# Energy or carbon? Exploring the relative size of universal zero carbon and zero energy design spaces

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## Abstract

One aim of zero carbon, or zero energy, buildings is to help slow climate change. However, regulatory definitions frequently miss substantial emissions, for example ones associated with the materials the building is constructed from, thereby compromising this goal. Unfortunately, including such emissions might restrict the design space, reduce architectural freedom or greatly increase costs. This work presents a new framework for examining the problem. The zero carbon/energy design and regulatory space forms a sub-space of the hyper-volume enclosing all possible designs and regulatory frameworks. A new mathematical/software environment was developed which allows the size and shape of this sub-space to be investigated for the first time. Twenty-four million building design/regulatory standard combinations were modelled and assessed using a tree classification approach. It was found that a worldwide zero standard that includes embodied emissions is possible and is easier to achieve if a carbon rather than an energy metric is adopted, with the design space twice the size for a carbon metric. This result is important for the development of more encompassing regulations, and the novel methods developed applicable to other aspects of construction controlled by regulation where there is the desire to examine the impact of new regulations prior to legislation.

Practical application:

As energy standards become more strict, and given the growth in non-regulatory standards (such as Passivhaus), there is the need to study the potential impact of any element of a standard on the range of designs that can be built or the materials that can be used. This work sets out a general framework and method for doing this. The approach and results will be of interest to policy makers, but also to engineers and architects wondering what the key constraints to design the adoption of various philosophies to low energy/carbon standards might have within their work. For example, the implications of the building standard (or client) requiring embodied emissions to be included or the energy balance period for renewable generation to be monthly, not annual.

## Keywords

Embodied carbon, embodied energy, low carbon buildings, net-zero energy

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## Introduction and background

There is a sense of urgency surrounding the need to reduce anthropogenic greenhouse gas emissions (IPCC, 2014) (National Research Council, 1979). National and international legislation (Crown, 2008) (European Parliament, Council of the European Union, 2010) (United Nations, 1998) is driving the development of building standards aimed at reducing to zero, or beyond, the emissions that are attributed to the construction sector – responsible for around 20% of total global greenhouse gas emissions (IPCC, 2014). However, while there are many such standards, in almost all cases, buildings are assessed on the basis of energy not carbon (Parkin, et al., 2015). A notable exception being the recently rescinded UK zero carbon homes standard, which assessed calculated annual carbon emissions (Department for Communities and Local Government, 2010). Although carbon emissions and energy demand are linked, they are not equivalent. Carbon emissions depend on the fuel, and processes, that are used to generate the energy used in the building or embodied in its materials. For example, the carbon intensity (CI) – the carbon emission released for each unit of energy generated – of UK gas is much lower than that of UK electricity (0.216 and 0.519 $kgCO_2e/kWh$, respectively) (as of 2018, the true value is now lower; however, this is the value given in the relevant building regulations and hence pertinent to later discussions) (Department of Energy and Climate Change, 2012).

There have been recent calls for a universal, i.e. global, zero energy/carbon standard (Williams, et al., 2016), and standards such as Passivhaus are becoming global under their own momentum. This raises the question of to what degree architectural freedom and design choice would be impacted by any universal standard and whether choosing carbon, not energy, as the core metric further constrains the design choice?

## The components of zero carbon and zero energy building standards

A review of global low and zero carbon and energy building standards can be found in Williams et al. (2016). It is interesting to note the wide range of elements that may, or may not, be included in a building standard. Aside from the choice between carbon and energy, even the types of energy demand assessed are not necessarily consistent. For example, a distinction is often made between regulated loads (heating, cooling, hot water, fans, pumps and fixed lighting) which are included in UK building standards (Department of Energy and Climate Change, 2012) and unregulated loads (anything else, e.g. plug loads – computers, televisions, washing machines, etc.) which are not. In contrast, the Passivhaus building standard is concerned with all energy demand in a building (Cotterell & Dadeby, 2012). However, rarely are embodied carbon, or embodied energy, considered – even though steel and cement alone are reported to account for 44% of UK industrial carbon emissions (Giesekam, et al., 2014). The range of approaches, and the missing of potentially important emissions, suggests various avenues for research. One clear research question being, how the range of possible buildings that could be built might be constrained by the particular choice of zero energy or carbon standard? Another, what elements within a standard are likely to be the most constraining, for example, the inclusion of embodied energy or the requirement to place all renewables within the footprint of the building? And finally, is it possible to construct a mathematical framework that would allow such issues to be studied?

## Embodied energy and renewables provision

There are many elements to any zero energy/carbon standard, and each needs a precise definition within the standard and a statement what is and is not included. To highlight some of the many issues, we present two examples: embodied energy/carbon and renewables provision; for a list of further elements and issues, see Williams et al. (2016).

Measuring embodied carbon and energy is itself a difficult and variable activity – see (De Wolf, et al., 2017) for an extensive discussion on the different methods used for assessing embodied carbon and the difficulties this presents in terms of consistency and transparency in building assessments. For some, based on the bottom-up, process method of assessment, the embodied metrics of a building are negligible when compared with its operational metrics (Dequaire, 2012) (Ramesh, et al., 2010). However, use of the top-down, input–output technique for the assessment of embodied metrics leads to the opposite conclusion (Ramesh, et al., 2010) (Acquaye & Duffy, 2010) (Acquaye, et al., 2011) (Crawford & Treloar, 2003) (Dixit, et al., 2013) (Stephan, et al., 2012). Furthermore, the ability of organic materials to sequester carbon adds an additional confusion. However, it is worth noting that deforestation has the effect of actively contributing to carbon emissions (Weight, 2011), so it is not necessarily safe to assume that the general use of timber products has a net beneficial impact on climate change (Hammond, et al., 2011). The use of straw as a negative embodied carbon building material is less controversial; it grows quickly and is a bi-product of food production (Sodagar, et al., 2011). As a building material, straw has a reported embodied carbon of -1.35 $kgCO_2e/kg$ (note the minus sign) (Sodagar, et al., 2011), although its embodied energy can at best be zero, but is likely to be positive due to fossil fuel based transport emissions.

One concept that is frequently applied in low and zero carbon and energy building standards is the ability of renewably generated energy to offset the energy demand of buildings (usually within an annual balance period). This allows the measured carbon emissions, or energy demand, to be reduced to zero or even made negative. There are numerous ways to generate renewable energy, but the use of photovoltaics (PV) is the most common method – in almost all cases, the PV is assumed to be mounted on the roof of the building. Given that the timing of renewable energy generation does not always match the timing of demand, this concept necessarily assumes some form of energy storage. Most building standards view the national electricity grid as a suitable place to 'store' such energy. However, for some authors, onsite self-sufficiency, usually through the use of batteries, is the ideal (Voss & Musall, 2013), presenting a particular challenge for locations with large seasonal variations in environmental conditions. It is worth noting that the embodied metrics of renewable energy generation are often overlooked and can be significant. For example, the embodied carbon value for PV modules was once estimated to be as much as 953 $kgCO_2e/m^2_{PV}$ (Nawaz & Tiwari, 2006). The general view is that embodied costs of such technology are falling, with future values predicted to be as low as 72 $kgCO_2e/m^2_{PV}$ (Mann, et al., 2014). However, it has been pointed out that global PV manufacture is tending to move from lower carbon economies in Europe to higher carbon economies in Asia (Louwen, et al., 2016).

These two examples – embodied emissions and renewables – are, as commented earlier, just two examples where the details of how they are included in a standard is likely to make a material difference to the design space. This suggests that it would be worth developing a general framework for the analysis of the potential impact of any choices.

## Research questions

The aim of this paper is to produce a method that allows the investigation of how the different constraints imposed on the design of a building by using climate change orientated building standards reduces the size (volume) of the design space (i.e. the space containing all possible designs, e.g. variants in height, materials, form, U-values, airtightness, number of floors, window type and size), and in particular whether the size of the design space is constrained more, or less, by demanding zero carbon, rather than zero energy buildings (ZEBs). It is suggested that the new approach used of: (i) combining the building space with a large list of possible regulations into a single parametric space; (ii) modelling all combinations of buildings and regulations; (iii) analysing the results using a tree classification to discover the implications of various combinations of the regulations for various buildings has the potential for de-risking buildings codes before they are finalised and allowing some of the architectural issues of any standard to be exposed.

## Methodology

The problem is set out in a completely general way and covers most relevant design and regulatory parameters (see Table 1 and Table 2). The idea is not to discover if a particular building is zero carbon (or energy), but to discover how the design space contracts and design limits arise as the regulatory framework becomes more aggressive. A parametric approach is taken, but uniquely, the regulatory space is also parameterised.

The design and regulatory spaces

In general, the building design space, **S**, consists of a large number of dimensions made from a mix of real, integer and Boolean variables, for example, building dimensions (real), number of storeys (integer) and the inclusion or not of active cooling (Boolean). A subset, **S'** of **S**, will be highly relevant to the energy use of a building or its carbon emissions and implicated in the regulations. The regulatory energy or carbon accountancy space, **R**, consists of a list of Boolean dimensions, for example, include (or not) embodied energy, allow (or not) remote generation from renewables and include (or not) non-regulatory electricity use. In addition, there is a space, **L**, specifying all possible locations any building might be sited. **L** also contains a description of the energy supply metrics of the location, for example the CI of the electricity grid. The list of variables considered was taken from (Williams, et al., 2016) and is detailed in Table 1 and Table 2.

In order to make the problem tractable, we limit the range of each variable in **S'**. The range of each variable has been chosen to be realistic and cover the full range of likely values (see Table 2). For example, both a low embodied carbon construction based on straw and a high embodied carbon one using brick are included, thereby covering both extremes. (Although other options like low embodied energy recycled brick exist, it is the extremes we need to identify.) The footprint of the building is allowed to range from 45 to 450m$^2$ in steps of 45m$^2$, giving 10 possible values for this dimension – it would be trivial to change these limits to study larger buildings. This gives a discretised space, **S''** with members s''. **L** is similarly limited, in this case to six locations, to give **L'**, again, other locations could be chosen.

**S''**, **L'** and **R** are combined into a single space, **Z**. A member (or case), z, of **Z** then identifies a single theoretical building examined under a single regulatory framework in a single location. With the combination of parameters studied, **Z** has 24 million members. The energy use (with generation from renewables considered negative) or carbon emissions (with the potential for some materials to sequestrate carbon) for each z of the 24 million in **Z** are then found by the use of a suitable energy/carbon model. Some members of **Z** will be found to be carbon or energy neutral or better. We term this subset $\mathbf{Z_z}$. A classification tree analysis can then be used to compare and contrast members of $\mathbf{Z_z}$ with the whole of **Z** or with members of **Z** which are not members $\mathbf{Z_z}$. Thereby answering questions such as, do most members of $\mathbf{Z_z}$ have fewer than 10 storeys? And, do most buildings require offsite renewables generation to be classified as zero energy? It is important to realise that the buildings studied are either $\epsilon$ of $\mathbf{Z_z}$ or not; i.e. the solution space is binary and no account is taken of how close to passing or failing the zero energy/carbon regulation a solution is. This mimics the real life situation, where a building must simply pass the regulation.

A new Standard Building Model (SBM) was developed in Matlab to simulate the construction and performance of multiple buildings in multiple global locations. Virtual materials objects, with embodied carbon and energy, and where applicable thermal resistance properties were combined by SBM to create virtual building objects (see Table 1). These were then assessed under defined conditions (locations, number of occupants, infiltration levels, etc.) to generate SBM cases (i.e. members of **Z**). The properties of the building objects and the specifications of the assessment conditions were varied, as detailed in Table 2. The overall result was the generation of 24.7 million SBM cases, filling the space **Z** and enclosing all the possible combinations of building design and assessment conditions simulated by SBM. In this work, only domestic buildings are considered, although this could easily be expanded to the different occupancy densities and loads found in commercial building.

Table 1: *SBM virtual objects (which forms the list of all parameters considered).*

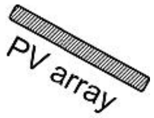
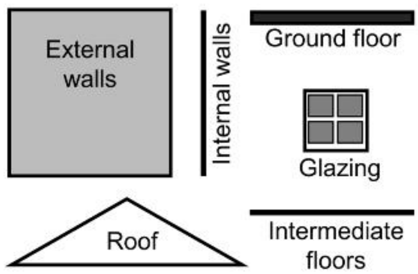
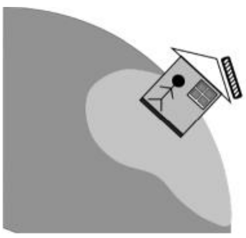
<table>
<tr><td rowspan="6">Object combination</td><td colspan="2">Standard Building Model Virtual Objects</td><td>Virtual Object properties</td></tr>
<tr><td rowspan="3">Renewables Objects<br>
<br>PV dimensions determined by Building Object dimensions</td><td>Materials Objects<br>
</td><td><ul><li>Embodied carbon (kgCO$_2$e per m$^2$)</li><li>Embodied energy (kWh per m$^2$)</li><li>Thermal resistance (m$^2$K/W) - only if external envelope component</li></ul></td></tr>
<tr><td>Materials Objects combine to create:</td><td></td></tr>
<tr><td>Building Objects<br></td><td><ul><li>Dimensions (footprint, height, etc.)</li></ul></td></tr>
<tr><td colspan="2">Building Objects and Renewables Objects combine with locations to create:</td><td></td></tr>
<tr><td colspan="2">Building System Objects<br><br>(PV onsite)<br><br>(PV remotely sited in Accra)</td><td><ul><li>Assessment conditions (no. occupants, infiltration levels)</li><li>Environmental conditions (temperature, insolation, energy grid)</li></ul></td></tr>
<tr><td colspan="4">Building System Objects are assessed using a methodology that has a defined<ul><li>Balance period (Annual or Monthly)</li><li>Boundary condition (Operational metrics only, or Operational + Embodied metrics included)</li></ul></td></tr>
<tr><td colspan="4">Each assessment outcome is one CASE</td></tr>
</table>

Table 2: *Building object properties and assessment conditions (i.e. the range of parameters considered).*

<table>
<tr><th></th><th>Variable</th><th colspan="6">Value range / Categories</th></tr>
<tr><td rowspan="9">Building Design</td><td rowspan="2">Principal construction material</td><td colspan="6">Brick</td></tr>
<tr><td colspan="6">Straw (assuming no carbon sequestration)<br>Straw (assuming carbon sequestration)</td></tr>
<tr><td>Footprint ($m^2$)</td><td colspan="6">45 – 450 $m^2$ in steps of 45 $m^2$</td></tr>
<tr><td>Width (m)</td><td colspan="6" rowspan="2">Limitations were placed on the aspect ratios permitted (to avoid modelling unreasonably narrow and/or tall buildings).<br>Valid building widths were calculated using aspect ratios 1, 0.5, 0.25 and 0.125 and<br>$$Building\ width = \sqrt{aspect\ ratio \times building\ footprint}$$<br>The modelled buildings have different wall depths, so an additional requirement was included that the internal floor area for one storey must be greater than 25 $m^2$.<br>1, 2, 4, 8, 16 and 32 storeys were modelled, with the same limitation on aspect ratios.</td></tr>
<tr><td>Height (storeys)</td></tr>
<tr><td rowspan="3">External wall U-values ($W/m^2K$)</td><td colspan="2">U-values ($W/m^2K$)</td><td>0.18</td><td>0.15</td><td>0.12</td><td>0.10</td></tr>
<tr><td rowspan="2">Insulation depth (mm)</td><td>In Brick buildings</td><td>110</td><td>130</td><td>180</td><td>220</td></tr>
<tr><td>In Straw buildings</td><td>380</td><td>475</td><td>600</td><td>700</td></tr>
<tr><td>Glazing area</td><td colspan="6">10, 20, 40 and 80 % of the external walls</td></tr>
<tr><td rowspan="3">PV Specification</td><td rowspan="3">PV specification (monocrystalline silicon)</td><td colspan="2"></td><td colspan="2">Embodied carbon ($kgCO_2e/m^2_{PV}$)</td><td colspan="2">Embodied energy ($kWh/m^2_{PV}$)</td></tr>
<tr><td colspan="2">Low embodied metrics[1]</td><td colspan="2">149</td><td colspan="2">241</td></tr>
<tr><td colspan="2">High embodied metrics[2]</td><td colspan="2">953</td><td colspan="2">318</td></tr>
<tr><td rowspan="9">Assessment Conditions</td><td>Occupant density</td><td colspan="6">No occupants; 35 $m^2$/person; 20 $m^2$/person</td></tr>
<tr><td rowspan="3">Glazing U-value ($W/m^2K$)<br><br>Regardless of U-value, embodied metrics for glazing do not change.</td><td>1.4</td><td colspan="5">Complies with UK Building Regulations 2014[3]</td></tr>
<tr><td>0.8</td><td colspan="5">Passivhaus compliant[4]</td></tr>
<tr><td>0.68</td><td colspan="5">Based on the ULTRA range[5]</td></tr>
<tr><td>Air infiltration</td><td colspan="6">0.042 + MVHR; 0.700; 0.343 air changes at normal pressure</td></tr>
<tr><td>Calculation boundary</td><td colspan="6">Operational only<br>Operational + Embodied</td></tr>
<tr><td>Balance period</td><td colspan="6">Annual; Monthly</td></tr>
<tr><td>Building location</td><td colspan="6">Athens; Carcassonne; Macapa; Mumbai; Oslo; Seattle</td></tr>
<tr><td>PV location</td><td colspan="6">Onsite; Sited remotely in Accra – always orientated for optimum PV generation</td></tr>
</table>

1 (Mann, et al., 2014)

2 (Nawaz & Tiwari, 2006)

3 (HM Government, 2013)

4 (Cotterell & Dadeby, 2012)

5 (Green Building Store, 2017)

Table 3: *Location, temperatures and electricity grid CIs (ordered by latitude).*

| City | Latitude (ºN) | Country | Mean annual insolation ($kWh/m^2_{horizonatal}$) | Mean annual temperature (ºC) | National electricity grid CI ($kgCO_2e/kWh$)[1] |
|---|---|---|---|---|---|
| Macapa | 0.04 | Brazil | 1,700 | 26 | 0.087 |
| Mumbai | 19 | India | 2,100 | 27 | 1.003 |
| Athens | 38 | Greece | 1,600 | 19 | 0.876 |
| Carcassonne | 43 | France | 1,300 | 13 | 0.078 |
| Seattle | 48 | USA | 1,200 | 9 | 0.610 |
| Oslo | 60 | Norway | 1,000 | 5 | 0.003 |

1 (IPCC Technology and Economic Assessment Panel, 2005)

The performance of each case was assessed in terms of both net carbon emissions and net energy demand (normalised to the internal floor area). A zero carbon building (ZCB) is defined as a case assessed to have net zero, or negative, carbon emissions. Similarly, a ZEB is defined as a case assessed to have a net zero, or negative, energy demand.

PV generated electricity is the offsetting mechanism relied on to reach the zero carbon or energy goal, and each SBM case can be classified as a ZCB, a ZEB, both or neither. Other possible building-mounted renewables for electricity generation have been ignored, as has facade-mounted PV. This is because such technologies (such as roof-mounted wind) have failed to find traction and their output highly dependent on the precise urban environment – which at this level of assessment is unknown.

## The standard building model

The SBM is an hourly heat loss/gain model which ignores the temporal impact of thermal mass (as this would require a dynamic model) and solar gains (as this would require detailed information about window location and the form of the external landscape). The assumption is that, as this work is discussing zero carbon or energy design, attempts will have been made to shade any glazing appropriately – this is unlikely to be the case for all buildings, but represents the kind of wording of desire likely to be found in an environmental building standard. The building footprint is determined by the external dimensions, whereas the internal floor area takes into account the external wall thickness. The SBM makes hourly estimates of the heat loss or gains through opaque and transparent elements by calculating the area-weighted mean U-value (i.e. the model is geometry free), with the temperature difference being given by the set-point and the hourly weather file (see below). Floor losses are ignored. Electrical gains and other parameters of the model are as given in the text below and in Table 1, Table 2 and Table 3. Occupancy density (for the estimate of metabolic gains) was set to 20–35$m^2$/person, biasing the work away from more wealthy occupants (35$m^2$/person being the Passivhaus Certification assumption). Each hour the gains are compared to the losses (including ventilation), and energy is used to meet the set points. Several of the assumptions in the model are unlikely to be valid in all countries, and others represent simplification of the situation, for example, the wide scale adoption of PV would lead to energy and carbon economies of scale; domestic electrical use would be a function of location and wealth. In short, we have tried not to model the buildings exactly, but how they might be considered within a domestic building code, where assumptions of occupancy densities, incidental gains, emission factors, the embodied energy of key materials, set-points, etc., are likely to be specified in the code and not building dependent. Other issues such as the pollution caused by the manufacturing of PV and other components and waste disposal at end of life have been ignored, as these are rarely found in building regulations. The SBM was validated against the Passivhaus standard and pre-existing work on embodied emissions from buildings (see Appendix 1).

The SBM has been designed to give an hourly estimate of energy use of the building for comparison with any renewables generation and then to sum over the accountancy period given by the regulation space **R**. The use of a dynamic simulation might alter the hourly estimates, but is likely to have little impact for the summed values and hence on the results. It is based on PHPP, the model used to develop all certified Passivhaus, and hence the physics is well tested on over 40,000 buildings and for a similar purpose: the comparison of energy consumption against a low energy standard.

## Building location

Six locations (**L'**) were chosen to allow for the simulation of a range of external temperatures, insolation levels and electricity grid CIs – from fossil fuel to renewables based societies. Table 3 shows the relevant characteristics of the different locations. Hourly external temperature data and insolation levels for the different locations are based on data from NASA (NASA, n.d.).

## PV location

All buildings were modelled for two scenarios. The first assumes that the PV array is roof mounted on the building. Under this assumption, the carbon offset value of PV generated electricity is negative, but of the same magnitude as the local electricity grid CI (as in Table 3). Buildings are modelled with a PV array sized to cover the entire roof (to give the maximum potential for the building to be zero energy/ carbon), angled for optimum annual electricity generation (in practice, however, there might be a minimum angle to avoid the accumulation of dirt). The size of the PV array depends on the shape of the building and determines the amount of electricity generated and the total embodied carbon and energy for PV.

The second scenario allows for offsetting via a remote renewable source located in a more favourable location. This represents the situation where a building standard allows remote offsetting or where national grids have been interconnected. Accra was chosen as the location for the remotely sited PV; given its low latitude (5.6°N), daily PV generation is relatively consistent across the year. This means that short-term (daily) storage of electricity in batteries is possible, thereby removing the need for such electricity to be 'stored' in the local electricity grid. In these circumstances, PV generation can satisfy electricity demand throughout the year without the need for support from traditional energy infrastructure. Under this assumption, the carbon offset value of PV generated electricity is negative, but of the same value as the electricity grid CI in Accra (see Table 4). A further negative CI element is added to the carbon offset value of the PV generated electricity to reflect the removal of the need to build traditional energy infrastructure. For example, the CI associated with just the construction of a 1GW nuclear power station has been calculated to be 0.0014 kg$CO_2$e/kWh (MacKay, 2009). Embodied metrics associated with the necessary onsite batteries are included in the overall building embodied metrics (see Table 4).

### Electricity demand

SBM assumes that electricity demand is largely tied to occupancy levels. Demand rises and falls throughout the day, with a constant base load included to account for appliances on standby mode or running continuously (e.g. fridges). The electricity demand profile is based on the patterns of demand identified in (Knight, et al., 2007) and varies hourly across the day, the week and the year. The overall electricity demand level is based on the usage of a typical UK family of four (Energy Savings Trust, 2012), with a value of 1350 kWh/a/person. The use of UK-based data here and at several points below does not impact on the global validity of the conclusions reached. The reason for using UK values is the desire to fix these variables in order to draw out the impact of the building-centric variables under study, and because the data are not sufficiently accurately known for the other locations.

Table 4: *Assumptions when the PV array is remotely located in Accra.*

| **SBM Assumption** | **Notes** |
|---|---|
| Accra electricity grid CI: 0.705 $kgCO_2e/kWh$ | Assuming the Africa average[1] |
| Electricity CI associated with traditional power station construction: 0.0014 $kgCO_2e/kWh$ | Based on[2] |
| Carbon offset value of remote PV generated electricity in Accra: -0.7064 $kgCO_2e/kWh$ | = -(0.705 + 0.0014) |
| Electricity demand CI based on the electricity grid local to the building | See national electricity grid CI values in Table 3 |
| Battery storage: NiMH | Assumed lifetime: 15 years |
| Battery embodied carbon: 283 $kgCO_2e$/occupant (over 15 years) | Based on[3] |
| Battery embodied energy: 458 kWh/occupant (over 15 years) | Based on the battery embodied carbon above and European electricity CI[4] = 0.617 $kgCO_2e/kWh$ |

1 (IPCC Technology and Economic Assessment Panel, 2005)

2 (MacKay, 2009)

3 (McManus, 2011) and (Brook & Bradshaw, 2014)

4 (Voss & Musall, 2013)

### Heating and cooling

Heating is used to raise the internal temperature to the heating set point (18°C when occupied, 13°C when unoccupied – based on Public Health England data (Public Health England, 2014) and (BS EN 15251, 2007)), and is reduced by hourly metabolic heat gains, and those from electrical equipment when present. Domestic hot water is not accounted for in the SBM energy demand calculations, and gains from domestic hot water use are not included either. The heating fuel is assumed to be gas (with the UK gas CI of 0.216 $kgCO_2e/kWh$) or electricity from the local grid, depending on which source has the lower CI.

Cooling is used to reduce the internal temperature to the cooling set point (25°C when occupied, 30°C when unoccupied – based on (Cotterell & Dadeby, 2012) and BS EN 15251. It is assumed that all windows can be opened, allowing the internal and external temperatures to reach equilibrium, when possible. This means that no cooling is active when the external temperature is below the cooling set point. It is also assumed that the windows will be closed when the cooling system is active. The cooling system in SBM has a coefficient of performance of 0.5814, based on (Szokolay, 2008) and is powered by electricity from the local grid (e.g. CI as in Table 3).

These set points are unlikely to be truly representative of all locations in the study, and many buildings would be operating within an adaptive comfort framework. They have been used to ensure uniformity, to avoid confounding factors and due to a lack of consistent data for some locations.

## Air infiltration

The buildings were modelled with three levels of air infiltration (Table 5). The heating system present in the SBM buildings depends on the levels of air infiltration. A traditional heating system is present when air infiltration levels are high, but is replaced by a mechanical ventilation with heat recovery (MVHR) unit when air infiltration is low, thereby mimicking the use of MVHR in air tight buildings such as those conforming to the Passivhaus standard.

Table 5: *SBM infiltration levels.*

| **Infiltration level (air changes per hour at normal pressure)** | **Notes**<br>**Given by *infiltration at typical pressures* = 0.07 x *infiltration at* 50 Pa** |
|---|---|
| 0.042 | Equivalent to 0.6 air changes at 50 Pa, i.e. the maximum uncontrolled infiltration level for Passivhaus compliance[1]. MVHR system (with an efficiency of 90 %) is included in embodied metric calculations to supply the fresh air needed for good air quality, as required in the Passivhaus building standard. |
| 0.343 | The uncontrolled infiltration required for Passivhaus good air quality compliance, based on 30 $m^3$/person per hour, and the Passivhaus default occupancy of 35 $m^2$/person[1]. Traditional heating system included in embodied metric calculations instead of the MVHR system. |
| 0.700 | Equivalent to 10 air changes at 50 Pa. The approximate infiltration level for UK Building Regulations compliance[1]. Traditional heating system included in embodied metric calculations. |

1 (Cotterell & Dadeby, 2012)

## Principal construction materials

The principal construction materials used in the buildings were either *brick* (brick, block and concrete with foam-based insulation) to represent a high carbon construction, or *straw* (timber with straw insulation), to represent a low carbon construction. Other possible cases, not modelled in this work, can be seen as intermediate to these extremes. The high carbon construction details are based on (Charlett & Maybery-Thomas, 2013). The low carbon construction details are based on (Pelly & Mander, 2014). In all cases, the ground floor consists of a solid concrete floor (as in Charlett and Maybery-Thomas). Internal walls for all buildings are based on the cross-laminated timber walls in (Pelly & Mander, 2014) to maximise the potential for carbon sequestration.

Straw buildings are assessed under two assumptions: carbon sequestration is applicable to timber and straw building components (i.e. embodied carbon for such elements is negative – this is a controversial position, but again, represents the extreme); or carbon sequestration is not applicable at all (i.e. embodied carbon for such elements is positive or zero).

## Calculation boundary

Two accountancy boundaries were applied to the assessment of the buildings. *Operational* includes only the carbon emissions, or energy demand, associated with the operation of the buildings (e.g. heating and electricity demand); *Operational + Embodied* also includes the carbon emissions, or energy, used to create (or stored in, in the case of sequestration) the fabric of the building.

All embodied energy data and operational energy values (demand and generation) are measured in terms of final energy, not primary energy. This makes the distinction between energy and carbon emissions more obvious and removes the possibility of the choice of heating/cooling fuel being more important than issues such as building fabric or architecture. The reported carbon emissions however are based on primary energy use. The embodied energy values for all materials and products were obtained from the literature and based on the bottom-up process method of assessment. By converting embodied primary energy values to final energy (via the mean European electrical primary energy factor), the role of the national energy mix of the manufacturing location is removed, thereby accounting for the potential to obtain materials from various locations. In a global study, such as this, it is impossible to guarantee where materials might be sourced over coming decades. However, this does mean that materials that always use different primary mixes in their manufacture (such as steel and aluminium) are less differentiated than a primary energy-based accountancy would suggest. Once better, worldwide, data on embodied emissions exist, and primary energy accountancy could be used instead.

CIs (or carbon emission factors) are applied to site energy demand and generation following the method used in the UK Standard Assessment Procedure (Department of Energy and Climate Change, 2012). These give a direct indication of the carbon emissions associated with the site energy balance. Using the same assumptions as in the energy scenario described above, embodied carbon values are also sourced from the literature (via the ICE database (Hammond, et al., 2011)). The manufacturing assumptions applied in the literature (which are often dependent on the method and location of production) are similarly applied in this work; the location of the modelled building does not alter its embodied carbon characteristics (an assumption required by the lack of data for most countries).

In this work, the building life is assumed to be 60 years, and the PV array and glazing are assumed to have lifetime of 30 years – i.e. these buildings need two PV arrays over their lifetime. Redecoration and maintenance are not included. This is a simplification, justified by the difficulty for accounting for redecoration in any building regulations. However, studies such as (Rauf & Crawford, 2013) indicate that they could be significant.

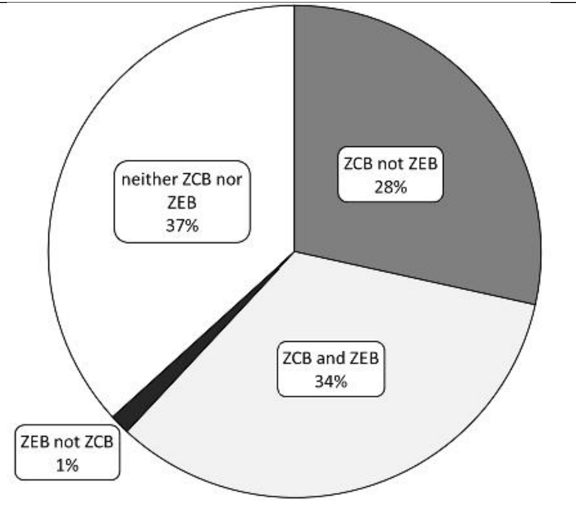
## Balance period

Two different balance periods were applied to 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.

Results

All possible combinations of the above construction and accountancy parameters were analysed by the SBM. Of the 24.7 million cases, 37% were found to be neither ZEB nor ZCB (Table 6). Sixty-two percent were found to be ZCB, whereas only 35% ZEB. This is the first indication that building standards based on carbon not energy might be more universal and less constraining of the design space. In addition, while a zero energy classification is almost always associated with a zero carbon classification, only around half the total number of ZCBs are simultaneously ZEBs.

Table 6: *Classification of cases.*




| | |
|---|---|
| ZCB not ZEB | Case classified as zero carbon, but not zero energy |
| ZCB and ZEB | Case classified as both zero carbon and zero energy |
| ZEB not ZCB | Case classified as zero energy, but not zero carbon |
| neither ZCB nor ZEB | Case not classified as zero carbon or zero energy |

The whole population of cases was analysed using a classification tree algorithm. The classification tree uses recursive partitioning to split the data into ever smaller subsets of similar classes. Beginning at the root node, the algorithm selects the feature (the input variable in Table 2) that is most predictive of the target class (ZCB or ZEB). The population is then split into subsets based on the feature values (the value range or category in Table 2). The algorithm continues to further split the nodes, based on the most predictive feature at that node, until a stopping criterion is reached. This occurs at a node if:

- . all of the cases fall into the same class; a pure node;
- . there are no remaining features to distinguish among cases;
- . the minimum leaf node size is reached (500,000 cases or 2% of the total population).

The feature that is most predictive of the zero carbon target (i.e. forms the greatest constraint) is the location of the building (see Figure 1). The first classification tree split divides the SBM population into those in locations with high electricity grid CIs and those with low electricity grid CIs. ZCBs and ZEBs were found in all locations (see Figure 4). Meaning that at least in theory, it is possible to build zero carbon or ZEBs in all the locations studied. However, from the energy perspective, the feature that is most predictive of the zero energy target (again, that which forms the greatest constraint) is the number of storeys (see Figure 2). This is unsurprising (and is in line with the findings in (Heinonen & Junnila, 2014) and (Stephan, et al., 2013) as the taller the building the greater the difficulty of the PV providing all the energy required. However, ZCBs were possible for all building heights, and ZEBs were possible in the cases of all but the tallest buildings (see Figure 3).

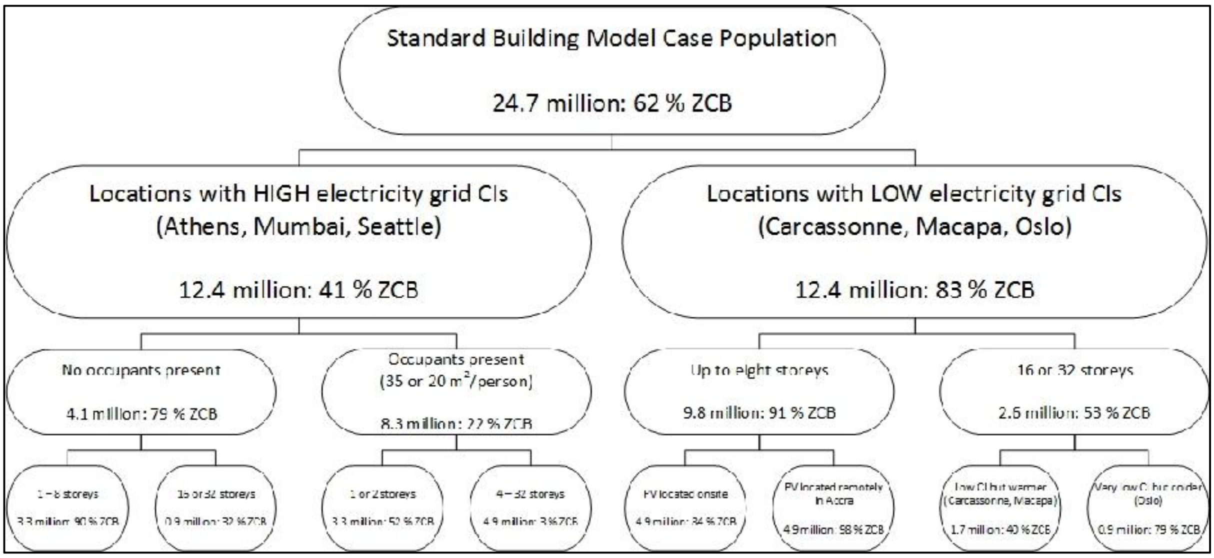



Figure 1: *Trimmed carbon classification tree showing the top four node levels*.

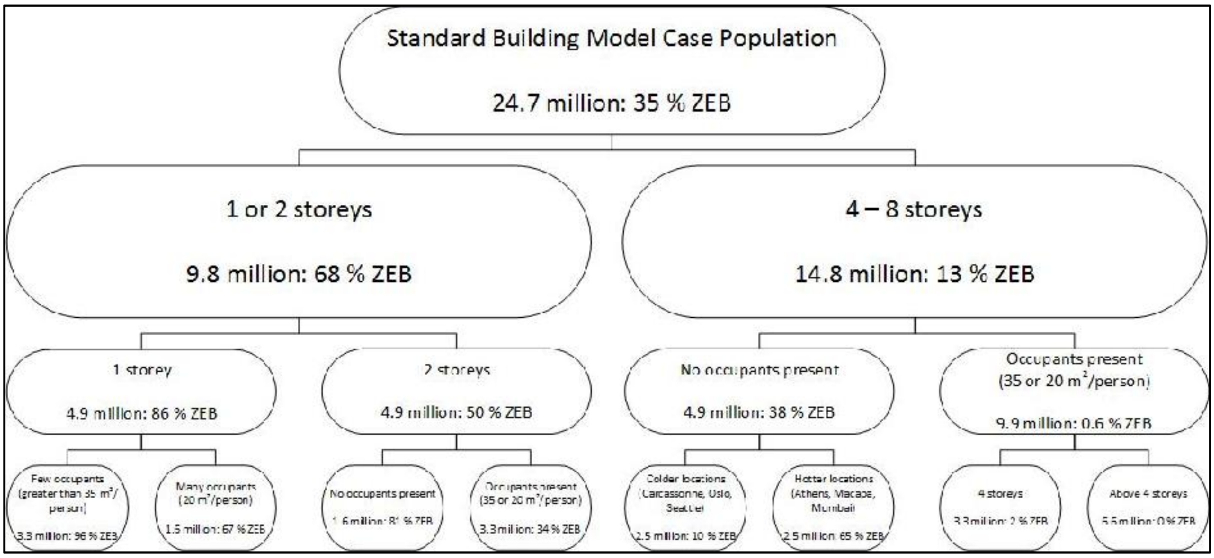



Figure 2: *Trimmed energy classification tree showing the top four node levels.*

Both the carbon and energy classification trees contain more node levels than shown in Figure 1 and Figure 2, which identify further, sometimes repeated, splitting features. All features identified were also scored and ranked according to their prominence rather than location in the classification trees using Equation 1. Table 7 shows the ranking of features as identified in the carbon classification tree. The highest scoring feature is ranked first.

Equation 1

$$Feature\ score = \sum_{\substack{Node\\levels}} \frac{Number\ of\ times\ feature\ appears\ in\ tree}{Node\ level\ at\ which\ feature\ appears}$$

It should be noted that ranking the energy classification tree features using Equation 1 reveals the same top four features, in the same order, as is the case for the carbon classification tree. The difference is that, in the case of energy, no further features are identified.

Table 7: *Ranked carbon classification tree splitting features.*

| **Feature ranking** | **Feature** |
|---|---|
| 1 | Building height |
| 2 | Location |
| 3 | Occupants |
| 4 | Balance |
| 5 | Boundary |
| 6 | PV location |
| 7 | Glazing % |

As well as the features identified as being important, it is worth noting the variables that have not been identified by the classification trees as splitting features at the level of detail shown in the trees. These are construction material (brick or straw), infiltration level, PV specification, glazing U-value, external wall U-value, building width and building footprint.

The location of the building is the feature ranked second in Table 7 as a predictor of reaching the zero target (i.e. it is the second most powerful constraint). However, rather than the location's climate being dominant, Figure 4 shows that the lower the location's electricity grid CI, the more likely it is that cases will be classed as ZCBs. It is also evident that the higher the electricity grid CI, the more likely it is that cases classed as zero carbon are also classed as zero energy and vice versa.

Figure 5 shows how the proportions of ZCBs and ZEBs fall at similar rates as the number of occupants increases.

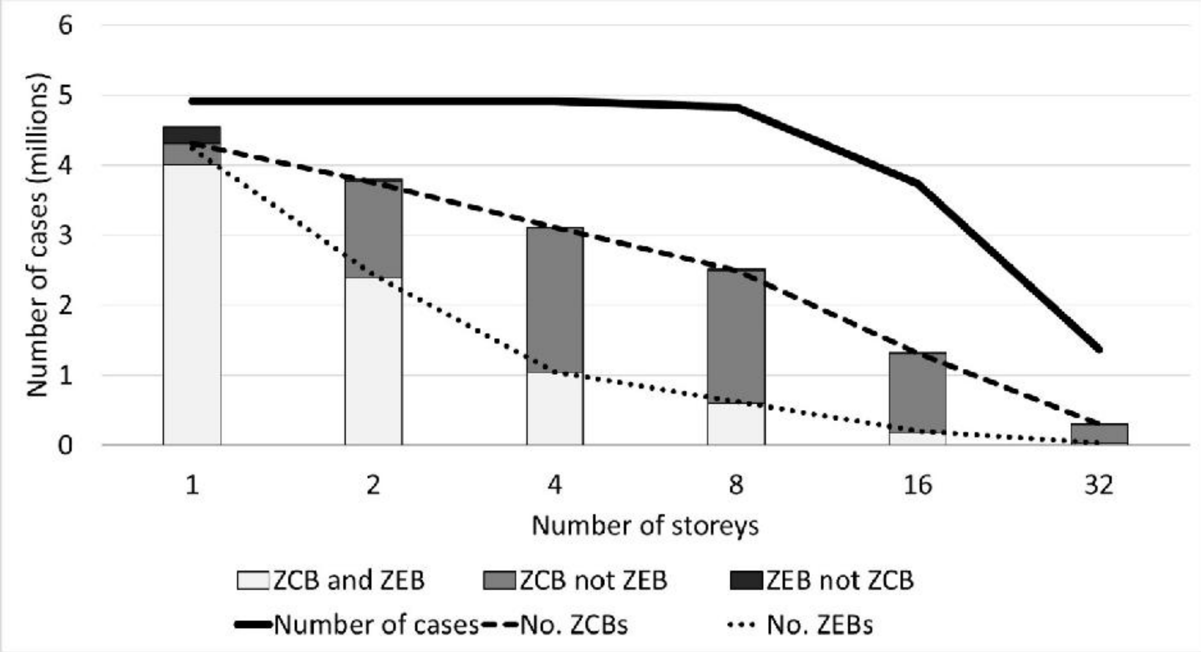



Figure 3: *Change in ZCB and ZEB proportions with building height. As a result of the aspect ratio restrictions, discussed in Table 2, the number of cases is 4.9 to 1.4 million depending on the number of storeys.*

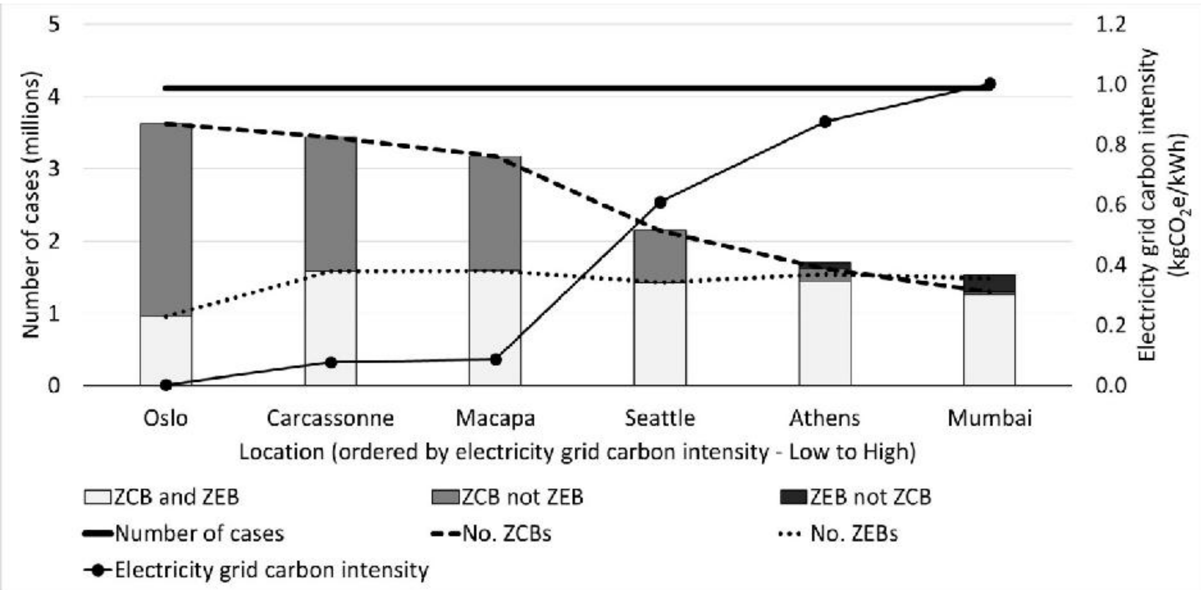



Figure 4: *ZCB and ZEB proportions for different locations. The number of cases is 4.1 million for each location.*

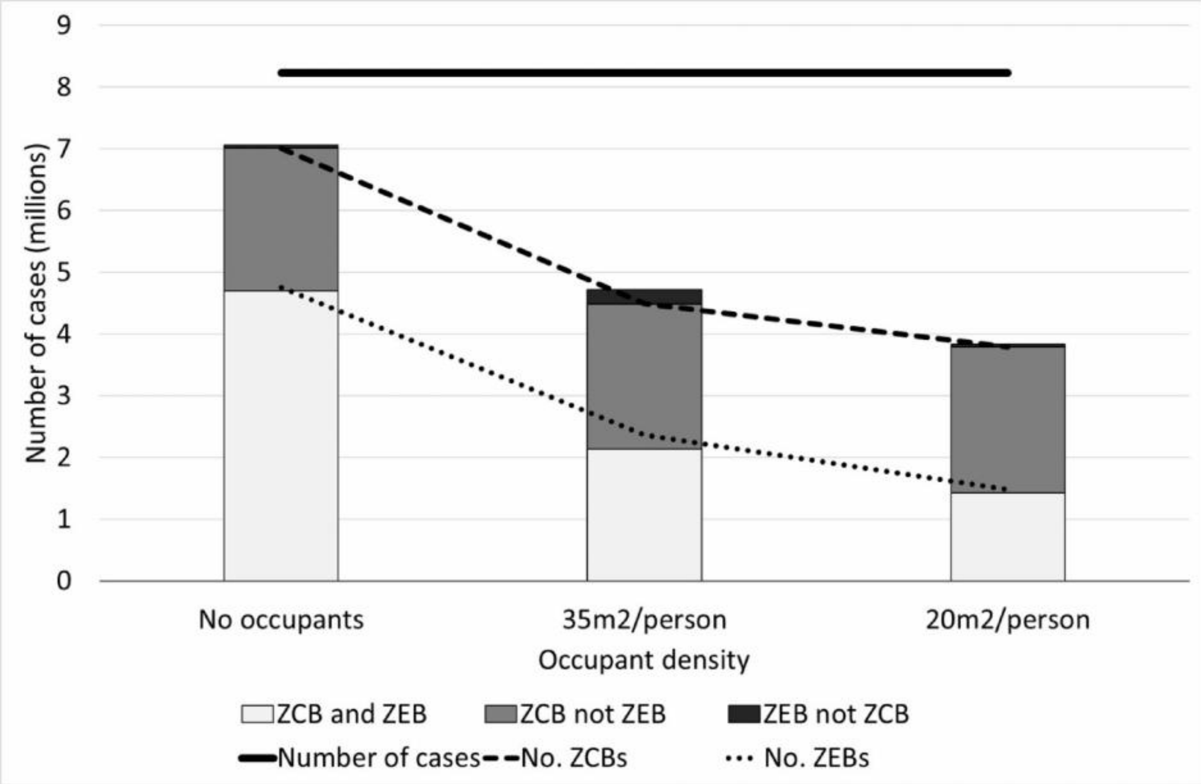



Figure 5: *ZCB and ZEB proportions for different occupancy levels. The number of cases is 8.2 million in each scenario.*

## Discussion

The results highlight three particularly prominent features that play a role in achieving a zero carbon, or energy, building in SBM: height, location and occupancy density. These three features are strongly linked to electricity demand and PV generation and the subsequent balance of carbon emissions and carbon offset. This list will be surprising to those that might have expected items such as U-value or construction material to be the key drivers. The exact nature of these results will be dependent on assumptions used in the modelling, and it would be wrong to draw too much attention to the values obtained. However, it is clear that the approach works and generates a rich vein of data for analysis using classification trees.

Location is important in both the carbon and the energy classification trees, but for different reasons. Insolation levels are strongly linked to location; lower latitudes tend to be associated with warmer, and sunnier, conditions. For this reason, it is easier to achieve a ZEB where the climate is warm but not hot and there is abundant sunshine (an unsurprising result), e.g. see the example building shown in Figure 6. In the carbon classification tree, location is the most important splitting feature. However, the split is on the basis of the electricity grid CI, not temperature or insolation as might be expected (a less expected result).

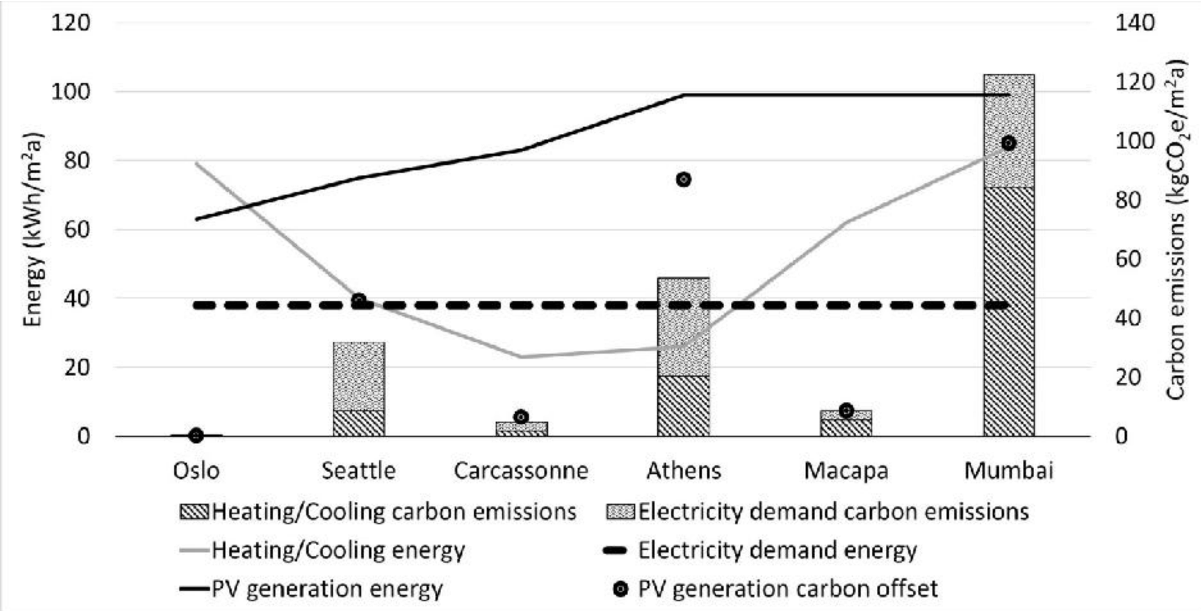



Figure 6: *Heating/cooling energy demand, PV generation and associated carbon emissions (or offset) for the same typical house-sized building (2 x storeys) in different locations. PV located onsite.*

In the scenario where the PV arrays are remotely located in Accra, both the magnitude of PV generation, and the ratio of carbon emissions from electricity demand to the carbon offset from PV generated electricity, are important. For example, the Accra to Oslo electricity grid CI ratio is 1:235, so each kilowatt hour of electricity generated in Accra offsets the carbon emissions from 235kWh of electricity demanded in Oslo. In addition, it is possible to generate far more PV electricity in Accra per unit area of PV array than in Oslo.

The PV location feature raises the issue of the philosophy of zero. While it is not yet practical to transfer PV generated electricity across the globe, the benefits of displacing emissions from carbon intensive electricity grids are globally relevant, regardless of the location of the displacement. A zero carbon philosophy is better placed, than a zero energy equivalent, to take advantage of an opportunity to remotely locate PV arrays. In addition, such a scenario would place no limitation on the zero building design space from the perspective of building location or building size.

Features appearing at deep node levels in the classification trees

The balance period and assessment boundary features only appear at the deeper node levels in the classification trees. In addition, most features relating to the thermal envelope properties do not appear in the trees at all at the level of detail in the classification trees in this work. These results have profound meaning for where focus needs to lie when designing environmental building codes.

It is also interesting to note that at no time is the population of cases split on the difference between PV with a high embodied carbon value and that with a low embodied value or between brick and straw buildings (even where carbon sequestration is included in the assessment). This indicates that, under the analysis presented here, the significance of embodied metrics alone is outweighed by the overall issue of energy demand and PV generation (e.g. see Figure 7). This however might not be true if the embodied data was assembled using different boundaries.

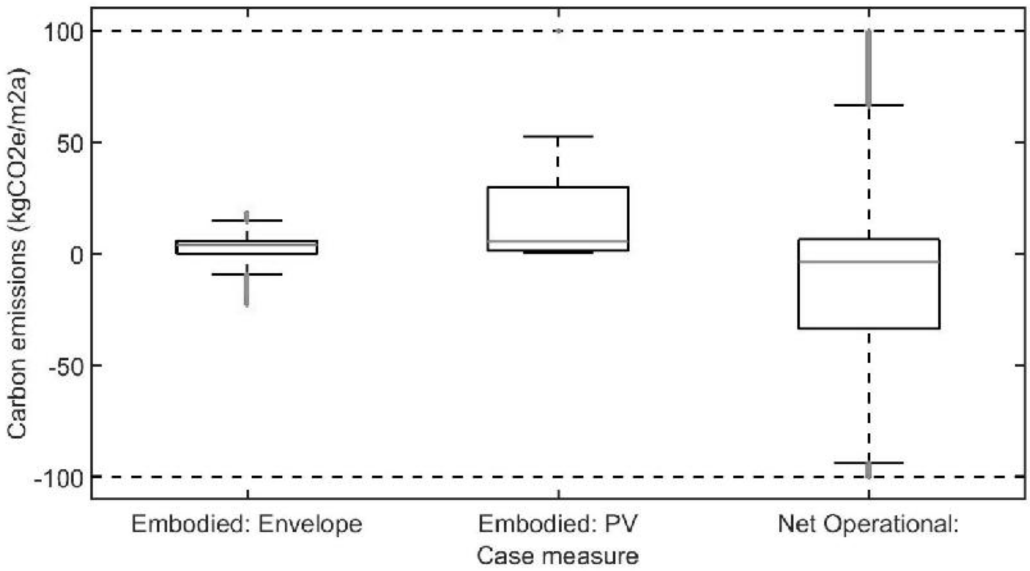



Figure 7: *Boxplots showing the range of values associated with different aspects of the net carbon emissions for each case. Boxes show the interquartile range (IQR). Maximum whisker length extends to 1.5 IQR of the upper and lower quartiles. Beyond the ends of the whiskers outliers are plotted individually.*

These results raise some interesting philosophical questions. The central one being: what should be included or not included in any practical standard? Should a standard be focused on the key issue – climate change – or on a proxy – energy use? It is interesting to note that Passivhaus has stuck firmly to a fabric-first, energy-based, no embodied emissions, standard. However, if we decarbonise the energy supply to buildings by the use of building mounted renewables faster than we decarbonise manufacture (including over-seas manufacture) of building components building, embodied carbon would become more important.

It is worth noting that there is enthusiasm from some quarters for a more carbon, possibly whole life, approach as evidenced by publications from (RICS, n.d.) and (BS EN 15804:2012 + A1:2013, 2013) (BS EN 15978 , 2011). It is also worth noting that others have anecdotally suggested that carbon compliance might be easier than energy compliance (e.g. by the use of biomass boilers in energy inefficient buildings); however, here, we present a systematic analysis of the situation over large search space to look at the general situation.

The work has various limitations. The use of a heat-balance energy method, rather than a dynamic simulation, might be seen as an over simplification. However, this is the method used for Certified Passivhaus design, in part because it needs less detail about the building. This makes it ideal when looking broad questions, rather than specific buildings. The model in its current form ignores solar gain. This is in part because such gains depend highly on architectural details. However, the approach could be extended to make such gains a parameter of the search space, and it would be interesting to see the impact of this on the results. Dynamic elements, such as thermal mass, could be included in a similar way. We have limited the renewables to PV. This due to its growing adoption, that it is easy to complete calculations of energy production for any location and because embodied carbon values have been published. However, there are other technologies, such as ground source heat pumps and biomass boilers that could be studied in further work, and it is unknown to what degree this makes some of the findings less general.

Conclusion

In this work, 24.7 million building specification-assessment rule combinations were generated to simulate the global construction of many different types of building complying with a variety of possible zero carbon, and energy, building standards.

It was found that a ZCB standard, because it focuses on carbon emissions, allows for a more varied design space. Several assumptions were made in the work, and it would be interesting to see how changing these, for example including solar gains, a more diverse range of occupancy densities, a more complex electrical gains timetable or including redecoration might change the some aspects of the message – if such data could be found. It would also be worth considering how a sensitivity analysis might be completed; or looking at the impact that the assumed boundaries of the study might have, after all, architecture is almost unbounded in its possibilities. The use of novel materials, or how the size of the space changes for extreme designs such as very tall, but slender buildings, would be worth studying. However, the value in this work lies not in the accuracy of heat loss estimations or the embodied energy of particular buildings, but in the idea of the value of calculating how the volume of the design space changes and is constricted under the influence of the building regulations that might be in place.

This work demonstrates that, on a global level, the design space is approximately 1.8 times greater if achieving zero carbon is the focus of building codes rather than zero energy, and also clearly demonstrates that, at a fundamental level, the use of carbon rather than energy opens up more opportunities than it eliminates. Hence governments are recommended to consider swapping the current energy focused approach to a carbon focused one (after due consideration is given to other complicating factors such as the method of implementation). Not only does the focus on zero energy reduce the design space by almost half in comparison with zero carbon (see Table 6), but a focus on carbon would also be in line with the reason for wanting zero energy/carbon buildings: reducing carbon emissions to protect humankind from climate change. In addition, the novel methods developed are applicable to many other aspects of construction controlled by regulation where there is the desire to examine the impact of new regulations prior to legislation.

## Acknowledgements

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## References

Acquaye, A. A. & Duffy, A. P., 2010. Input-output analysis of Irish construction sector greenhouse gas emissions. *Building and Environment,* pp. 784-791.

Acquaye, A., Duffy, A. & Basu, B., 2011. Embodied emissions abatement - A policy assessment using stochastic analysis. *Energy Policy,* pp. 429-441.

Brook, B. W. & Bradshaw, C. J. A., 2014. Key role for nuclear energy in global biodiversity conservation. *Conservation Biology,* pp. 1-11.

BS EN 15251, 2007. *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.* London: BSI.

BS EN 15804:2012 + A1:2013, 2013. *Sustainability of construction works - environmental product declarations - core rules for the product category of construction products.* London: BSI.

BS EN 15978 , 2011. *Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method.* London: BSI.

Charlett, A. J. & Maybery-Thomas, C., 2013. *Fundamental Building Technology.* Abingdon: Routledge.

Cotterell, J. & Dadeby, A., 2012. *The Passivhaus Handbook: A practical guide to constructing and retrofitting buildings for ultra-low energy performance.* Cambridge: Green Books.

Crawford, R. H. & Treloar, G. J., 2003. *Validation of the use of Australian input-output data for building embodied energy simulation.* Eindhoven, IBPSA, pp. 235-242.

Crown, 2008. *Climate Change Act 2008.* London: The Stationary Office Limited.

De Wolf, C., Pomponi, F. & Moncaster, A., 2017. Measuring embodied carbon dioxide equivalent of buildings: A review and critque of current industry practice. *Energy and Buildings,* Volume 140, pp. 68-80.

Department for Communities and Local Government, 2010. *Code for Sustainable Homes: Technical Guide.* London: RIBA Publishing.

Department of Energy and Climate Change, 2012. *The Government's Standard Assessment Procedure for Energy Rating of Dwellings.* Watford: BRE.

Dequaire, X., 2012. Passivhaus as a low-energy building standard: contribution to a typology. *Energy Efficiency,* pp. 377-391.

Dixit, M. K., Culp, C. H. & Fernandez-Solis, J. L., 2013. System boundary for embodied energy in buildings: A conceptual model for definition. *Renewable and Sustainable Energy Reviews,* pp. 153-164.

Energy Savings Trust, 2012. *Powering the Nation: Household electricity-using habits revealed,* London: Energy Savings Trust.

European Parliament, Council of the European Union, 2010. *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.* Strasbourg: EU.

Ezema, I. C., Olotuah, A. O. & Fagbenle, O. I., 2015. Estimating embodied energy in residential buildings in a Nigerian context. *International Journal of Applied Engineering Research,* 10(24), pp. 44140-44149.

Giesekam, J., Barrett, J., Taylor, P. & Owen, A., 2014. The greenhouse gas emissions and mitigation options for materials used in UK construction. *Energy and Buildings,* pp. 202-214.

Green Building Store, 2017. *Ultra.* [Online]
Available at: http://www.greenbuildingstore.co.uk/products/ultra-casement-outward-passivhaus-certified-timber-window/
[Accessed 17 May 2017].

Hammond, G., Jones, C., Lowrie, F. & Ise, P., 2011. *Embodied Carbon: the Inventory of Carbon and Energy (ICE).* Bracknell: BSRIA.

Haynes, R., 2013. *Embodied energy calculations within life cycle analysis of residential buildings.* [Online]
Available at: http://www.etoolglobal.com/wp-content/uploads/2012/10/Embodied-Energy-Paper-Richard-Haynes.pdf
[Accessed 1 June 2018].

Heinonen, J. & Junnila, S., 2014. Residential energy consumption patterns and the overall housing energy requirements of urban and rural households in Finland. *Energy and Buildings,* Issue 76, pp. 295-303.

HM Government, 2013. *The Building Regulations 2010: Approved Document L1A: Conservation of fuel and power in new dwellings.* London: NBS.

IPCC Technology and Economic Assessment Panel, 2005. *Safeguarding the ozone layer and the global climate system: Issues related to hydrofluorocarbons and perfluorocarbons,* Cambridge: Cambridge University Press.

IPCC, 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Geneva: IPCC.

Kim, S. et al., 2013. Life comparative analysis of energy consumtion and CO2 emissions of different building structural frame types. *The Scientific World Journal,* pp. 1-5.

Knight, I. et al., 2007. *European and Canadian non-HVAC Electric and DHW Load Profiles for Use in Simulating the Performance of Residential Cogeneration Systems,* Ottawa: Department of Natural Resources Canada.

Louwen, A., van Sark, W. G. J. H. M., Faaij, A. P. C. & Schropp, R. E. I., 2016. Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development. *Nature Communications,* Volume 7, pp. 1-9.

MacKay, D. J. C., 2009. *Sustainable Energy - without the hot air.* Cambridge: UIT Cambridge Ltd.

Mann, S. A. et al., 2014. The energy payback time of advanced crystalline silicon PV modules in 2020: a prospective study. *Progress in Photovoltaics: research and applications,* Volume 22, pp. 1180-1194.

McManus, M., 2011. Environmental consequences of the use of batteries in sustainable systems: battery production. In: *2nd International Conference on Microgeneration and Related Technologies.* Glasgow: University of Strathclyde.

NASA, n.d. *NASA Surface meteorology and Solar Energy.* [Online] Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov [Accessed 10 April 2015].

National Research Council, 1979. *Carbon Dioxide and Climate: A Scientific Assessment,* Washington, DC: The National Academies Press.

Nawaz, I. & Tiwari, G. N., 2006. Embodied analysis of photovoltaic (PV) system based on macro- and micro-level. *Energy Policy,* Volume 34, pp. 3144-3152.

Parkin, A., Mitchell, A. & Coley, D., 2015. A new way of thinking about environmental building standards: Developing and demonstrating a client-led zero-energy standard. *Building Services Engineering Research and Technology,* 37(4), pp. 413-430.

Paulsen, J. & Sposto, R., 2013. A life cycle energy analysis of social housing in Brazil: Case study for the program "MY HOUSE MY LIFE". *Energy and Buildings,* Volume 57, pp. 95-102.

Pelly, R. & Mander, T., 2014. The Nucleus at Hayesfield Girls' School Bath: achieving low embodied carbon using renewable materials. *The Structural Engineer,* 92(10), pp. 12-18.

Pelsmakers, S., 2012. *The Environmental Design Pocketbook.* London: RIBA Publishing.

Public Health England, 2014. *Minimum home temperature thresholds for health in winter - A systematic literature review,* London: PHE publications.

Ramesh, T., Prakash, R. & Shukla, K. K., 2010. Life cycle energy analysis of buildings: An overview. *Energy and Buildings,* pp. 1592-1600.

Rauf, A. & Crawford, R. H., 2013. The relationship between material service life and the life cycle energy of contemporary residential buildings in Australia. *Architectural Science Review,* Issue 56, pp. 252-261.

RICS, n.d. *Whole life carbon assessment for the built environment.* [Online] Available at: https://www.rics.org/uk/upholding-professional-standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-built-environment/ [Accessed 18 October 2018].

Saynajoki, A., Heinonen, J. & Junnila, S., 2011. Carbon footprint assessment of a residential development project. *International Journal of Environmental Science and Development,* 2(2), pp. 116-123.

Sodagar, B. et al., 2011. The carbon-reduction potential of straw-bale housing. *Building Research and Information,* 39(1), pp. 51-65.

Stephan, A., Crawford, R. H. & de Myttenaere, K., 2012. Towards a comprehensive life cycle energy analysis framework for residential buildings. *Energy and Buildings,* pp. 592-600.

Stephan, A., Crawford, R. H. & de Myttenaere, K., 2013. Multiscale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia. *Building and Environment,* Issue 68, pp. 35-49.

Suzuki, M. & Oka, T., 1998. Estimation of the life cycle energy consumption and CO2 emission of office buildings in Japan. *Energy and Buildings,* 28(1), pp. 31-41.

Szokolay, S. V., 2008. *Introduction to Architectural Science: The Basis of Sustainable Design.* 2nd ed. Oxford: Elsevier.

Treloar, G., Fay, R., Ilozor, B. & Love, P. E. D., 2001. An analysis of the embodied energy of office buildings by height. *Facilities,* 19(5/6), pp. 204-214.

United Nations, 1998. *Kyoto Protocol to the United Nations Framework Convention on Climate Change.* [Online] Available at: http://unfccc.int/resource/docs/convkp/kpeng.pdf [Accessed 13 July 2014].

Voss, K. & Musall, E., 2013. *Net Zero Energy Buildings: International projects of carbon neutrality in buildings.* Munich: Detail.

Weight, D. H., 2011. Embodied through-life carbon dioxide equivalent assessment for timber products. *Proceedings of the Institution of Civil Engineers: Energy,* 164(EN4), pp. 167-182.

Williams, J. et al., 2016. Less is more: a review of low energy standards and the urgent need for an international universal zero energy standard. *Journal of Building Engineering,* Volume 6, pp. 65-74.

Yan, H. et al., 2010. Greenhouse gas emissions in building construction: a case study of One Peking in Hong Kong. *Building and Environment,* 45(4), pp. 949-955.

Appendix I. Validation

To test the validity of the SBM requires both the energy demand and the embodied algorithms to be considered separately. For the energy demand, a house was modelled replicating as closely as possible the specifications recommended for a PH standard building and a building that complies with UK building regulations. The SBM calculated annual heat energy demand was then compared with that defined by two building standards (see Table 8). In both cases, the SBM output is higher than the estimate, or requirement, for the two comparison standards. However, SBM does not account for solar gains, which are estimated to be around 11 kWh/m$^2$a.10 In addition, SBM does not account for gains from the domestic hot water system, which are estimated to be between 5.8 and 14.4 kWh/m$^2$a for a Passivhaus standard construction, but may be as much as 18.6 kWh/m$^2$a for a typical UK house (Cotterell & Dadeby, 2012). When these other sources of heat gains are included, the SBM output reflects the standard requirements, indicating that the energy algorithm is valid.

Table 8: *Comparison of SBM output with UK Building Regulations and the Passivhaus standard for a building located in Watford, UK.*

| **SBM component** | **Based on UK building regulations** (Department of Energy and Climate Change, 2012) | | **Based on the Passivhaus standard** (Cotterell & Dadeby, 2012) | |
|---|---|---|---|---|
| | **Reference values** | **SBM input** | **PH standard requirements** | **SBM input** |
| Heating set point (°C) | 21 | 21 | 20 | 20 |
| Cooling set point (°C) | 25 | 25 | 25 | 25 |
| Wall U (W/m$^2$K) | 0.18 | 0.14 | 0.15 | 0.15 |
| Floor U (W/m$^2$K) | 0.13 | 0.17 | 0.15 | 0.18 |
| Roof U (W/m$^2$K) | 0.13 | 0.11 | 0.15 | 0.13 |
| Glazing U (W/m$^2$K) | 1.4 | 1.4 | 0.8 | 0.8 |
| Infiltration at normal pressure (ach/hr) | 0.511 (based on 5m$^3$/m$^2$h at 50 Pa) | 0.511 | 0.042 (0.6 @ 50 Pa) | 0.042 |
| MVHR present (eff. = 0.9) | No | No | Yes | Yes |
| | | **SBM output** | | **SBM output** |
| **Av. Env. U (W/m$^2$K)** | | 0.28 | | 0.23 |
| **Electricity demand (kWh/m$^2$a)** | | 38 (not PE) | | 38 (not PE) |
| **Heating required (kWh/m$^2$a)** | **60 (Estimate for southern England)** (Pelsmakers, 2012) | **95** <br> **(65 including solar and DHW gains estimate)** | **15 (Passivhaus maximum)** (Cotterell & Dadeby, 2012) | **28** <br> **(3 – 11 including solar and DHW gains)** |

The SBM embodied emission estimates are presented as summary statistics in Table 9. Table 10 shows a range of estimates found in the literature. The median embodied energy from the SBM is 10.5 kWh/m$^2$a, whereas the mean value in the literature is 32.8 kWh/m$^2$a. However, the latter figure is in primary, not final energy. The conversion between primary and final is location dependent, but values of 2–3 are common, indicating that the values are in reasonable agreement, and the values within the literature are definitely with the spectrum of values (Table 9) produced by SBM. In the case of embodied carbon, the discrepancy is larger: 5.5 kg$CO_2$e/m$^2$a for SBM) against 12 kg$CO_2$e/m$^2$a for the literature. Within the range of values given in the literature, however (Table 10), this discrepancy is small and hence acceptable.

Table 9: *SBM embodied estimates (brick-based buildings).*

| | Embodied carbon ($kgCO_2e/m^2a$) | Embodied energy ($kWh/m^2a$) |
|---|---|---|
| Maximum | 18.3 | 31.6 |
| 75th percentile | 6.6 | 12.2 |
| Median | 5.5 | 10.5 |
| 25th percentile | 3.8 | 8.7 |
| Minimum | 2.4 | 6.3 |

Table 10: *Embodied estimates found in the literature.*

| EE kWh/a (primary) | EC $kgCO_2e/m^2a$ | References |
|---|---|---|
| 46.3 | 14.0 | (Suzuki & Oka, 1998) |
| 13.9 | 4.2 | (Suzuki & Oka, 1998) |
| 20.8 | 6.7 | (Suzuki & Oka, 1998) |
| 19.4 | 6.8 | (Kim, et al., 2013) |
| 27.1 | 9.2 | (Kim, et al., 2013) |
| - | 33.3 | (Saynajoki, et al., 2011) |
| 49.5 | - | (Treloar, et al., 2001) |
| 50.9 | 15.1 | (Haynes, 2013) |
| - | 6.3 | (Yan, et al., 2010) |
| 34.2 | - | (Ezema, et al., 2015)50 |
| 33.3 | - | (Paulsen & Sposto, 2013) |
| 32.8 | 12.0 | Mean |