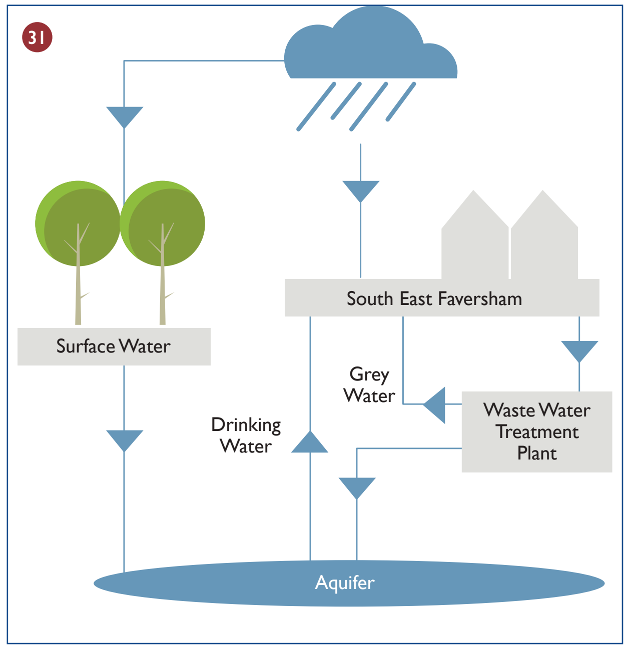
tree lined streets, thus removing the conflict between tree routes and services. Where services must run in closer proximity, they will be contained within zones protected by root barriers.

Sustainable Energy

Photovoltaic panels and slates will feed into a 'micro grid' to supply energy efficient homes and businesses that incorporate ground or air source heat pumps (see figure 30). The power generated will go directly to community battery hubs that will typically serve 300 – 400 homes, these hubs will regulate the distribution back across the development storing any excess energy once full energy will be exported to the national grid. During periods of low generation green energy will be brought in from the national grid. This system will provide low-cost energy for homes and businesses and will be linked to street lighting and electric vehicle charging of private vehicles and a car club.

Water Neutrality

Surface water will be returned to the chalk aquifer that lies under the site via a sustainable urban drainage system that utilises green verges planted with trees, and positive drainage towards swales and soakaways that follow the contours of the existing landscape form (see figure 31). This strategy dictates no surface water leaves the development boundary and any excess water tops up the aquifer below the site. A similar approach is being taken for wastewater, with a dedicated on-site



wastewater recycling centre, where, through a process of anaerobic digestion in settlement tanks sewage will be processed and cleaned leaving solid matter for use as fertiliser and clean or 'grey water' for re-use (see figure 32).

This locally cleaned 'grey water' is piped back to homes in a secondary supply for toilet flushing and potentially some white goods. This system will significantly reduce the amount of potable water used in each home and avoid individual homes needing to install their own space hungry grey water systems. It is being proposed to the Environment Agency that any excess cleaned 'grey water' is then treated as filtrated surface water and used in the landscape or returned to the chalk aquifer.

This approach is intended to preserve local water supplies for use by future generations, saving on energy and the use of chemicals used in larger off-site water treatment works. In addition, by reducing pressure on existing treatment plants it will not be contributing to the potential discharge of storm water and wastewater, helping protect our precious water ways, coastlines, eco systems and human health.

CASE STUDY 3

Travis Perkins, WholeHouse

— LEE JACKSON

The Beauty of Standardisation

Bespoke design and being different has become one of the unique distinctions of regional house builders to present themselves Independently in the marketplace. However, this makes the journey to Zero Carbon really difficult, if not impossible within such a flexible and ever-changing design process (see figure 33).

Imagine a process where only 20% of the design work has been completed before you start and the only point it was 100% complete was at the end or just before completion. On top of this several parts of the construction don't even have a formal design drawing or schedule, as the design is created during the installation process by skilled installers, who find the best solution on the day with the materials available.

Based on this, how do you calculate accurate information and make educated decisions to reduce carbon within the built environment? One way to drive this forward is adding a Design Freeze. Simply don't start construction until every small part of the design is completed, engineered and resolved upfront.

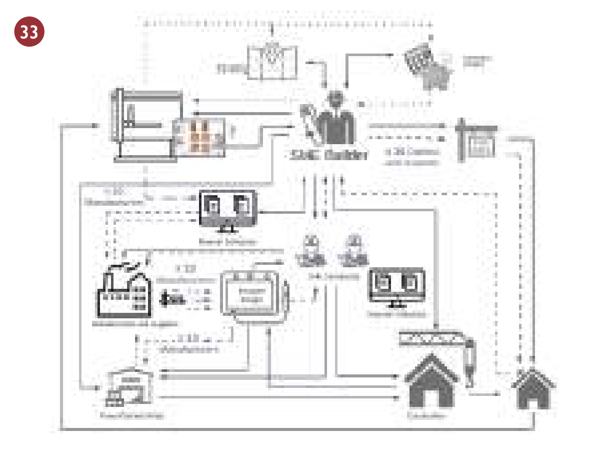
In reality, this is really difficult due to the speed needed from consent to build, a final design, and the commencement on site. Standardisation can allow the detailed design to be worked through in advance while allowing flexibility in the final product. This approach also enables the use of digital design tools to build buildings in the virtual world, creating digital twins faster and more cost-effectively, driving the data needed to support informed decision-making on topics like the embodied carbon contained within a building.

WholeHouse is an intelligent Digital Portal that will pass control back to Regional House Builders, allowing them to design individual homes with the knowledge that all the detail behind their design has been carried out upfront by industry experts (see figure 34). WholeHouse provides construction drawings for all parts of the build, driven from a single digital twin (see figure 35) with every component modelled, allowing visualisation of the build as well as every single element within the construction, containing data that can be used to drive informed decisions.

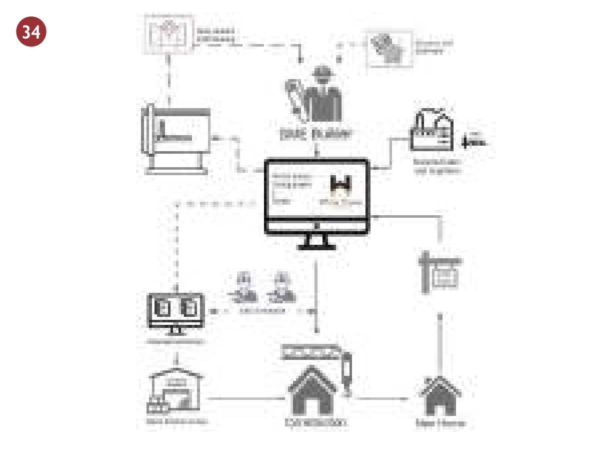
The digital twin can be used to track and compare values for cost, carbon, and performance along with anything else that the data is available for, unlocking the door to Innovation, Efficiency and most importantly Progress in a drive to build towards a better future.

Standardisation does NOT mean, all the same (see figure 36), it's the opposite when used correctly at an elemental level, unlocking the ability to offer an infinite amount of permutation and variation in a design while providing the missing key to building high quality places for people that can enhance the world we all live in. Illustrating the continued improvements being made in our industry as we become digital and innovate with new products and solutions.

CURRENT DESIGN PROCESS



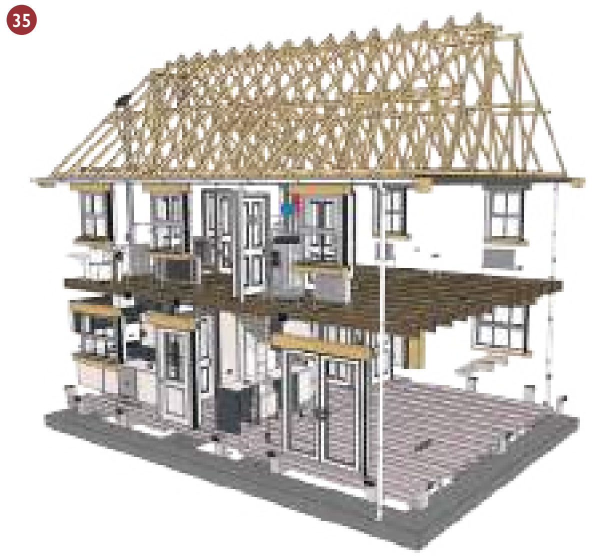
FUTURE DESIGN PROCESS



80%

OF THE DETAILED DESIGN WORK IS CREATED AFTER WORK ON SITE HAS STARTED

DIGITAL TWIN



CASE STUDY 4

SNRG

Shared next generation sustainable living solutions with sustainable energy and mobility systems to deliver Net Zero communities

— RICHARD SCOTT

Identifying the 3 key problem areas for a housing solution to address (see figure 40), this concept for an all-electric next generation sustainable community, exemplifies the SNRG SmartGrid, whilst demonstrating modular timber off-site construction and co-housing principles. In doing this SNRG gained an understanding of its residential customers' needs over the next 5 years.

The Build to Rent (BtR) cohousing community of 110 homes is arranged as a courtyard around a shared garden with allotments, greenhouses and eating & play areas (see figures 37 & 38).

A suite of enhanced amenities including Cafe with CoWorking space, Library of Things, Laundry and Multi-use space fosters a sense of community.

To support low to zero car ownership on-site, the courtyard includes a Mobility Hub for EV Charging, eBikes & eScooters.

Volumetric modular construction is adopted for enhanced quality, speed and efficiency. The concept features the SNRG SmartGrid; a zero carbon energy infrastructure, which is fully funded and policy compliant (see figures 39 and 42). On larger sites multiple SmartGrids of 450 homes each can be combined.

The understanding gained through this holistic approach continues to inform SNRG's engagement with housing clients and provides a benchmark for how best to realise the full benefits of the SNRG SmartGrid.

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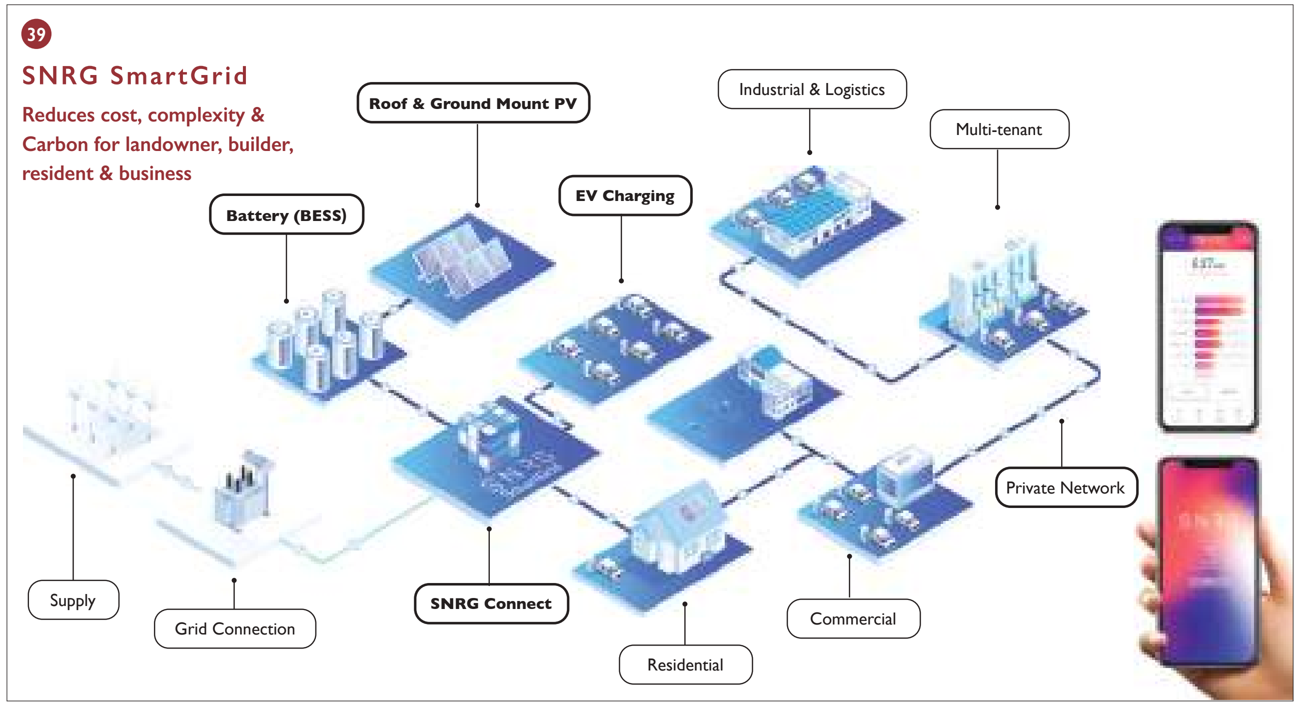

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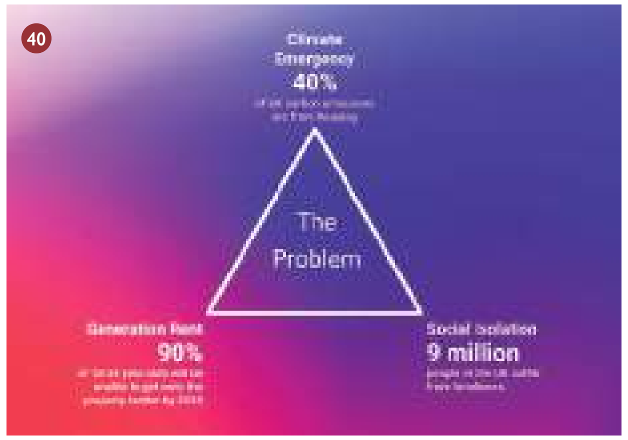

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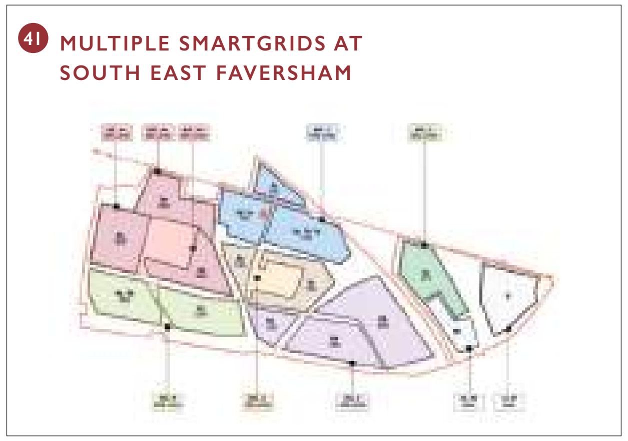

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SmartGrid Master Developer – Key Features

Sales values uplift from rooftop Solar PV
https://solarenergyuk.org/resource/the-value-of-solar-property-report/

Developer Benefits

- **£0** Network, Communal Storage & Metering Cost (Funded by SNRG)
- **Funding for Solar PV**
- **Grid Saving** Reduced Peak Demand (Subject to solution design)
- **>1.4 tonnes** CO_2 saved / home / yr (Compared to dual fuel)

Sales Value

- **Sales Value Uplift** 1.9%-2.7% / home (Rooftop Solar PV)
- **10 - 30% reduction on energy bills**
- **Smart Connected Homes**

CONCLUSION

— DR DAVID HOWARD

This report has drawn together a broad range of evidence from qualitative and quantitative studies of the built environment to assess the implications of, and possibilities for, achieving a radical, transformative, and necessary shift towards providing Net Zero homes for urban and rural populations. Over six hundred research projects and analyses were examined to explore the effects of fuel poverty; household energy efficiency; indoor air quality; embodied energy, and the 'hidden' costs of construction in relation to Net Zero goals for buildings. Similar to the findings of the Commission on Creating Healthy Cities[166] report this year, the evidence shows that the direct and indirect outcomes of sustainable construction translates to healthier people living in healthier places, increasing the benefits and lowering the costs across economic, social, and ecological contexts. The climate's and human health can be embodied in everyone's home, when placed at the heart of sustainable and profitable urban development.

As the opening sections reveal, sometimes the increasing complexities of design and production systems, new technologies, and market drivers construct complicated barriers that hide simpler solutions to the basic challenge of providing sustainable, affordable shelter. The climate crisis and COVID-19 pandemic challenged house providers to place human and environmental health at the foundation of new, or revisited, ways of delivering safe and healthy dwellings. While evidence supports the importance of creating healthy places for work, living and leisure, this report on Net Zero Homes was also fuelled and energised by the drive and commitment shown by landowners in the *Building a Legacy* forum together with small to medium-sized builders who met earlier this year in Oxford to engage with their shared and disparate challenges for the delivery of sustainable homes.

Ben Bolgar's opening reflection on the Net Zero Homes workshop at the Global Centre on Healthcare and Urbanisation[167] at Kellogg College in Oxford highlighted the importance of leveraging local and regional networks to provide more sustainable housing. The gathering brought together innovative practices and ideas for land ownership, thoughtful stewardship, and giving small and medium-sized building enterprises, access to larger urban development interests by sharing building systems, supply chains and group financing. Discussion and the recognition of shared goals, and accepted differences, underpinned by the importance of experimentation - as evidenced above – revealed an emergent, practical strategy to deliver accessible Net Zero Homes in the form of the Regional Building Hub model (Figure 1). The idea of Regional Building Hubs emerged from the Oxford discussions to address the barriers faced by all around the table wishing to build more sustainable houses, and move towards delivering Net Zero Homes. Such hubs would place the region as a core framework for facilitating greater connections, trust, understanding and shared practical knowledge between landowners and small to medium-sized builders, and with larger-scale housing developers open to engaging with new, regional ways of facing national, and ultimately global, construction challenges. All agreed that the system of how houses are built today and how existing houses are upgraded needs revising in the light of current economic and environmental constraints, from re-routing material and skills supply chains, to more straightforward and meaningful communications across the scales and silos of the current construction scene – not least, and most relevant to this report, how do we access the evidence, implement the knowledge, and build the capacity to deliver practical net zero homes?

Figure 43: Regional Building Hub model

The idea of Regional Building Hubs emerged from these conversations between landowners and builders, supported by the evidence presented in this report, as a pragmatic means to provide employment; to support regional economies; to respond directly to the climate crisis, and to deliver Net Zero Homes for UK residents. Sourcing regional materials as much as possible, forming building coalitions across varied scale enterprises, and looking towards more sustainable or 'patient' forms of capital investment and return underpin this approach. Both landowners and builders recognised their mutual concerns, which the collective knowledge and shared practice of a Regional Building Hub could address. A directory and map of regional capacity and resources, for materials, crafts and skills, hosted by each hub was agreed as a positive step forward. Apprenticeships, generating workable hybrid means of blending traditional crafts and new technologies, and the often not-so-simple practice of communicating knowledge and experiences between people, even 'educating' homeowners about building options and embodied carbon, were further discussed and recognised to be key leaps to make towards Net Zero Homes, which a Regional Building Hub could expediate.

This report has garnered the evidence which might move us in the direction of delivering Net Zero Homes. Builders, landowners, homeowners, and financiers have discussed their own potential connections and interests in this course of action. Embodied energy in existing housing stock presents a significant and immediate challenge, not least in finding a consistent and comparable means of measuring a building's life cycle, in terms of production and operational energy use. Nevertheless, 'detoxifying' construction materials, and improving energy efficiency have tangible and often immediate benefits. For example, as this report shows, the NHS could annually save an estimated 42p for every £1 spent on effectively retrofitting fuel poor homes. Changes within the house building sector can have dramatic and positive impacts on occupants' health and well-being, and for wider society and the environment. Regional Building Hubs may provide the catalyst to remould the cast of the current housing system, and to deliver new patterns of sustainable and successful engagement with today's built environment for the benefit of tomorrow.

ENDNOTES

THE FUTURE OF OUR HOUSING STOCK
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TERMS OF REFERENCE

Biodiversity Conservation India Limited (BCIL)
Building Research Establishment Environmental Assessment Method (BREEAM)
Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)
Energy Company Obligation (ECO)
Energy Performance of Buildings Directive (EPBD)
Energy Performance Certificate (EPC)
Indoor Environmental Quality (IEQ)
International Energy Agency (IEA)
Leadership in Energy and Environmental Design (LEED)
Low Income Low Energy Efficiency (LILEE)
Low-Income High Costs (LIHC)
Maximum Material Condition (MMC)
Mechanical Ventilation Heat Recovery (MVHR)
Monitoring & Evaluation (M&E)
Net Zero Energy Building (NZEB)
Organisation for Economic Co-operation and Development (OECD)
Post-Occupancy Evaluation (POE)
Towards Zero Carbon Development (T-Zed)
Volatile Organic Compounds (VOCs)
United States Department of Energy (DOE)
United States Environmental Protection Agency (EPA)
World Health Organization (WHO)

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Chloe Curtis, Eleanor Cosford, Juan Valencia, Lucy Main and Michael O-Connor.

WITH MANY THANKS TO OUR FOUR CASE STUDIES:

Elite NuGEN, The Duchy of Cornwall, Travis Perkins and SNRG.

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