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RESEARCH

Net-zero buildings: when carbon and energy metrics diverge

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Abstract

Many climate change-related building frameworks are designed to improve environmental performance by requiring reduced net energy demand, as it is widely assumed that energy demand (*e.g.* delivered/final, primary, primary non-renewable) is a good proxy for carbon emissions. However, energy grids are becoming less carbon intensive, meaning that the climate change mitigation value of renewably generated energy is not static, and is likely to decrease. In this research, a global integrated building carbon and energy model was created to explore how assessed building performance responded to stepwise variation in multiple building features. Operational and embodied metrics were measured concurrently on the basis of carbon emissions and delivered final energy demand, and included renewable energy generation (via roof-mounted photovoltaics), resulting in two 12.3 million-point data sets. Logistic regression was used to identify patterns in the data sets using binary building classifications (zero or non-zero energy or carbon). The results demonstrate that the profiles of the energy and carbon metric data sets do not mirror each other, indicating that a delivered energy demand assessment is not necessarily a good proxy for carbon emissions. The divergence of these metrics is likely to grow in future as energy grids are increasingly decarbonised.

Policy relevance

The energy metric is often relied upon as an indicator of climate-related building performance. However, policy-makers and designers should instead focus their attention on a carbon metric in order to achieve the drastic reduction in carbon emissions needed for the 1.5°C limit on rising global temperatures. Grid generated energy (particularly electricity) tends to be viewed as universally carbon intensive, so offsetting even a small amount with renewable energy is seen as beneficial. This research demonstrates that design philosophies underpinning zero-energy building (ZEB) assessment outcomes are likely to be driven by environmental factors (*i.e.* overcoming temperature and insolation challenges). However, the zero-carbon equivalent is likely to be more closely associated with the characteristics of the electricity grid servicing the building. This study highlights the fact that, to accrue real benefits, long-term policy and design decisions need to factor in the changing nature of the carbon implications of energy demand and generation.

Keywords: buildings; carbon emissions; carbon metrics; energy grids; net zero; performance; zero carbon

1. Introduction

In 2014, the Intergovernmental Panel on Climate Change (IPCC) reported that atmospheric concentrations of greenhouse gases (GHGs) were at levels unprecedented in at least 800,000 years (IPCC 2014). Although, by then, the detrimental effect of anthropogenic GHG emissions on the Earth's climate had long been discussed (NRC 1979), and despite the introduction of international legislative commitments to reduce such emissions (UN 1998; EU 2010), the IPCC's report identified that emissions were continuing to grow (IPCC 2014). The following year, the United Nations' (UN) 2015 Paris Agreement was ratified, committing the global community to cap global temperatures at a maximum of 2°C above pre-industrial levels (UN 2015). However, the IPCC has more recently warned that even with this cap,

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significant climate-related risks remain, and a stricter limit of 1.5°C should be targeted (IPCC 2018). The special report on global warming from which this warning originates presents a stark challenge to the global community: to meet the 1.5°C target, global net anthropogenic CO_2 emissions must decline by about 45% from 2010 levels by 2030, reaching net zero by 2050 (IPCC 2018).

The global construction industry is well placed to address the climate change challenge in part. The construction and operation of buildings results in nearly 20% of global GHG emissions (IPCC 2014). In addition, buildings present potential sites for renewable energy generation. For example, part of the European strategy to reduce carbon emissions is a mandatory requirement that all buildings built from 2021 onwards should be 'nearly zero-energy', with the remaining energy demand satisfied by renewable energy generated on site, or nearby (EU 2010). Indeed, it has been estimated that photovoltaics (PV)-based electricity will represent a significant share of Europe's electricity mix, potentially as high as 25% by 2030 (EPIA 2012).

1.1. Energy, carbon and GHG emissions

The performance of buildings, with respect to climate change, is often assessed on the basis of energy demand rather than carbon emissions (Parkin, Mitchell & Coley 2015), with energy demand relied on as a proxy for carbon emissions. Energy generation is largely achieved through the combustion of fossil fuels and is responsible for around 65% of global GHG emissions (IPCC 2014). Given the close association between energy generation and GHG emissions (often discussed in terms of carbon emissions), the assumption that reduced energy demand will lead to reduced carbon emissions is perhaps natural. However, the link between energy generation, energy demand and carbon emissions is not straightforward.

Energy used directly in buildings is known as delivered, or site, energy. The International Organization for Standardization (ISO) defines delivered energy as:

> energy, expressed per energy carrier, supplied to the technical building systems through the assessment boundary, to satisfy the uses taken into account or to produce the exported energy. (ISO 2017)

This energy demand may be measured on site, or, where the building has not yet been constructed, estimated based on the characteristics of the building and the environment in which it will be situated. However, for energy performance and compliance purposes, the European Union (EU) requires energy demand to be expressed in terms of primary energy (PE) (EU 2018). The definition of PE used in this context is 'energy that has not been subjected to any conversion or transformation process' (ISO 2017).

In general, PE refers to the quantity of energy generated or consumed, usually away from site, in order to deliver one unit of energy for use on site. It can be further categorised as renewable or non-renewable, and it is described by calculated PE factors (PEF) which differ between energy carriers. For example, for fossil fuels, the definition of PE is based on the thermal energy that can be realised, usually by combustion, which is then converted into an energy carrier such as electricity, incurring losses in the process (Hitchin 2019). This is an example of non-renewable PE, as the energy is generated from a source which is depleted by extraction of the raw fuel material (ISO 2017), and the PEF gives an indication of the detrimental effect of such energy consumption on resource levels. Applying the PE principle to renewable energy is less intuitive as the initial source of PE is not so easily identifiable.

In a review of the calculation conventions used to determine PEFs, Hitchin (2019) notes that several different definitions of PE are used internationally, particularly in the case of renewable PE, and that different PE calculation methodologies are employed in different countries. International conventions about the extent to which extraction and initial cleaning and processing of fossil fuels should be included differs; embodied energy—that used to produce the equipment for extraction or energy transformation (*i.e.* the PV modules needed to transform sunlight into electricity)—is not normally included in PE calculations; and even the definition of a renewable resource is interpreted in different ways (Hitchin 2019). This means that it is not a simple task to compare PEFs across countries, or even energy carriers, and it is impossible to make consistent comparisons without knowledge of the calculation convention applied.

While PEFs give an indication of the energy generation, and associated resource depletion, needed to satisfy energy demand on site, carbon emissions metrics are more closely tied to the impact of delivered energy demand on climate change. ISO 52000-1 (2017) defines carbon emissions coefficients as describing 'the amount of CO_2 that is released from doing a certain activity, such as burning one tonne of fuel in a furnace'. Therefore, there is a strong link between these coefficients and PEFs for non-renewable energy sources such as fossil fuels. However, the strength of this relationship starts to break down for energy sources that are less clearly defined as non-renewable. For example, nuclear energy is a form of PE that is not usually considered to be renewable, suggesting that its PEF should be relatively high and based on thermal energy released, which would therefore include losses in the heat to electricity transformation. However, the generation of thermal energy from (processed) nuclear fuel releases no CO_2 emissions, so a lower PEF based on electricity generated, after generation losses have been incurred, would be more closely aligned with the respective CO_2 emissions factor. Hitchin (2019) notes that there is no international consensus on the PE basis for energy sources such as renewable energy, biomass, nuclear energy and the combustion of waste material, although some countries have laid out their own national rules in this regard.

1.2. Electricity and GHG emissions

CO_2 is not the only, or the most potent, GHG, but it is the most prevalent (76%, with a global warming potential (GWP) of 1 kg CO_2e). Other GHGs include methane (16%; GWP = 28 kg CO_2e) and nitrous oxide (6%; GWP = 298 kg CO_2e) (IPCC 2014). The carbon dioxide equivalent metric (CO_2e) collectively accounts for these, and other, GHGs, their relative concentrations and their individual potency, not just CO_2 specifically.

In the UK, electricity is generated by a variety of different types of power station using different fuels, resulting in different emissions of CO_2e per unit of electricity generated. In addition, the mix of fuels used to generate UK electricity changes with time, meaning that the GHG emissions from one unit of UK electricity are not static. For example, electricity generation from coal decreased by 70% in the period 2015–17 (BEIS 2018b). The fall in the emissions for all fuels in **Table 1** indicates the increase in methods used to generate electricity that are less carbon intensive than burning coal. Note that the data in **Table 1** are provided in terms of CO_2 emissions rather than the CO_2e.

The fuel-mix profiles of electricity grids across the globe are also not uniform and are changing in response to national and international climate change-mitigation policies. This means that, with respect to climate change, the value of offsetting grid electricity with renewably generated electricity (*i.e.* from PVs) is not the same across the globe and is changing with time.

When considering the effect of the aspirational transition of electricity grids to 100% renewable energy, the Passivhaus Institute (PHI) concluded that the currently applied electricity PEFs would no longer be a useful mechanism for the sustainable evaluation of energy efficiency in buildings (Krick 2015). This is because the normal application of PE treats renewable energy as having a PEF of zero (as mentioned above, embodied energy tends to be ignored in the calculation of PE), so every building connected to a 100% renewable electricity grid would have a PE demand for electricity of zero. In such a scenario, building assessments based on PE would not be able to differentiate between conservative or profligate uses of electricity in buildings. To solve this problem, the PHI has proposed a new primary energy renewable (PER) metric that additionally accounts for the challenges of storing and retrieving renewable energy (Krick 2015).

The continuing transition to 100% renewable energy has already had implications for the current PE concept given that the mixture of available primary sources feeding into an electricity grid today will often vary within a year or a day. For example, the GridCarbon app, primarily developed to report on carbon emissions, shows the real-time UK electricity grid fuel-mix breakdown, the changes in which can be viewed throughout the day (Rogers & Parson 2019). An electricity grid with a large PV component will therefore have different average PEFs for air-conditioning and lighting, so the use of a simple annual grid PEF could result in misleading signals for priorities between alternative energy-efficiency design options (Hitchin 2019).

The PEF challenges raised by the transitioning electricity grids are equally applicable to carbon emissions metrics; changes in these metrics have the potential to alter building assessment outcomes, and consequently what is desirable in the initial design of buildings. For example, a 2011 UK study comparing different design approaches (including ground-source heat pumps, thermal solar and PV) in new low-energy homes concluded that ground-source heat pumps had the highest carbon emission rate over a projected 20-year period (Monahan & Powell 2011). However, the study assumed that the carbon intensity (CI) of the UK electricity grid—the carbon emissions resulting from each kWh of energy demanded—would fall from 0.53 to 0.37 kg CO_2/kWh over the period in question. In reality, the UK electricity CI fell to 0.225 kg CO_2/kWh in 2017 (**Table 1**), and the UK Committee on Climate Change (CCC) is now recommending heat pumps as a route to reducing carbon emissions from homes (CCC 2018). More recently, a report looking at the costs and benefits of tighter building standards in the UK highlighted that, as a result of the decarbonisation of the UK electricity grid, PV is *not* a substitute for low-carbon heat (Currie & Brown 2019). In addition, in order to reflect the current state of national energy grids, the UK government is planning to update both UK PEFs and GHG emissions factors alongside updating the UK Building Regulations in the near future (BEIS 2017).

1.3. Factors affecting net-zero-carbon and net-zero-energy buildings in use

A substantial body of literature discusses the environmental assessment of buildings and identifies important features in the design of low and net-zero energy and carbon buildings. The focus of interest varies from purely operational, considering specific definitions of the import/export and load/generation energy balances (Sartori, Napolitano & Voss

Table 1: CO_2 emissions from the UK electricity supplied, 2015–17.

Fuel	Emissions (tonnes CO_2/GWh electricity supplied)		
	2015	2016	2017
Coal	909	931	918
Gas	382	378	357
All fossil fuels	625	497	460
All fuels (including nuclear and renewables)	335	265	225

Source: BEIS (2018b).

2012), to wider assessment boundaries including operational, embodied, maintenance and even transport energy demand associated with the life of a building (Stephan, Crawford & de Myttenaere 2012). The properties of the thermal envelope are often considered significant as a result of the need to minimise heat energy demand in colder climates (Cotterell & Dadeby 2012; DECC 2012; Passive-on 2007). Indeed, data for 2016 indicate that 37% of the 468 MtCO_2e total UK GHG emissions across different sectors were attributable to heating (**Table 2**).

In the case of net-zero-carbon or net-zero-energy buildings, the challenge of dealing with seasonal energy demand/renewable energy generation balances is the main cause for concern (Parkin *et al.* 2015; Sartori *et al.* 2012; Voss & Musall 2013). It is noticeable that such issues tend to be particularly relevant in developed (and usually colder) countries where environmental building standards have a longer history. In recent years, the more globally applicable questions of embodied carbon and embodied energy have also arisen (Acquaye & Duffy 2010; De Wolf, Pomponi & Moncaster 2017; Rauf & Crawford 2013; RICS 2018). This paper does not address these issues directly, although the assessment boundary used in this work does include embodied metrics (as described in section 2.1). However, it is recognised that embodied carbon is an important consideration in the context of net-zero-carbon buildings.

Where previous studies have addressed the above issues, it is usually in relation to one case study building or a few buildings (Ampatzi & Knight 2012; Hall *et al.* 2013; Monahan & Powell 2011; Stephan, Crawford & de Myttenaere 2013a). A detailed building analysis is often presented, with suggestions for the optimum 'solution' where multiple design options are the object of the research. However, context-specific issues (*e.g.* climate, insolation, electricity grid CI, occupant density) are often treated as constants, and are often the caveats raised in concluding remarks. For example, research into residential energy consumption patterns in Finland concluded that:

> the energy mixes may vary even more than the energy consumption rates. Thus, if the underlying target is to find ways to reduce the environmental burdens resulting from energy production, attention should be paid to the fuels being used as well. (Heinonen & Junnila 2014: 302)

Similarly, a study looking at multiple dwelling types in one neighbourhood acknowledged that:

> since this paper uses an Australian neighbourhood, other case studies, in different contexts should be assessed in order to verify the findings. Culture, infrastructure, technology, climate and other aspects might influence the findings. (Stephan, Crawford & de Myttenaere, 2013b: 48)

Finally, in research looking at the importance of embodied versus operational energy in one case study house, Rauf and Crawford (2013: 260) noted that:

> in milder climates, less energy may be required to heat and cool an equivalent building and this may result in a significant increase in the importance of initial and recurrent embodied energy.

1.4. Modelling building performance

In order to discuss the performance of buildings that have not yet been built, it is necessary to have a tool that allows a performance metric to be estimated. Building models are usually employed to do this, often at a design stage to compare design options and check compliance with standards or regulations (Coakley, Raftery & Keane 2014; CIBSE 2013; Szokolay 2008). For example, the UK's National Calculation Methodology (NCM), integrated into the Standard Assessment Procedure (SAP), was devised as an assessment tool to demonstrate compliance with Building Regulations (CIBSE 2013; DECC 2012). Similarly, the Passivhaus Planning Package (PHPP) is a design tool to help designers achieve the Passivhaus ultra-low-energy standard (Cotterell & Dadeby 2012). Used in this way, the value of the assessment metrics produced by these models lies in their ability to determine whether a proposed building satisfies a particular set of compliance requirements. This goal is quite different to that of trying to predict accurately the performance of the

Table 2: Estimated UK greenhouse gas (GHG) emissions attributable to heating, 2016.

End use	UK GHG emissions from heating	
	% of total UK emissions	tonnes CO_2e/GWh heat supplied
Space heating	17	183
Hot water	4	189
Cooking	2	242
Industrial processes	14	442

Sources: Based on data from BEIS (2018a, 2019a, 2019b).

proposed building, for example, from the perspective of delivered energy demand. However, the resulting assessment metric is sometimes mistakenly taken to be such a prediction (CIBSE 2013).

It is often the case that real buildings in operation do not perform as modelled at the design stage—a phenomenon commonly referred to as the performance gap (Coakley *et al.* 2014; Zero Carbon Hub 2014; CIBSE 2013). This is not simply because compliance modelling is incorrectly interpreted as prediction modelling, but also because the behaviour of real buildings is the result of the interaction of many components that make up the complex building–services–user relationship (Szokolay 2008). This is difficult to represent with precision. In order to combat this problem, and with the continuing development of computing power, building models have become increasingly detailed. For example, of the 36 interlinked spreadsheets that make up the PHPP, two sheets are dedicated to compiling detailed information about just the windows in the building, requiring information about even the widths and *U*-values of window frames, and the orientation of each window (Cotterell & Dadeby 2012).

A review of methods to match building energy-simulation models with measured data identifies four commonly used energy-simulation models—DOE-2, EnergyPlus, TRNSYS and ESP-r—describing them as prognostic law-driven simulation tools (Coakley *et al.* 2014). The common challenge for all these models is their aim to predict accurately the behaviour of a complex system, and much effort and time can be spent on trying to achieve a perfect representation of a building. For example, Coakley *et al.* (2014) describe a variety of approaches intended to alleviate the precision challenges faced by building energy-simulation models.

The way building models tend to be used has meant that their general development has been in the direction of being able to represent a real building better with a view to design optimisation and performance prediction. This is valuable from the perspective of understanding individual buildings, but it does not allow for easy comparison between buildings, particularly where different contexts come into play. By the time a model is employed, important design decisions have already been made and any optimisation is based on assumptions about contextual factors locked into the design and accompanying model. As mentioned above, these contextual factors limit the ability to compare building design decisions across multiple buildings in varying contexts.

The sophisticated building models referred to above can take building designs forward for refinement, but they are less suited to addressing questions about the fundamental assumptions upon which the initial designs are built. In contrast to approaching the analysis of buildings from the perspective of the detailed, and inevitably context-specific, individual building design features, this research sought to address these factors from a broader angle. This paper investigates how the interplay of specific building features and contextual issues affects the likely outcome of environmental building assessments from the perspective of net carbon emissions and net delivered energy demand.

2. Methods

In this work buildings are modelled as 'objects' that represent building systems. The objects have associated features with defined characteristics, representing components of the building system. For example, each building object has a defined external wall surface area, the size of which depends on the shape/size of the building footprint and the height of the building. As building components, the external walls also have defined thermal insulation properties. The size and thermal properties attributes of the external walls, in combination with similar attributes of other components (*i.e.* the size and thermal properties of the windows), determine the overall thermal performance of the building envelope. In combination with external temperature conditions, this determines the heating (or cooling) site energy demand of each object.

The building objects do not attempt to describe precisely the environmental performance of buildings in the same way as the models described above. The purpose of the building objects is to allow comparison between the high-level building assessment outcomes, across many buildings, that result from multiple design and contextual inputs. In this way, the initial assumptions that usually influence early design decisions, and therefore predefine fundamental aspects of a building model, are tempered.

2.1. Standard Building Model (SBM) objects

The SBM was developed in MATLAB to create domestic building objects, assign their features and determine the outcome of an environmental assessment of each building object. It calculates the carbon emissions and delivered energy demand associated with a dwelling based on inputs that describe the dwelling's delivered electricity demand, heating (and/or cooling) demand, energy savings and GHG emissions reductions resulting from PV generation, and carbon and energy embodied in the fabric of the building.

Although modelling building energy demand usually relies on PE metrics, this approach was not taken with SBM. The policy and calculation methodology nuances that are inherent in PEFs, as discussed above, limit the consistency with which they can be applied across a large number of buildings in different locations. In addition, low carbon energy, which plays a central role in net-zero-carbon buildings, is not transparently and consistently represented in PEFs currently.

Delivered energy demand was used as the energy metric to demonstrate how the features of the building objects result in different demands for energy at the site level. The carbon emissions metric was used to identify how this demand for delivered energy translates into impact on climate change.

SBM building objects were modelled to be placed in six different locations, allowing them to be exposed to a range of external temperatures and insolation levels, and connecting them to electricity grids with differing CIs. The locations used in this work were chosen to provide three main latitude groupings for variation in insolation (low, intermediate and high) along with three main Köppen–Geiger climate classification groupings for variation in climate (hot; mild winter/hot summer; mild or severe winter/warm summer; Szokolay 2008), coupled with two main electricity grid CI groupings for variation in electricity CI (high and low). The details of the location characteristics are shown in **Table 3**. The locations' groupings (latitude, climate and electricity grid CI) are summarised in **Table 4**.

SBM uses weather data sourced from NASA as inputs to describe the environmental conditions (*i.e.* external temperature and insolation) to which the building objects are subject on an hourly basis. The NASA data available come directly from, or are calculated using, meteorological parameters taken from NASA's Modern Era Retro-analysis for Research and Applications (MERRA-2) assimilation model (Stackhouse *et al.* 2018). The MERRA-2 model uses satellite measurements, along with surface observations, spanning the period 1981–present, to generate global estimates of a range of atmospheric variables. The data are available on a global grid with a spatial resolution of 0.5° latitude by 0.5° longitude.

Aside from the technical features of the PV system, the amount of electricity generated by a PV array depends on its surface area and the amount of sunlight to which it is exposed. In SBM, every building system included a roof-mounted PV array that is the same size as the building footprint/roof. This meant that the size of the building object PV array varied with the length and/or width of the building. All SBM building objects are cuboid, with defined aspect ratios used to identify and remove unrealistically narrow and tall building system objects from the data set (**Table 4**). In addition, the wall depths vary depending on insulation levels, so any SBM object with an internal floor area <25 m^2 per storey was also removed from the data set for similar reasons.

In the SBM dwellings, electricity demand is dependent upon occupant density (*i.e.* electricity demand level input is based on kWh per person). The demand levels, including lighting, are based on data from EST (2012), and the domestic electricity demand profile is based on Knight *et al.* (2007). Occupancy densities, and therefore levels of electricity demand, were varied within the SBM object population (**Table 4**). Heating energy is assumed to be provided by gas with a CI of 0.216 kg CO_2/kWh (as in SAP; DECC 2012), unless the local electricity grid CI is lower, in which case heating is assumed to be powered by electricity from the local grid. SBM does not include energy demand for the supply of hot water.

SBM is a simple heat and energy balance model based on an hourly time step. As indicated in **Table 4**, two different balance periods were applied for the assessment of the PV generation/energy demand balance. In the annual scenario, excess PV generation occurring at one time in the annual cycle (*e.g.* in summer) is used to offset demand at another point in the cycle (*e.g.* in winter). In the monthly scenario, excess PV generation must be used within the monthly cycle. For calculation purposes, any surplus left at the end of the month is lost, meaning that summer generation cannot be used to offset winter demand.

Embodied metrics associated with the fabric of the building systems (including the PV and mechanical ventilation with heat recovery (MVHR) where applicable) are also included in SBM. In the case of the PV in particular, as the most energy and carbon-intensive element of the fabric of the building objects, the variation in embodied values was based on the highest and lowest values available in the literature at the time of SBM development. Later analysis of the SBM data generated showed that the impact of even these relatively extreme embodied values was far less significant in the overall building object population landscape than was the impact of the metric of measurement—net delivered energy demand or net carbon emissions. This paper, therefore, concentrates on the operational, rather than embodied, metrics.

The result of each SBM assessment calculation is a continuous variable describing the net carbon emissions (kgCO_2e), or delivered energy demand (kWh), of a building object with 13 specified feature characteristics (as described in **Table 4**), normalised to the internal floor area. Building object assessments where the output net carbon or energy value is ≤0 are classified as zero-carbon buildings (ZCBs) and/or zero-energy buildings (ZEBs), respectively.

Table 3: Locations, temperatures and electricity grid carbon intensities (CIs) (ordered by latitude).

City	Latitude (°N)	Country	Mean annual insolation (kWh/$m^2_{horizonatal}$)	Mean annual temperature (°C)	National electricity grid CI (kg CO_2e/kWh)[a]
Macapa	0.04	Brazil	1700	26	0.087 (low)
Mumbai	19	India	2100	27	1.003 (high)
Athens	38	Greece	1600	19	0.876 (high)
Carcassonne	43	France	1300	13	0.078 (low)
Seattle	48	United States	1200	9	0.610 (high)
Oslo	60	Norway	1000	5	0.003 (low)

Source: [a]IPCC (2005).

Table 4: Standard Building Model (SBM) building object features and characteristics.

Input variable feature	Feature characteristic
Building object location (location groupings by latitude; climate; electricity grid carbon intensity)	Macapa (low; hot; low)
	Mumbai (low; hot; high)
	Athens (intermediate; mild winter/hot summer; high)
	Carcassonne (intermediate; mild winter/hot summer; low)
	Seattle (high; mild winter/warm summer; high)
	Oslo (high; severe winter/warm summer; low)
Wall construction material	Brick
	Straw (assessment includes carbon sequestration)
	Straw (assessment excludes carbon sequestration)
Assessment boundary	Operational only
	Operational plus embodied
Assessment balance period	Annual
	Monthly
Infiltration level (air changes per hour at normal pressure)	0.042 (MVHR included in embodied assessment boundary)[a]
	0.700 (no MVHR)
	0.343 (no MVHR)
Occupancy density (m^2/person)	No occupants
	35
	20
Photovoltaic (PV) specification	Low embodied metrics (149 kg CO_2e/m^2_{PV}/241 kWh/m^2_{PV}) (Mann *et al.* 2014)
	High embodied metrics (953 kg CO_2e/m^2_{PV}/318 kWh/m^2_{PV}) (Nawaz & Tiwari 2006)
Glazing *U*-value (W/m^2K)	1.4, 0.8, 0.68
Wall *U*-value (W/m^2K)	0.10, 0.12, 0.15, 0.18
Glazing (%)	10%, 20%, 40% and 80% of the external walls
Footprint (m^2)	45–450 m^2 in steps of 45 m^2
Width (m)	Valid building widths were calculated using aspect ratios 1.0, 0.5, 0.25 and 0.125 and: $\text{Building width} = \sqrt{\text{aspect ratio} \times \text{building footprint}}$
Number of storeys	1, 2, 4, 8, 16 and 32 storeys, with the same limitation on aspect ratios as above

Note: [a]MVHR, mechanical ventilation with heat recovery.

The overall result of the combination of building objects and their assigned features was two 12.3 million × 14 matrices in which the first 13 columns identified the feature characteristics and the last column was either the net carbon, or the net energy, assessment calculation output. For example, just over 2 million building system objects were simulated for each location identified in **Table 3**. Each individual building object in the data set consists of a unique combination of the remaining 12 feature characteristics subsequently listed in **Table 4**, and it results in a net carbon and net energy assessment outcome. **Table 5** shows the breakdown of the total population of SBM building system objects by location, and the resulting numbers of ZCBs and ZEBs.

2.2. Building object data analysis

Given the high-level nature of the building object assessment outcomes, it was not deemed appropriate to rely on the values generated by the SBM to infer meaningful relationships between the quantitative assessment outcomes and the building object inputs. As discussed above, SBM is not a sophisticated building simulation model that can be used to answer optimisation questions. Instead, analysis of the results focused on the proportions of the building object population that met the net-zero-carbon or energy threshold. This approach limits the risk that very large positive or negative assessment results, associated with building objects of unconventional dimensions or aspect ratios, skew the interpretation of the resulting object assessment landscape. The populations of ZCBs and ZEBs within the overall population of building system objects were analysed using logistic regression and odds ratios (ORs).

Table 5: Breakdown of total Standard Building Model (SBM) building object population, and resulting zero-carbon buildings (ZCBs) and zero-energy buildings (ZEBs), by location.

Location	Total SBM building objects …	of which ZCBs	of which ZEBs
Macapa	2,056,320	1,481,073	793,810
Mumbai	2,056,320	679,762	766,178
Athens	2,056,320	812,869	766,803
Carcassonne	2,056,320	1,586,597	775,284
Seattle	2,056,320	1,041,562	690,297
Oslo	2,056,320	1,608,924	439,267
Total	12,337,920	7,210,787	4,231,639

The logit transformation maps probabilities, ranging from 0 to 1, to log odds, ranging from negative infinity to positive infinity, which can be plotted against predictor variables (equation 1). Logistic regression was used to identify relationships between the binary assessment outcomes (*e.g.* probability of a ZCB) and the predictor variables (*e.g.* external temperature at the building object location):

$$\text{Logit}(\text{ZCB}) = \log_n(\text{Odds}(\text{ZCB})) \tag{1}$$

where:

$$\text{Odds}(\text{ZCB}) = \frac{P(\text{ZCB})}{1 - P(\text{ZCB})}$$

$$P(\text{ZCB}) = \frac{\text{Number of ZCBs in the population}}{\text{Number of objects in the population}}$$

The OR is the ratio of the odds of an event occurring in one group versus the odds of it occurring in another group. If the odds of a ZCB in each of the groups are $\text{Odds}_1(\text{ZCB})$ (the first group) and $\text{Odds}_2(\text{ZCB})$ (the second group), then the odds ratio is given by equation (2). ORs were used to explore the similarities in, or differences between, the net-zero-carbon and energy building object assessment landscapes. For example, the data in **Table 5** can be used to show that, for the whole population of building objects, OR(ZCB/ZEB) = 2.7; the odds of a building object being classified as a ZCB are nearly three times greater than it being classified as a ZEB. This value rises to 3.9 when looking at only the object population assessed on a monthly basis:

$$\text{OR} = \frac{\text{Odds}_1(\text{ZCB})}{\text{Odds}_2(\text{ZCB})} \tag{2}$$

OR = 1 A ZCB is equally likely to occur in both groups
OR > 1 A ZCB is more likely to occur in the first group
OR < 1 A ZCB is more likely to occur in the second group

3. Results

While the SBM objects are designed to represent real buildings, it is acknowledged that the level of detail (or number of features) required to describe a real building is far greater than the capacity of SBM. For this reason, analysis of the SBM-generated data focused on how the population of SBM objects perform in comparison with each other, responding to their assigned feature characteristics, rather than how each object performed as an individual unit. As opposed to trying to identify which combination of feature characteristics would produce the optimum SBM building object, this research was interested in identifying which features played the greatest roles in shaping the populations of SBM objects that achieved the ZCB or ZEB goal.

Logistic regression identified the relationship between the different location characteristics and the odds of ZCBs and ZEBs occurring at those locations. **Figures 1** and **2** show that the logit(ZCB) for the locations depends on the CI of the local electricity grid, while the logit(ZEB) is related to the locations' mean annual temperatures.

The OR of ZCBs to ZEBs for each location are shown in **Figure 3**. OR(ZCB/ZEB) determines the likelihood of a ZCB occurring in the population compared with the likelihood of a ZEB occurring. It is evident that an inverse relationship

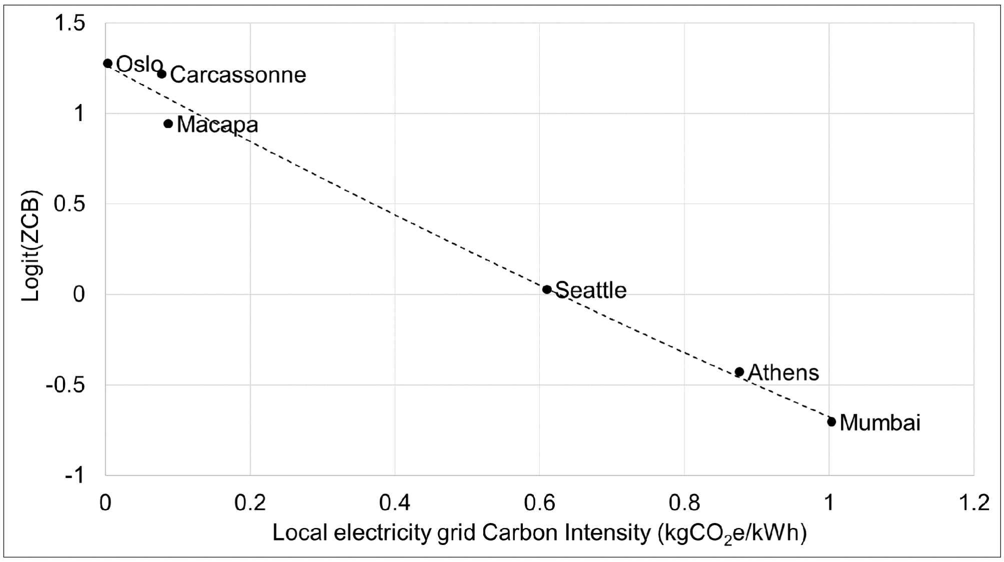

Figure 1: Relationship between logit(ZCB) and local electricity grid carbon intensity (CI).

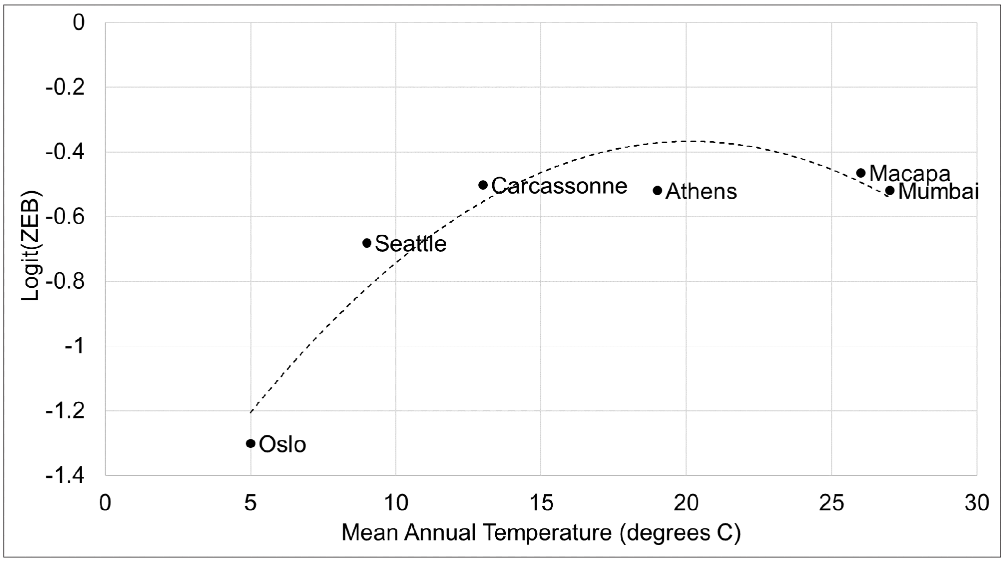

Figure 2: Relationship between logit(ZEB) and mean annual temperature.

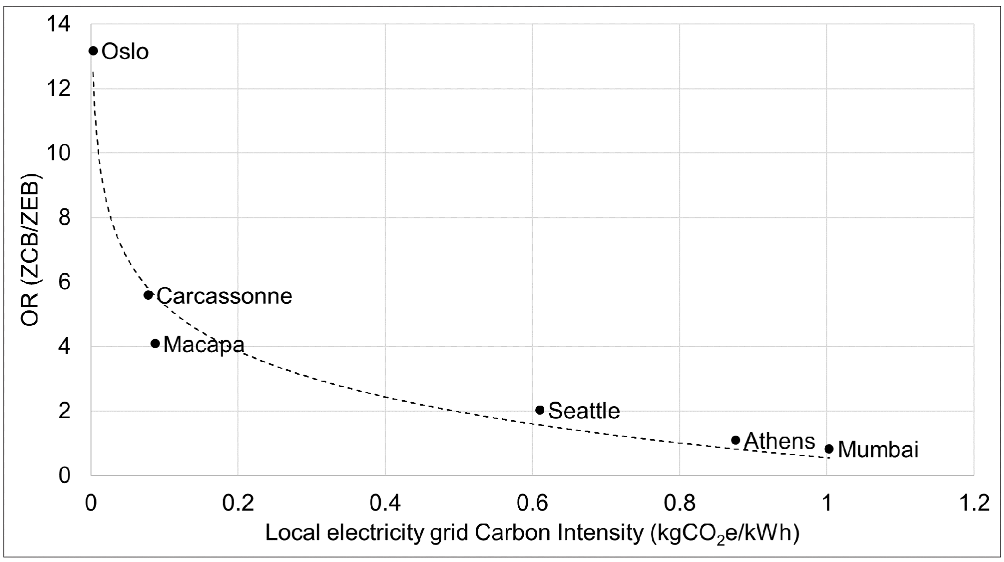

Figure 3: Relationship between OR(ZCB/ZEB) and electricity grid carbon intensity (CI).

exists between the OR(ZCB/ZEB) and the local electricity grid CI, with the OR exponentially decreasing in the range [14,0] per unit of CI in the range [0,1]. This indicates that the lower the electricity grid CI, the greater the disparity between Odds(ZCB) and Odds(ZEB) under the application of the same building object framework.

4. Discussion

It is evident from **Figures 1** and **2** that when the building objects are modelled in different locations, the resulting difference in proportions of ZCBs and ZEBs is caused by different factors. The odds of ZCBs in the SBM building object populations are determined by the local electricity grid CIs. The odds of ZEBs are instead largely caused by climate conditions (in **Figure 2**, mean annual temperature is the independent variable, but a similar profile is seen in relation to insolation levels at different locations).

When viewed through the lens of the energy metric, the profile of the building object population reveals an unsurprising landscape. Environmental conditions (external temperature and insolation levels) play a significant role in determining the likelihood of a building object achieving a net-zero-energy status; P(ZEB) generally decreases with decreasing external temperature. When carbon emissions are the focus of the SBM zero-building assessment instead, not only are insolation levels and the internal–external temperature differences important contributors to the net-zero-carbon goal, but so is the carbon-offsetting value of PV-generated electricity. These factors interact with each other to produce some less obvious results.

Figure 1 shows that, rather than environmental conditions dominating the SBM building object population profile, there is a clear negative relationship between P(ZCB) and the local electricity grid CI. In part, this is because the heating within the SBM building objects is assumed to be provided by gas, with CI = 0.216 $kgCO_2/kWh$, or electricity from the local electricity grid, depending on which fuel has the lower CI (see **Table 3** for the electricity grid CIs used). A low electricity grid CI is particularly beneficial from the perspective of cold locations using electricity to power the heating, as this means that the significant potential for heating demand does not automatically translate into a significant carbon burden.

Where the electricity grid CI is low and electricity demand outstrips PV generation (as a result of low insolation levels, high cooling demand and/or tall buildings), there is a greater possibility of offsetting any small carbon debt associated with operational energy demand with negative embodied carbon where any carbon-sequestration properties in the fabric of the building are included in the assessment (*i.e.* as is the case for the straw-walled building objects). The opposite is true in the case of locations with high electricity grid CIs. Where the offsetting value of PV electricity is high, because the electricity grid CI is high, excess generation creates a large carbon credit that can offset carbon emissions from heat demand, and embodied carbon. However, where electricity demand is likely to exceed PV generation, and the electricity grid CI is high, this translates into a significant carbon debt which is unlikely to be offset entirely by any negative embodied carbon in the building fabric. Overall, the nuances embedded within the carbon metric play an important, but not obvious, role in determining whether SBM building objects achieve net-zero-carbon status.

4.1. Changes in the metric landscapes with time

Figures 1–3 present views of the ZCB and ZEB landscapes as they currently stand. However, **Figure 1** also provides a glimpse into the evolution of the ZCB landscape. It is the ambition of many governments around the world that national electricity grid CIs will reduce in future, for example, as is the aim of the EU (2009). As this happens, **Figure 1** indicates that P(ZCB) is likely to increase for the locations towards the right of **Figure 1**, regardless of the local environmental conditions (temperature and insolation). In contrast, notwithstanding the effects of climate change, environmental conditions at different locations are unlikely to change dramatically over time. This indicates that the ZEB landscape, as shown in **Figure 2**, is unlikely to change in future—assuming the application of the same SBM building object features.

Figure 3 indicates that the ZCB and ZEB landscapes are likely to differ in future. As electricity grid CIs reduce, the discrepancy between the odds of ZCBs occurring and the odds of ZEBs occurring will grow. Therefore, it will be increasingly difficult to justify the assumption that a net-zero-energy design will produce a building that is equally beneficial from the perspective of reduced carbon emissions. As discussed above, the PHI has already suggested that, in a future where all energy is renewable, the PEFs used today to benchmark building energy demand, and also used as a proxy for carbon emissions, will become meaningless.

5. Conclusions

Global climate change is driven by GHG emissions, predominantly CO_2. Many different building assessment frameworks implemented around the world aim to reduce the contribution of buildings to climate change. However, most such frameworks focus on reducing net energy demand, whether delivered, primary or primary non-renewable.

In this study, a new conceptual framework was developed that describes a building as a system of interacting components, including:

- building energy-demand profiles (heating and cooling, lighting and occupants' use of plug-in appliances);
- PV energy-generation profiles (and the associated offset of carbon emissions from energy demand); and
- the properties of the building itself (thermal envelope characteristics and embodied carbon/energy properties).

The components of the conceptual framework formed the basis for building the SBM with 13 variable object parameters. The new framework includes components that are often disregarded or simplified in more established low- and zero-energy/carbon building frameworks, for example, occupant energy demand (plug loads), energy grid CIs and embodied carbon/energy. The outcomes of building component interactions were assessed with regard to net carbon and energy balances, resulting in objects defined as ZCBs, ZEBs, both or neither. SBM was used to simulate a population of 12.3 million building objects covering six global locations, each assessed on the basis of both carbon and energy metrics.

This work did not seek to provide a definition of a net-zero-carbon building to be adopted globally. SBM is not a sophisticated building modelling tool capable of refining net-zero-building designs to suit particular locations and contexts. Instead, this research has investigated how the feature characteristics of a variety of building objects impact the likelihood of an SBM building object achieving a net-zero-carbon, or net-zero-energy, goal given a variety of location and contextual scenarios.

This work has identified that, contrary to the usual assumptions, the features required to achieve a net-zero-carbon building are not necessarily the same as those needed for net-zero energy, and are likely to change with time. It was found that the characteristics of locations' electricity grids (*i.e.* electricity CIs) are better predictors of the probability of achieving a ZCB than are the locations' environmental characteristics (*i.e.* mean annual temperatures).

Energy was measured in terms of the delivered, rather than the primary, or primary non-renewable, metric. As discussed in section 1.1, PE non-renewable measurements may be strongly linked to carbon emissions measurements in high fossil-fuel-consuming economies. Therefore, for the high CI locations (Athens, Mumbai and Seattle), PE non-renewable landscapes can be expected to reflect more closely the respective carbon emissions landscapes. However, for the low CI locations (Carcassonne, Macapa and Oslo), where energy generation is predominantly renewable and/or nuclear, the relationships between these carbon and energy landscapes are likely to be complicated by the specific definition(s) of PE applied.

As the international community strives to achieve a net-zero-carbon global economy, energy grids, particularly electricity grids, will necessarily transition to a low CI state. This work highlights that during this transition, the carbon emissions factors, which are the foundation for some fundamental building design decisions, also need to be recognised as transitory. The concept of PEFs will also need to take this into consideration. Design features that are beneficial in the design of net-zero-carbon buildings have the potential to change with time, and features promoted in net-zero-energy building designs will not necessarily result in the reduced carbon emissions assumed. This has implications for the design and inclusion of building components (*e.g.* whether or not to include a heat pump), but also for the way building models address energy demand and carbon emissions. Just as building simulation models have developed to address energy demand dynamically (and not to just assess peak loads), so too do the models need to consider the CI of energy demand dynamically, across both the day and the year (as the Passivhaus Institute's PER factor tries to do), but also over the coming years.

5.1. Factors for further consideration

Embodied carbon plays only a secondary role in the work reported here; the operational demand/generation carbon balance is the primary issue. However, awareness is growing that the importance of carbon emissions associated with creating buildings in the first place should not be overlooked. For example, the recently announced net-zero-carbon target for the UK economy to achieve by 2050 has been criticised for allowing the 'offshoring' of UK carbon emissions, as imported products and services will not be included in the UK's net carbon emissions total (CarbonBrief 2019). The offshoring of carbon emissions may be particularly pertinent in the case of ZCBs where renewable energy-generating technology included in the design to achieve a net-zero goal is manufactured using carbon-intensive energy abroad. For example, Meng *et al.* (2018) discusses the links between the global redistribution of carbon emissions and the evolving complexity of supply chains. The research describes how the peaking of China's carbon emissions is coinciding with a shift of low-end, resource-intensive manufacturing to emerging markets elsewhere in Asia whose own carbon emissions are increasing as a result.

The embodied metrics used here were calculated using the process method of assessment which has been criticised for ignoring emissions that occur further up the supply chain of manufactured goods (Stephan *et al.* 2012), with the result that embodied carbon can be seen as a less significant issue. However, the role of embodied carbon may be more prominent under the application of the input–output technique for assessing embodied carbon, which aims to include all direct and indirect emissions in the metric (Acquaye, Duffy & Basu 2011).

During the transition to a net-zero-carbon economy, it is likely that the demand for electricity will increase, not just for buildings but also for transport. Questions about how to increase supply and store energy—possibly as building design features—are likely to become increasingly important. In relation to carbon emissions, the question of materials used and embodied carbon will become more prominent, as has already been predicted (Ibn-Mohammed *et al.* 2013). Materials such as cement, which are energy intensive to produce and also result in non-energy-related carbon emissions (Lehne & Preston 2018), will become much greater burdens for any building design aiming to achieve a net-zero-carbon goal.

Author contributions

All authors qualify as authors, as defined in the authorship guidelines, and have given permission to be listed on the submitted paper. AP formulated the ideas and methodology for this paper, including development of the Standard

Building Model, and wrote the initial manuscript. MH devised the data analysis methodology and provided critical advice on its application and the subsequent interpretation of the data in this work. DC provided overall supervision and critique of the development of ideas and methodology.

Competing interests

The authors have no competing interests to declare.

Data availability

All data used in this work is publicly available at: https://doi.org/10.15125/BATH-00465.

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