Less is more: A review of low energy standards and the urgent need for an international universal zero energy standard

Joseph Williams[a], Rachel Mitchell[a], Vesna Raicic[a], Marika Vellei[a], Graham Mustard[a], Amber Wismayer[a], Xunzhi Yin[a], Stephen Davey[a], Muzzamil Shakil[a], Yuanzhang Yang[a], Anna Parkin[a], David Coley[a,*]
[a] Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY UK
* Corresponding author. Tel.: +44 1225 385531. Email address: d.a.coley@bath.ac.uk

Abstract

There are in excess of 70 low or zero energy/carbon building definitions/standards in circulation around the world. However there are few zero energy or zero carbon buildings. This suggests that despite, or possibly because of, a continuing debate over definitions, aspiration has not been met by reality. In this paper the most important 35 standards are reviewed and a correlation between activity in standard generation and completed buildings is presented. Combining this with the requirement for an 80% cut in carbon emissions, a consideration of the proportion of humanity that live in countries without any standards and the ratio of new-build activity vs. pre-existing stock, leads to a conclusion that there is an urgent need for a binding international zero (rather than low) energy/carbon standard that can be adopted world-wide. It is argued this is only possible if carbon is ignored in favour of energy, and many lifecycle issues put to one side. In part this is because of changing national carbon intensities within the energy supply chain, but it is also due to unresolved issues in carbon and energy accountancy. It is hence suggested that such issues are left to optional additional local standards.

Keywords: zero energy buildings, building codes, building standards

1. Introduction

The latest IPCC synthesis report [1] notes that since 1970 cumulative CO_2 emissions from global fossil fuel combustion, cement production and flaring have tripled, and that climate change is already having an observable impact on the more vulnerable and exposed parts of the world. This is not only via the occurrence of more extreme weather events but is also from impacts on sensitive natural ecosystems, fishery stocks and the production of crops [1]. Due to the importance of the issue, it has been a longstanding requirement of countries to address their production of greenhouse gasses via the Kyoto and other protocols.

Buildings are a major contributor to world carbon emissions both operationally and during construction, with the energy consumption of buildings being around a third of total energy use worldwide [2]. As world population grows and the level of urbanisation increases, the amount of energy required by buildings is also set to increase. The building industry therefore has a key role in helping to reduce carbon emissions by providing buildings that minimise their energy use and general impact. Governments and others have started to rise to this challenge. For example, in the UK the construction and operation of the current building stock accounts for around 30 to 40 per cent of the country's total carbon emissions, and so has been a focus within the Government's overall strategy for reducing emissions [3], the policy situation is similar in much of the developed world.

Given the need to cut world carbon emissions by 80% to ensure climate change is limited to a rise of no more than 2-4°C in mean global temperature [1], all sectors, from transport to electrical generation, to buildings will need to undergo a transformation. Some sectors are likely to find this more difficult than others. With little progress toward non-fossil fuel based aviation having been made, oil still dominating land transport, nuclear power only paying a minor role and the diurnal or seasonal storage of renewable energy proving technologically difficult, several sectors are unlikely to be able to achieve an 80% cut in the required timeframe. Logic therefore dictates that the built environment may well need to offer a greater than 80% cut – quite possibly a 100% reduction to a zero energy/carbon state. By reflecting on the current complexity of the low energy/carbon standards landscape, this paper argues that, to be effective and adopted worldwide, it might be necessary for any zero energy/carbon building standard to be relatively simple.

The concept of buildings that have no energy requirements or are producers of no carbon emissions is therefore an important one, however the details of what a building must achieve to be classed as one of these is still debated. The literature has many examples of definitions of zero carbon or energy buildings (Table 1) and defining what is meant by these terms is often seen as complex and challenging [4, 5]. Supplementary to these definitions there are in excess of 35 low energy standards in active use across the world. These differ in both their ideology and their methodology, and they use a variety of metrics for verification. Low, rather than zero, energy/carbon buildings have been built in reasonable numbers, however given the need to cut carbon emissions by 80% [1], the size of the historic building stock and the lack of progress on lowering transport emissions [3] it is clear that at least new build needs to be zero energy/carbon.

The future impact of any standard is hard to quantify, as it no doubt depends not only on the standard but also the degree of application it finds. This will vary around the world with the specific demand and levels and nature of construction. For example a large proportion of the building stock in many countries already exists and so for a standard to find wide use in these areas applicability to retrofit is an important consideration. However, from the data presented later, it would seem the impact has been minor, despite a proliferation of suitable standards.

This work first considers existing definitions of low and zero energy buildings as debated in the literature, their applications, and differences. The review goes on to focus on the currently applied standards, both optional and mandated, around the world and assesses their relation to the definitions regarding the metrics used and the inclusion, or not, of concepts such as embodied energy.

By looking at the proportion of humanity that live in countries without zero carbon/energy standards and the ratio of new-build activity vs. pre-existing stock, the paper argues that there is an urgent need for a simple universal definition of a zero energy building, and that to be practicable it is likely to ignore carbon in favour of energy and not include embodied energy or any lifetime issues. It is then suggested that carbon, embodied energy and lifecycle issues are left to either national standards, or possibly secondary, non-compulsory, additions to the standard rather than be at the heart of the standard.

2. Standards

Our ancestors lived in houses that would pass most elements of many of today's low energy/carbon buildings standards. Heat was provided by biomass, lighting from non-fossil oils, domestic hot water heat almost zero, the overall kWh/m^2 consumption very low - mainly due to only heating a very small volume of the building, and accepting very low temperatures in cold climates – or allowing high internal temperatures in hot climates. Electricity use would have been zero. Even with the introduction of coal the consumption would have remained low: 15 kWh/m^2 (the Passivhaus requirement) and a floor area of 200 m^2 implies an annual demand of 3000 kWh. With coal in 1800 selling in London at 28 shillings a ton [6] and assuming a calorific value of 5.6kWh/kg, this implies an annual cost of 15 shillings per annum. The daily wage of a craftsman at the time was 37 pennies [6], so this implies 5 days labour - a modest amount. However, homes were not built to Passivhaus standards and the efficiency of a coal grate would have been 20% at best. The mean annual UK heating demand (including domestic hot water) is now around 16,000 kWh [7], and a typical boiler efficiency 80%. This implies a typical home in 1800 would have used 11 tons of coal per annum if it had maintained today's typical set point temperatures and hot water use. This is 5 months wages, indicating that lower temperatures were unavoidable, and that fuel poverty is not a new phenomenon. Many around the world still live within such thermal and budgetary constraints.

The modern concept of a building that is self-sufficient is not new, with early concept houses such as the MIT Solar House and the Bliss House from the 1930s and 1950s respectively, representing some of the earliest attempts to meet energy demand with on-site generation [8]. In these cases the autarkic principle, although not demonstrating complete energy self-sufficiency, was to provide all the space heating requirements by on-site solar throughout the year. Even in these simple early exemplars we see that the concept of zero energy is clearly linked to a set of limiting parameters including the boundary of the site, the space heating demand and the time scale of the balance. From looking at the range of standards now on offer debate about these parameters seems to continue.

Historically, the discussion about the key parameters to use in defining a building as "zero energy", has been wide ranging. A summary by Kilbert and Fard [9] of the definitions of net zero and zero energy buildings arranged in order of appearance and supplemented with additional relevant definitions is shown in Table 1. It is clear that there is a constantly changing landscape and the debate continues. Additionally, Kapsalaki and Leal [10] for example add a further definition of Zero Energy Buildings (ZEBs) that is more specific about the sources of energy and refers in the definition to a building that does not use fossil fuels but instead gets all of its energy from solar energy and other renewable sources. 2015 saw the introduction of two more Passivhaus standards with very complex energy balance principles lying behind them [11]. So it is clear that the landscape of definitions is not a shrinking one. This can cause difficulty for client and architect, as it implies a lack of clarity and can encourage the adoption of the easiest to meet standard, or no standard at all. It is equally likely that this lack of clarity might cause issues for world governments if any standard played a future role in climate negotiations.

Table 1: Summary of zero energy building definitions as presented by Kilbert and Fard [9].

Source	Definition
Esbensen and Korsgaard, 1977 [12]	A zero-energy house (ZEH) is considered to be self-sufficient in space heating and hot water supply during normal climate conditions in Denmark.
Gilijamse, 1995 [13]	A ZEH is defined as a house where no fossil fuels are consumed, and annual electricity consumption equals annual electricity production. Unlike the autarkic situation, the electricity grid acts as a virtual buffer with annually balanced delivers and returns.
Iqbal, 2004 [14]	A ZEH is one that optimally combines commercially available renewable energy technology with the state-of-the-art energy efficiency construction techniques. In a zero-energy home no fossil fuels are consumed and its annual electricity consumption equals annual electricity production. A zero-energy home may or may not be grid-connected. In a zero-energy home annual energy consumption is equal to the annual energy production using one or more of the available renewable energy resources.
Charron, 2005 [15]	Homes that utilize solar thermal and solar photovoltaic (PV) technologies to generate as much energy as their yearly load are referred to as net zero energy solar homes (ZESH).
Torcellini et al., 2006 [16]	A zero-energy building (ZEB) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable energy technology.
EISA, 2007 [17]	A net-zero energy (NZE) commercial building is a high-performance commercial building designed, constructed and operated: (1) to require a greatly reduced quantity of energy to operate; (2) to meet the balance of energy needs from sources of energy that do not produce greenhouse gases; (3) to act in a manner that will result in no net emissions of greenhouse gases; and (4) to be economically viable.
Mertz et al., 2007 [18]	A net-zero energy home is a home that, over the course of a year, generates the same amount of energy it consumes. A net-zero energy home could generate energy through PV panels, a wind turbine or a biogas generator.
Rosta et al., 2008 [19]	A ZEH produces as much energy as it consumes in a year

Laustsen, 2008 [20]	Zero net energy buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grid. Seen in these terms, they do not need any fossil fuel for heating, cooling, lighting or other energy uses, although they sometimes draw energy from the grid.
Green Building Advisor, 2010 [21]	Net zero-energy buildings (nZEB) are those producing as much energy on an annual basis as it consumes on-site, usually with renewable energy sources such as PV or small-scale wind turbines.
European Parliament, 2010 [22]	The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.
Aelenei et al., 2010 [23]	The nZEB concept can be defined as a building that over a year is neutral meaning that it delivers as much energy to the supply grid as it uses from the grid.
Voss et al., 2010 [24]	The understanding of an nZEB is primarily based on the annual balance between energy demand and energy generation on the building site. An nZEB operates in connection with an energy infrastructure such as the power grid.
Hernandez and Kenny, 2010 [8]	A life cycle zero-energy building (LC-ZEB) is one where the primary energy used in the building in operation plus the energy embodied within its constituent materials and systems, including energy generating ones, over the life of the building is equal to or less than the energy produced by its renewable energy systems within the building over their lifetime.
Salom et al. (2011) [25]	A nZEB can be succinctly described as a grid-connected building that generates as much energy as it uses over a year. The 'net zero' balance is attained by applying energy conservation and efficiency measures and by incorporating renewable energy systems.
Sartori et al., 2012 [26]	A nZEB is a building with greatly reduced energy demand that can be balanced by an equivalent on-site generation of electricity, or other energy carriers, from renewable sources.
Lund et al. (2011) [27]	A ZEB combines highly energy-efficient building designs, technical systems and equipment to minimize the heating and electricity demand with on-site renewable energy generation typically including a solar hot water production system and a rooftop PV system. A ZEB can be off or on-grid.

Other important standards and proto-standards and supporting materials are those of ASHRAE (ANSI/ASHRAE/IESNA Standard 90.1-1999) and their Vision 2020 document; ISO standards TC163, 205 and 16343; and the European Energy Performance of Buildings Directive.

Following the approach used by Kilbert and Fard [9], we can summarise these definitions in the following equations. The period of balance or comparison can be a month, a year or other time frame, but the shorter the period the more difficult it will be to balance them. If the energy balance is greater than zero in an equation, the result is a net positive energy solution.

(1) Net zero site energy:

$$r_s - m \geq 0$$

where m is the consumption measured by the utility meter; and r_s is the measured renewable energy produced onsite.

(2) Net zero-source energy:

$$r_s - (m + g) \geq 0 \text{ or } r_s - p \geq 0$$

where p is primary energy = $m + g$; and g is the energy losses in the utility system due to energy conversion and transmission.

(3) Near zero energy (EU only):

$$r_{sn} - p \cong 0 \text{ or } r_{sn} - p \rightarrow 0$$

where r_{sn} is the renewable energy produced on-site or nearby by the building owner.

(4) Net zero cost (i.e. the financial value of the energy produced equals that of the required energy. This though does not mean the two balance in energy or carbon units, as they may be from different sources, for example production of electricity but use of natural gas. Being a financial balance the approach might be naturally attractive to building owners.):

$$\$r_{sn} - \$m \geq 0$$

where \$m is the cost of purchased grid-based energy; and $\$r_{sn}$ is the income from the renewable energy produced on-site or nearby by the building owner.

(5) Net zero exergy:

$$\sum \epsilon_{ex} - \sum \epsilon_{im} \geq 0$$

where $\sum \epsilon_{ex}$ is the exergy exported to the grid; and $\sum \epsilon_{im}$ is the exergy imported from the grid

(6) Net-zero carbon:

$$CO_2r - CO_2m \geq 0$$

where CO_2m is the $MtCO_2$ emitted from grid-based energy sources and CO_2r is the $MtCO_{2e}$ avoided by carbon neutral energy sources provided by building owner or utility.

(7) Net zero total energy:

$$r - (p + e) \geq 0$$

where e is the embodied energy of building components amortized on an assumed lifetime.

(8) Net zero energy location (net zero total energy plus transportation):

$$r - (p + t) \geq 0 \text{ or } r - (p + t + e) \geq 0$$

where r is the renewable energy provided by the building owner or purchased from a utility; and t is the commuting energy of building users/occupants.

From Table 1 it is possible to extract some of methodical principles:

1. The basic units used vary: final energy, primary energy, carbon or finance.
2. Connection to the grid might or might not be allowed.
3. Energy use is normally calculated over a year.
4. The reduction of fossil fuel use can be the focus, rather than the reduction of energy.
5. A narrow or broad definition of renewable energy might be included. For instance only building integrated solar technologies might be allowed. Or a wider range of non-local sources might be included.
6. There is an emphasis on energy efficiency, but the level required varies.
7. The uses of energy that need to be included vary.

The metrics used by any definition are arguably reflective of the ideology, but also may reflect the desire to make a definition more accessible. The main debate here is over the use of carbon verses energy as both have relevance with respect to climate change, energy security and economics.

While the use of carbon directly reflects the climate change impact, to assign a value for CO_2 emissions requires one or more conversion factors. The result therefore becomes dependent on the carbon content of any grid energy used and so limits comparison between countries, as the carbon intensity of supply will vary. The range found (see Figure 1) of 0.02kgCO_2/kWh to over 1kgCO_2/kWh shows that a global definition based on carbon emissions would potentially have a different impact on energy use, which would be more onerous for one country compared to another. Hence it would be difficult to get agreement to adopt it as an international standard. Furthermore, the carbon intensity of energy grids around the world is changing rapidly, so there is a methodological problem in calculating the lifetime carbon emissions of any building. This becomes even more difficult if the embodied carbon of redecoration and refurbishment is to be included in the standard.

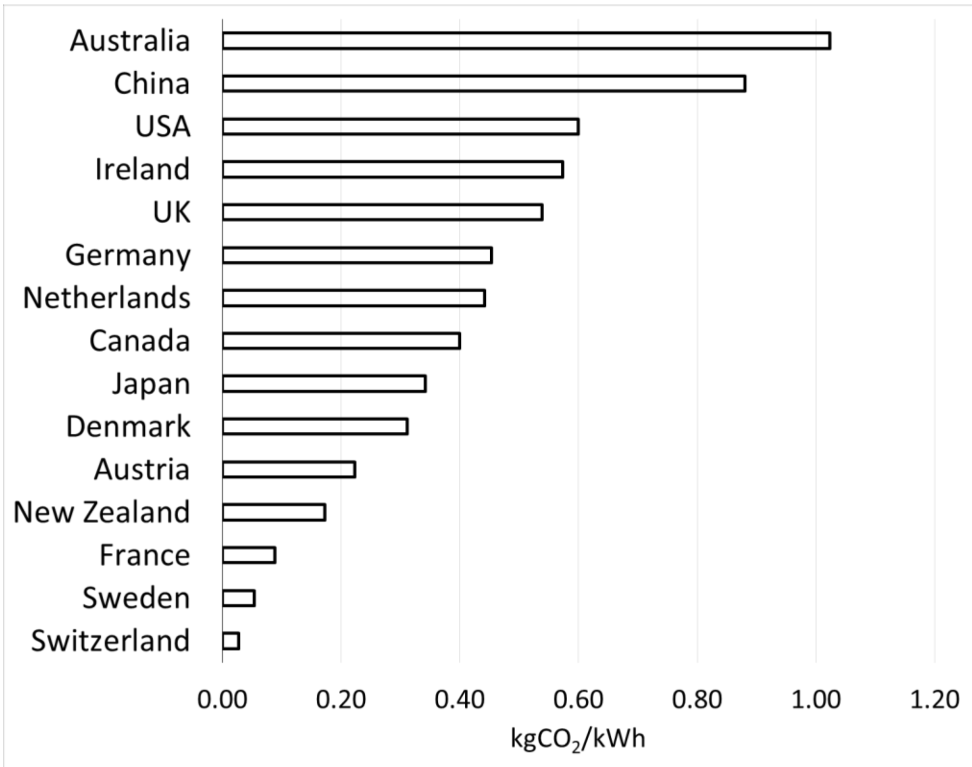

Figure 1: Energy grid carbon intensities in different countries (data from [28]).

Final energy, or energy delivered on site, requires no accountancy conversion and so is arguably a clearer, less time or location varying, way of quantifying and comparing the performance of a building and thus may be better as the basis for a global definition. It is however more detached from the original problem and so the use of primary energy is often used instead. This is the energy used at the first point of useful utilisation [16], for example the energy burnt at the power station, and while, like CO_2, this will reflect the locality of the building, it is only dependent on the efficiencies of the system and not the carbon content of the fuel source.

Some definitions consider not allowing any fossil fuel use on the basis that even if energy or carbon is accounted for by paying back through the generation of renewable energy, this will not undo the fact that fossil fuels are being used by the building. This approach can be argued against by posing questions about what happens if the owner replaces the biomass boiler, for example, with a gas boiler, because gas is cheaper than wood.

The time scale of the definition is also considered within the literature. If lifecycle analysis is to be included then regardless of the units chosen, a building should repay its embodied content over its operational life, which would be subject to further definition. This is a concept that is gaining significance in most industries but its uptake within the construction industry has been slow;

however as the energy efficiency of buildings improves the significance of embodied energy compared to operational energy will change and its relevance increase.

The definition of embodied energy/carbon is itself not straightforward. A variety of methods are used to calculate the embodied metric, and the method used can have a significant impact on the outcome of the calculation. The *process technique* essentially sums the embodied energies of the constituent parts of a building, and is the most common method [29,30,31]. It relies on the availability of an accurate and detailed database of materials and components, such as the Inventory of Carbon and Energy [32], containing data relevant to the supply chain for the building in question. Some argue that this method of assessing embodied energy/carbon is limited as it does not take into consideration energy demands, or carbon emissions, resulting indirectly from the building's construction [33]. For example, while site clearance activities and groundworks are an essential part of a development, their energy/carbon costs are not evident in the fabric of the building. An alternative method is to base calculations on the energy intensities of relevant economic sectors. Acquaye et al. [34] and Acquaye and Duffy [35] demonstrate how input-output analysis techniques can be used to determine national energy intensities per monetary unit for various sectors (i.e. how much energy is consumed for each pound spent in that sector). These energy intensities can then be multiplied by the prices of building materials and components to give an estimate of the total embodied energy of the building. While this technique will account for all the direct and indirect energy inputs, its accuracy is limited by aggregation errors, as all components from the same economic sector will have the same energy intensity [33]. On a global scale further complications will arise due to currency exchange rates. Until a consistent approach to the calculation of embodied energy/carbon is determined, it is difficult to see how this issue could be successfully incorporated into a global zero carbon building standard.

Temporal considerations also arise when a building is defined as net low or zero over a period via the use of a grid connection. For example does the building need to balance on a daily, monthly or annual basis? Clearly, the shorter the balance period the greater the oversizing of the renewables system will be. This problem is avoided for a standalone, off-grid, building that at no point creates an energy or carbon deficit in its on-site energy use. However it is likely to be in carbon or energy debt for decades with respect to embodied energy/carbon due to the batteries or other energy store used, so the demand for a standalone solution would seem to be flawed. Also most consider that this is too hard to achieve in a cost or resource effective manner due to the implications of onsite storage. However, if a certain level of energy storage efficiency is achieved in future, such considerations may gain relevance.

The scope of the definition both in terms of what uses of energy are included and what renewables are permitted are also key questions and must be evaluated for a building to meet a particular definition. Performance of any building will also be dependent on the occupants and their use of electricity, including plug loads. This raises the question of at what level a building's responsibility for energy consumption stops? At its simplest level this might be an argument over including unregulated energy (such as plug loads), or not. For example the UK definition of a zero carbon building does not include unregulated energy. However as energy efficiency measures increase, unregulated energy use and subsequent emissions become a significant proportion of the energy load and therefore there is an argument that these elements should be included. At a further level of abstraction, there is a clear contradiction in creating a standard that includes the embodied energy of the construction and the energy use of electrical items, but not the embodied energy of those items.

The scope of renewables is also considered in several standards, and this includes a debate over what should be included and whether off-site renewable energy can be considered. For example there are concerns whether off-site input can be consistently counted upon. These debates raise the question of how much of the emphasis of any definition should be on renewable energy generation and how much should be on efficiency savings as a way of minimising the load. At risk here is that under several definitions a building may be energy inefficient but include a large amount of renewable energy. A biomass heated building being a potential example. Heffernan et al. [36] provide a detailed discussion on a number of zero energy balance issues including which energy uses should be included, the boundaries in relation to energy generation and the timescale of the balance.

3. Global Relevance

As previously stated there are numerous low energy/carbon building standards implemented across the world each using a different definition. Figure 2 analyses the major ones in terms of their core parameters. The 35 standards considered were: OIB, Czech BC, BR10, D3, RT2012, Effinergie, EnEV, DNGB, Passivhaus, Italy NC, Tech. Reg. Construction (Lithuania), Planning and building act (Norway), RCCTE, South Africa BC, CET, Boverket, MukEn, Minergie-A, Minergie-P, Minergie-Eco, Bouwbesluit, Part L, BREEAM, CfSH, IECC, LEED, Canada NEC, LEED Canada, Equilibrium, BEE, ECS (Japan), CASBEE, Australia BC, NatHERS, and H1EE.

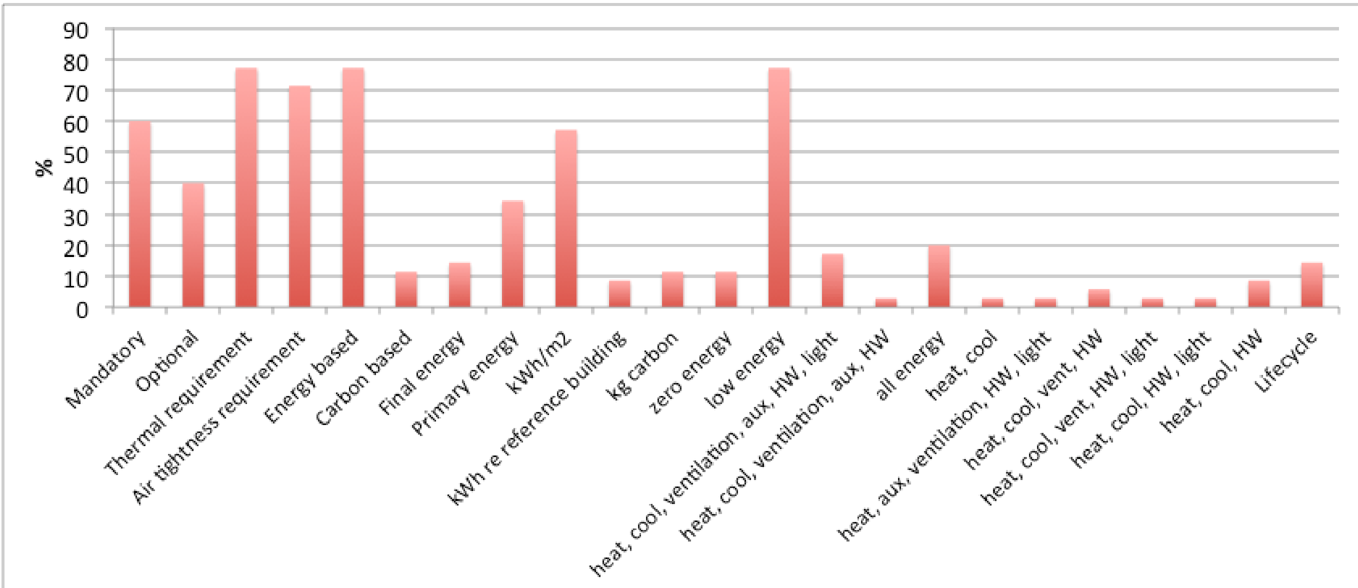

Figure 2: Core parameters of the 35 major low or zero energy building standards around the world presented as the percentage that are presented in terms of each parameter. For example 70% of them have an air tightness requirement. Data taken from [37], [38] and [28].

From Figure 2 we see that fabric thermal performance and airtightness are common features, the use of energy metrics out number carbon ones 7:1, the use of primary energy is common, phrasing the standard in terms of carbon is uncommon, there are 7 times the number of low-energy standards than zero-energy ones, there is great diversity in what energy uses need to be included, and finally, that the use of lifecycle analysis (such as including embodied energy) is rare.

In order to ascertain the impact that standards might be having it is important to consider their locality. This allows the possible impact of a standard to be gauged by comparing its coverage to the global patterns of construction. The geographical coverage of the standards considered in this study are presented in Figures 3, 4 and 5. The number of recorded zero energy buildings in each country is also shown (data taken from the Global Building Performance Network [37], the International Energy Agency BEEP database [38] and the Zero Carbon Compendium report [28]). The full list of countries and standards covered in the study is given in the appendix. Figure 3 shows the number and types (mandatory or optional) of low/zero energy/carbon building standards in place in a number of countries around the world. Figures 4 and 5 show global and regional maps identifying the number of building standards in place in each country along with the respective number of zero energy buildings reported to exist there.

Predictions of the future levels of urbanisation in Asia, Africa and the rest of the world up to 2050 (Figure 6 [39]) can be considered as a rough indicator of construction level trends: it is clear that the growth will be in Africa and Asia, yet the zero-energy focus lies elsewhere. Figure 7 shows that there is little correlation between the number of low/zero energy/carbon standards a country has and the number of zero energy buildings built within a country (R^2=0.397). This suggests that having more standards in a country does not imply more penetration and use of a zero energy/carbon standard within that country.

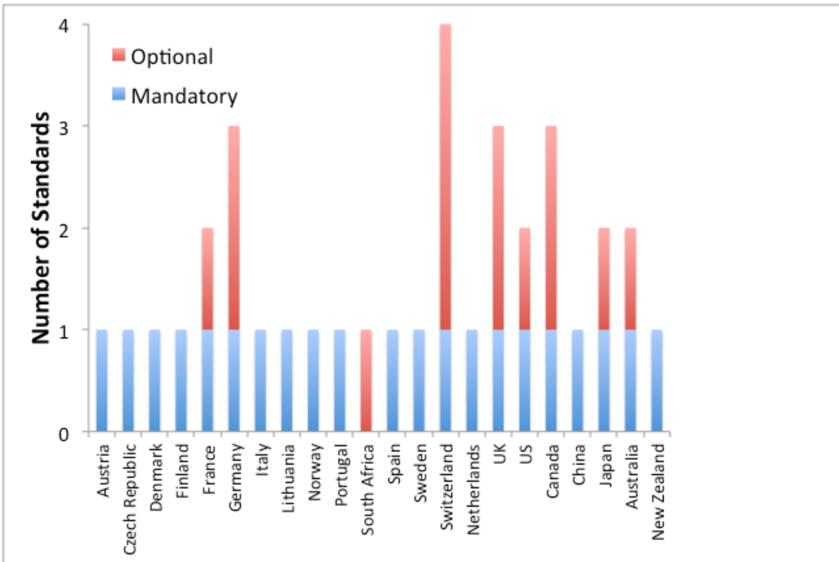

Figure 3. Number of mandatory and optional standards across the world.

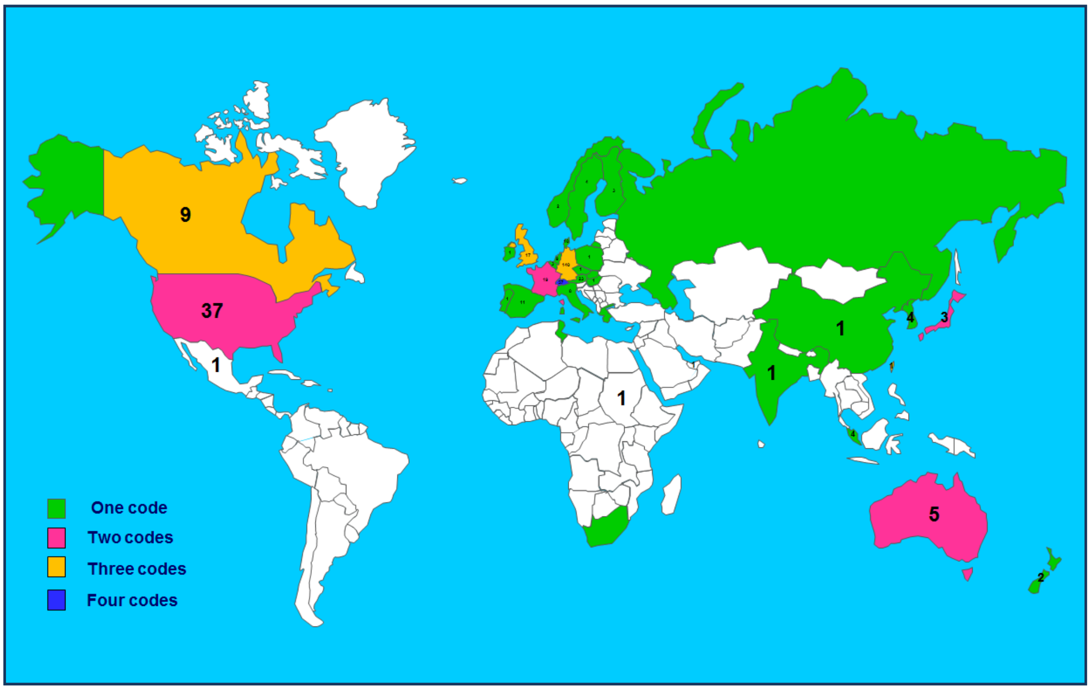

Figure 4: Distribution of building standards and zero energy buildings across the world. The number of low energy buildings is far greater.

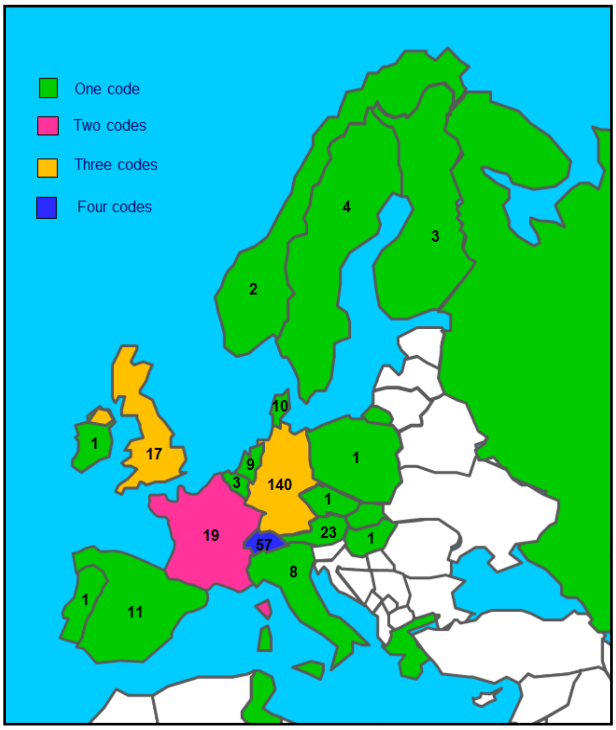

Figure 5: Distribution of building standards and zero energy buildings across Europe. The number of low energy buildings is in the tens of thousands.

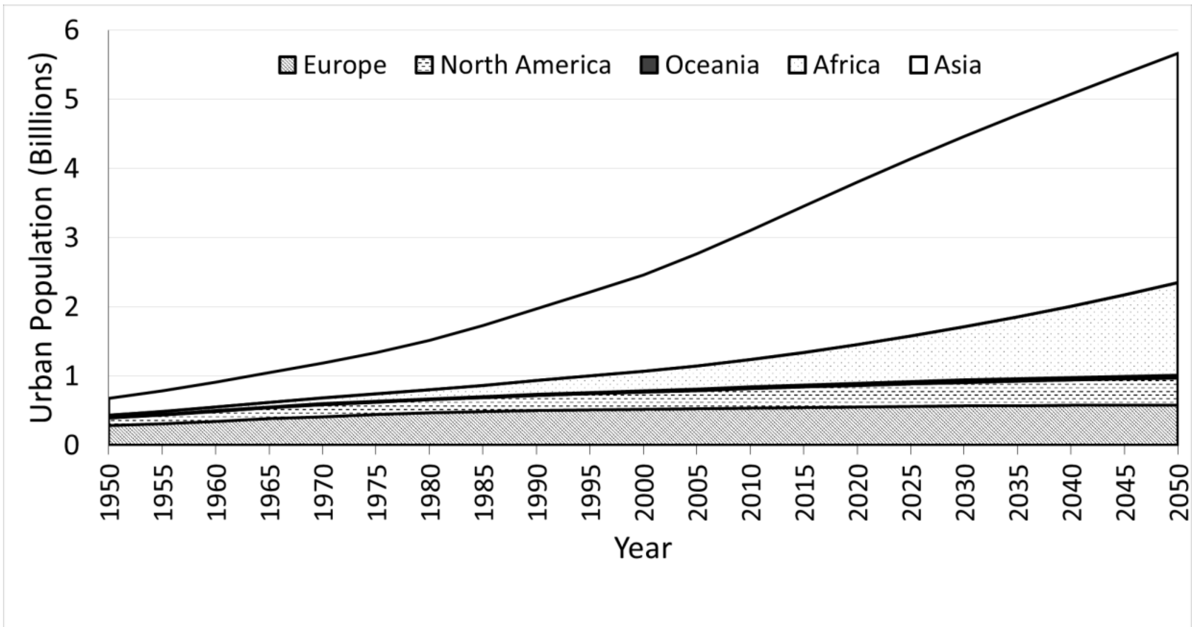

Figure 6: Mid-year urban population estimates by region. It is clear that most growth has for some time been, and will continue to be, outside of regions that have well developed zero energy standards. Data from [39].

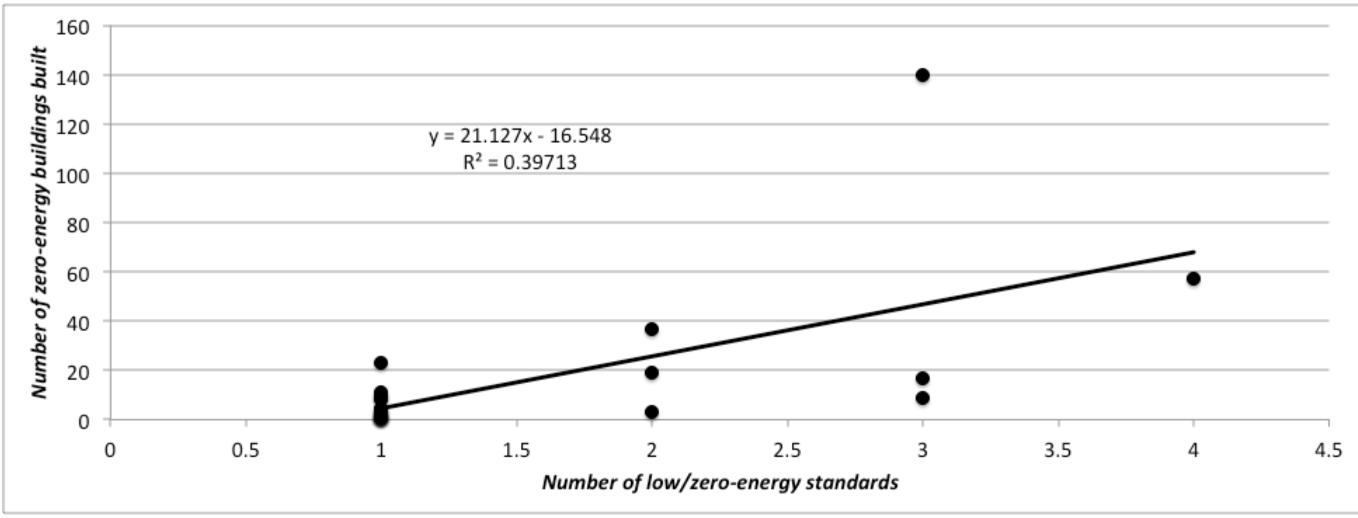

Figure 7. Correlation between number of low/zero-energy standards operational within a country and the number of zero-energy buildings built for the countries shown in Figures 4 and 5. Note the R^2 value is very low, indicating no correlation.

Ireland and Finland's comments in their EU directive compliance plans [40,41] put forward the view that the regulation of energy use of new buildings may be ineffective in reducing overall energy use if significant numbers of buildings built to less rigorous previous standards still remain. Others have made the same point [42]. As there is no worldwide database of existing building stock, the following uses data from two countries as indicators.

Taking Romania as an example, the allowed primary energy use for new buildings has been reducing over time (Table 2). Assuming these reflect the energy performance of the buildings built at these dates, and the evidence is that (at least for new low energy buildings) buildings typically use more, not less, energy than suggested by the building standard under which they were constructed [43,44], there is a clear need for deep retrofit in order to bring them inline with proposed zero energy standards.

Table 2 Romanian energy standards [45,46]

Date	**kWh/m²**
Before 2005	856
2005-2010	458
2018	333
2020	279
2050-beyond	206

An indication of the way that building quantities can vary over time is seen in data from the Slovak Republic (Table 3). The falling house construction rates possibly show the impact of the global recession, even so, at less than 1 new house per 425 people per annum it is unlikely zero-energy standards for new buildings will have much impact on energy consumption in the built environment, whatever the economic future. We can expect the situation to be similar in much of the world.

Table 3 Slovak house building statistics [47].

	2007	2008	2009	2010	2011
Number of completed dwellings	16,473	17,184	18,834	17,076	14,608
Number of dwellings started	18,116	28,321	20,325	16,211	12,740

4. Analysis

For the above data we can see that:

1. there is no shortage of standards;
2. these are inconsistent (see Figure 2), with different ones focusing on different goals (carbon or energy), and including different items (all energy use, only regulated energy use, lifecycle energy);
3. there is no correlation between the number of standards and building activity or the human population of a country;
4. there is no correlation between number of standards and the number of zero-energy buildings (R^2=0.397);
5. in future, most buildings will be built in countries with no active zero-energy standard; and
6. given the need for an 80% cut in emissions by 2080, the building community has not risen to the challenge of climate change and radical, urgent, world-wide, change is needed.

Whilst there are a wide range of definitions of low and zero carbon and energy buildings, there are certain levels of consensus. Across the standards looked at, thirty of them include a balance to determine a building's performance and the other five relied on prescriptive measures to guarantee a level of performance. Of the metrics used by all the schemes that have an energy/carbon requirement, kWh/m^2 of primary energy was the most common. The UK and Japan are the only major countries using kg of carbon as the defining unit.

Of the standards looked at, only four are for zero rather than low energy. All of the zero targets were from optional schemes. Of the four schemes the most demanding are the top level for the UK Code for Sustainable Homes and Equilibrium. These require a balance covering regulated and non regulated energy use. It is arguable that these two are the closest examples of meeting any of the ZEB definitions fully, however Minergie-P also fulfils the requirements for a ZEB depending on what is encompassed in the balance. The new Passivhaus premium and Passivhaus Plus standards will also be highly demanding in this regard.

One of the most striking points that comes from the data is that all summed the energy use over a year and all allow for grid connection. This is obvious in some respects as the climate a building will experience is cyclical over a year, and studies have shown the cost implications of onsite storage can be large [48], however this may not be so in the future: It will be interesting to see if buildings become both producers and storage facilities rather than just consumers and generators.

The life cycle assessment element within the standards and optional assessments also shows a very clear pattern towards not being regularly applied to real buildings, and this would explain why it is a much more prominent feature in the optional standards, rather than national building codes. However the true importance of the life cycle impact of products is only now being fully realised, and with more tools and information becoming available accounting for it within building projects will likely increase. However it is at present unclear how embodied energy/carbon or the general lifecycle of buildings should be treated within a standard. For example, some material choices are likely to lead to designs which need less frequent repair or decoration, but who within the framework of any standard would be able or trusted to make such judgments in a fair, accountable and transparent way? Likewise, the lifetime of some materials is greater than others. For example, concrete rather than lightweight sheeting, but buildings are often torn down before their lifetime has been reached; again, how are such judgments to be made within a standard? For refurbishment, redecoration and maintenance accounting for carbon becomes particularly difficult in a world of changing carbon intensities of supply, and with a global supply chain. For example, how is one to estimate the embodied carbon of paint purchased from an unknown supplier in twenty years' time? The UK-based Integrated Material Profile And Costing Tool (IMPACT) [49] is being developed to address these kinds of questions. However, while IMPACT is a method and dataset designed to

perform whole building environmental assessment anywhere in the world, it is acknowledged that its UK dataset may not be applicable to materials produced locally in other countries [49].
In this study 35 national and independent design standards where considered in detail. Of these 21 are mandatory building standards that are implemented within countries. By cross referencing the two largest free to access databases of building standards [37,38] a further 35, also non-mandatory, regional codes can be identified. Figure 4 indicates that there are very large areas of the world that are not covered by any form of low energy building standard. Most of the rest is covered by a single standard, which is very unlikely to be zero energy. Only a very small proportion of the world is covered by very low or zero energy standards. It is clear that the greatest penetration of low energy standards is in Europe where the majority of countries already have strict national building standards, but even here the delivery of zero energy buildings has been slow.

Looking at construction worldwide, China is responsible for almost half the world's new building activity [50], and if China aspires to Western levels of comfort then this will cause a large increase in resource demand. India has the third largest building sector (the US has the second) and large migration from rural areas, which predominately use biomass, to urban areas which are dependent on oil and electricity – this will further drive increases in energy demand [51]. Therefore while the focus of defining and constructing low and zero energy buildings tends to be in Western Europe and the US, the majority of new building activity is in rapidly developing economies where these concepts are less well developed and almost never implemented.

The IPCC [1, Chapter 9 p4] argue that '*building standards with strong energy efficiency requirements that are well enforced, tightened over time and made appropriate to local climate and other conditions have been among the most environmentally and cost-effective ways to decarbonise buildings*'. Given that in many countries the built environment sector is the largest emitter of carbon, it is clear that urgent action is needed. Yet it would appear that zero-energy buildings are nowhere the norm, and in much of the world are non-existent. This is particular so if existing buildings are considered. Maybe we should not be surprised that adoption by governments, clients, or industry has been so slow, and it could be argued that the plethora of definitions discussed above has not helped. It is interesting that the car industry seems to have been far more effective in making progress. One noteworthy non government-directed recent development has been the use of occupant/client led definitions of zero energy building standards [52]. These sidestep issues of national agreement, or buy-in from the construction industry.

It is hence suggested that there is an urgent need for an international focus at the highest level for the creation of a worldwide definition of a low-energy building that can be adopted by all nations.

5. Conclusion

Buildings are responsible for 30-40% of final energy consumption and reducing this energy demand would have a significant impact on reducing global carbon emissions. Due to the need for an overall 80% cut in carbon emissions, and indications that some sectors will find it impossible to achieve such a cut, buildings are likely to need to move to a zero energy model. However, there is clearly a very wide range of zero energy/carbon building standards and currently no agreed standard definition which is globally accepted has been suggested; Passivhaus possibly comes the closest to one, but is only a low, not zero, energy standard.

From the worldwide picture of the construction of zero energy buildings, there appears to be no correlation between activity in creating and implementing definitions within building standards and buildings being delivered on the ground. The focus of this activity is Western Europe and outside this region many countries are totally inactive in this regard.

This paper argues that while defining what a zero energy or zero carbon building is can be important and act as a driver for the development of low energy and low carbon buildings, progress in terms of numbers of buildings built has been small and sporadic. Therefore the impact these high performing buildings will have on overall global carbon emissions reduction is limited. The numbers of buildings being developed is relatively small and tends to focus on new build homes in developed economies. These buildings will remain as exemplars to show what is technically feasible, but otherwise their impact can be considered small.

Clearly the approach to defining and delivering significantly increased numbers of zero energy/carbon buildings needs to reflect the different needs in different economies and include different approaches. For example, in countries with the legacy of an older building stock (primarily developed economies), the focus needs to shift to retrofit. Whereas in the emerging economies the focus would be on new build. It is also important to appreciate the need for political will in this ongoing effort; potentially the biggest driving force for, or against, the development of zero energy/carbon buildings. For example, in 2007 the UK Government announced that the top level of the Code for Sustainable Homes would become the domestic zero carbon standard and would be mandatory for all new build homes from 2016 onwards [53]. However, the burden of financial and industrial concerns led to the gradual relaxing of this mandatory requirement during the following years [36,54], and, finally, its complete demise in 2015 [55].
Therefore the focus should be on rapidly agreeing a strong single international building standard applicable to include both new build and refurbishment that encourages national governments to build on this universal definition to include other issues. It is argued that given the difficulty of considering carbon, or embodied energy, these two issues, and others such as transport to and from the building by occupants, electric vehicle charging etc. should not be considered in any such high-level definition and rather left to national or local governments.

This definition will not be easy to create. One stumbling block will be how to deal with time varying building integrated renewables particularly once they form a large fraction of generation. Another will be how to avoid the performance gap, or whether to make the standard based on performance rather than prediction to remove the issue. Hence the research focus needs to shift from an ever-increasing interest in minutiae to thinking about the form of such a pan-world definition. This needs to be of a form that can be applied as rapidly as possible to the world's stock of buildings, and to the new ones that are created as those in poverty gain a first world living standard. There are estimated to be 190 million buildings within the European Union [56]. This implies that, even if world population does not increase, then a population-proportional estimate suggests that a developed world might expect to need 2.77 billion buildings: All zero energy. If this task is going to be completed within an emission reduction schedule that points to a near zero carbon world in 2080, this implies 43 million buildings need to be built or refurbished to zero energy standards each year. Without this world carbon emissions will remain high.

Acknowledgement: the authors would like to thank EPSRC for their support via grant EP/L016869/1.

References

[1] IPCC, *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*, IPCC, 2014, Geneva.

[2] Srinivasen, RS, Braham, WW, Campbell, DE, and Curcija, CD, *Re(De)fining Net Zero Energy: Renewable energy balance in environmental building design*. *Building and Environment*, 2012, 47, pp.300-315. DOI: 10.1016/j.buildenv.2011.07.010

[3] *Low Carbon Construction Innovation and Growth Team Final Report*, Department for Business, Innovation and Skills, 2010, London, England.

[4] Pan, W, *System boundaries of zero carbon buildings*. Renewable and Sustainable Energy Reviews, 2014, 37, pp.424-434. DOI: 10.1016/j.rser.2014.05.015

[5] Hui, SCM, *Zero energy and zero carbon buildings: myths and facts*. Proceedings of the International Conference on Intelligent Systems, Structures and Facilities (ISSF2010), 12 January 2010 Hong Kong, pp.15-25.

[6] Clark, G and Jacks, D, *Coal and the Industrial Revolution, 1700–1869*, European Review of Economic History 2007 1(1) pp 39-72, DOI: http://dx.doi.org/10.1017/S1361491606001870

[7] *Energy Consumption in the UK, Chapter 3: Domestic energy consumption in the UK between 1970 and 2014*, 2015, Dept. of Energy and Climate Change, London.

[8] Hernandez, P and Kenny P, *From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB)*, Energy and Buildings, 2010, 42, pp.815-821. DOI: 10.1016/j.enbuild.2009.12.001

[9] Kibert, CJ and Fard, MM, *Differentiating among low-energy, low-carbon and net-zero-energy building strategies for policy formulation*, Building Research and Information, 2012, 40, pp.625-637. DOI: 10.1080/09613218.2012.703489

[10] Kapsalaki, M and Leal, V, *Recent progress on net zero energy buildings*. Advances in Building Energy Research, 2011, 5, pp.129-162. DOI: 10.1080/17512549.2011.582352

[11] Krick, B., The New Proposed Passive House Classes Explained. *passive house +*[Online], Issue 9. Available from: http://passivehouseplus.ie/magazine/insight/the-new-proposed-passive-house-classes-explained.html [Accessed 12 February 2016].

[12] Esbensen, TV and Korsgaard, V, Dimensioning of the solar heating system in the zero energy house in Denmark, Solar Energy, 1977, 19(2), 195–199.

[13] Gilijamse, W, Zero-energy houses in the Netherlands, in Proceedings of Building Simulation '95, 1995, Madison, WI, US, pp. 276–283.

[14] Iqbal M, A feasibility study of a zero energy home in Newfoundland, Renewable Energy, 2004, 29(2), 277–289.

[15] Charron, R, A Review of Low and Net-Zero Energy Solar Home Initiatives, Natural Resources Canada, 2005, pp. 1–8.

[16] Torcellini, P, Pless, S, Deru, M and Crawley, D, Zero Energy Buildings: A Critical Look at the Definition. *ACEEE Summer Study*, 14–18 August, 2006 Pacific Grove, California, U.S. Department of Energy 2006.

[17] EISA CRS Report for Congress: Energy Independence and Security Act of 2007: December 21, US Government, 2007, Washington, DC.

[18] Mertz, GA, Raffio, GS and Kissock, K, Cost optimization of net-zero energy house, in Proceedings of the Energy Sustainability Conference, 2007, pp. 477–488.

[19] Rosta, S, Hurt, R, Boehm, R and Hale, M, *Performance of a zero-energy house. Journal of Solar Energy Engineering*, 2008, 130(2), 021006.

[20] Laustsen, J, Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Buildings, 2008, OECD/IEA, Paris.

[21] GreenBuildingAdvisor, The GBA Glossary, Green Building Advisor, 2010 (available at: http://www. greenbuildingadvisor.com/glossary).

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

[23] Aelenei, L, Goncalves, H and Rodrigues, C, The road towards 'Zero energy' in buildings: lessons learned from SOLARXXI building in Portugal, in Proceedings of the EUROSUN 2010 International Conference on Solar Heating, Cooling and Buildings, Graz, Austria, pp. 28–35.

[24] Voss K, Musall E, Lichtmeß M, From low energy to net zero energy buildings – status and perspectives, Journal of Green Building, 2011, 6(1) 46–57.

[25] Salom J, Widen J, Candanedo JA, Sartori I, Voss K, Marszal A, Under- standing Net Zero Energy Buildings: evaluation of load matching and grid interaction indicators, in: Proceedings of Building Simulation, Sydney, AU, 14–16 November, 2011.

[26] Sartoria I, Napolitanob A and Vossc K, (2012), *Net zero energy buildings: A consistent definition framework*, Energy and Buildings, 2012 Volume 48, Pages 220–232.

[27] Lund H, Marszal A and Heiselberg P, Zero energy buildings and mismatch compensation factors. Energy and Buildings, 2011, 43(7), 1646–1654.

[28] PRP Architects, *Zero Carbon Compendium: Who's doing what in housing worldwide*, 2009, NHBC Foundation, London.

[29] Culakova M, Vilcekova S, Burdova EK and Katunska J. Reduction of Carbon Footprint of Building Structures, *Chemical Engineering Transactions*, 2012, 29, pp.199-204.

[30] Himpe E, Trappers L, Debacker W, Delghust M, Laverge J, Janssens A, Moens J and Van Holm M, Life cycle energy analysis of a zero-energy house. *Building Research and Information*, 2013, 41, pp.435-449.

[31] Proietti S, Sdringola P, Desideri U, Zepparelli F, Masciarelli F and Castellani F,. Life Cycle Assessment of a passive house in a seismic temperate zone. *Energy and Buildings*, 2013, 64, pp.463-472.

[32] Hammond G. and Jones C, *Embodied Carbon: The Inventory of Carbon and Energy (ICE)*, 2011, BSRIA, Bracknell, England.

[33] Stephan A, Crawford RH and de Myttenaere K, Towards a comprehensive life cycle energy analysis framework for residential buildings. *Energy and Buildings*, 2012, 55, pp.592-600.

[34] Acquaye AA and Duffy AP, Input-output analysis of Irish construction sector greenhouse gas emissions. *Building and Environment*, 2010, 45, pp.784-791.

[35] Acquaye AA, Duffy AP and Basu B, Embodied emissions abatement - a policy assessment using stochastic analysis. *Energy Policy*, 2011, 39, pp.429-441.

[36] Heffernan et al. Redefining zero? A critical review of definitions of zero energy buildings and zero carbon homes. *CIBSE Technical Symposium*, 11-12 April, 2013 Liverpool John Moores University, Liverpool.

[37] *Global Buildings Performance Network,* 2013 [Online]. Available from: http://www.gbpn.org/ [Accessed 16 January 2015].

[38] *Building Energy Efficiency Policies,* International Energy Agency, 2014 [Online]. Available from https://www.iea.org/beep/ [Accessed 16 January 2015].

[39] *World Urbanization Prospects*, Dept. of Economic and Social Affairs, United Nations Secretariat, 2014, New York.

[40] Department of Communications, Energy & Natural Resources, Article5: Exemplary Role Of Public Bodies' Buildings, Submission By Ireland To The European Commission 2014, Ref: Ares 7173, Dublin, Ireland.

[41] Finland's National Energy Efficiency Action Plan NEEAP-3, Report pursuant to Article 24(2) of the Energy Efficiency Directive (2012/27/EU) to the European Commission, 2014, Helsinki, Finland.

[42] Conseil Européen des Professions Immobilières, A Guide to the Energy Efficiency Directive, CEPI, 2013, Bruxelles, Belgium.

[43] Green Construction Board, *The Performance Gap: Causes and Solutions* [Online], 2013, Available from: http://greenconstructionboard.org/images/stories/pdfs/performance-gap/2013-03-04%20Closing%20the%20Gap_Final%20Report_ISSUE.pdf [Accessed 2 February 2015]

[44] CIBSE, TM54: *Evaluating operational energy performance of buildings at the design stage*. Chartered Institution of Building Services Engineers, 2013, London England.

[45] Shady, A. and Adina, A.M, *Romanian Standards for Energy Performance in Buildings Translation of the Romanian Standards for Energy Performance in Buildings*, Sustainable Buildings Design Lab, Université de Liège, Belgium, 2015.

[46] Pedro, J.B, Meijer and F, Visscher, H, *Technical building regulations in EU countries: comparison of their organisation and formulation*, CIB World Congress 2010, Manchester 2010.

[47] Dol, K. and Haffner, M, *Housing Statistics in the European Union 2010*, The Hague: Ministry of the Interior and Kingdom Relations and OTB Research Institute for the Built Environment, 2010, Delft University of Technology.

[48] McManus, M, Environmental consequences of the use of batteries in sustainable systems: battery production, *2nd International Conference on Microgeneration and Related Technologies*, 4-6 April 2011, University of Strathclyde, Glasgow.

[49] *Impact,* [Online]. Available from: http://www.impactwba.com/pagec.jsp?id=7 [Accessed 5 January 2016].

[50] Allwood JM. and Cullen JM, *Sustainable Materials With Both Eyes Open*, 2012, UIT, Cambridge.

[51] Jennings M, Hirst N, and Gambhir A, *Reduction of carbon dioxide emissions in the global building sector to 2050*. London: Grantham Institute for Climate Change, (GR3), 2011.

[52] Parkin AB, and Coley DA, A new way of thinking about environmental building standards: Developing and demonstrating a client-led zero-energy standard, Building Services Engineering Research and Technology 36(7) 2015 doi:10.1177/0143624415615328

[53] Department for Communities and Local Government, 2007. *Building a Greener Future: policy statement*. London: Communities and Local Government Publications.

[54] House of Commons, 2015. *Public Bill Committee Thursday 8 January 2015 (Afternoon): Infrastructure Bill [Lords]*. London: The Stationary Office Limited.

[55] HM Treasury, 2015. *Fixing the foundations: Creating a more prosperous nation*. London: HM Treasury.

[56] Jeremy Rifkin J, *The Third Industrial Revolution: How Lateral Power Is Transforming Energy*, Palgrave Macmillan, 2013, London, ISBN-10: 0230341977.

Appendix: Standards around the world

	Country	Number of NZE Buildings	Number of Standards	Name of the Standard
1	Australia	5	2	Building Code of Australia, NatHERS
2	Austria	23	1	OIB
3	Belgium	3	1	PEB
4	Canada	9	3	Canada National Energy Code, LEED Canada, Equilibrium
5	China	1	1	BEE
6	Czech Republic	1	1	Czech Republic Building Code
7	Denmark	10	1	BR10
8	Finland	3	1	D3
9	France	19	2	RT2012, Effinergie
10	Germany	140	3	EnEv, DNGB, Passivhaus
11	Greece	0	1	Regulation for Energy Performance of Buildings (REPB or "KENAK") and associated Technical Guidelines of the Technical Chamber of Greece (TGTCG)
12	Hungary	0	1	National City Planning and Building Requirements' (OTÉK)
13	India	1	1	Energy Conservation Building Code
14	Ireland	1	1	Building Regulations: Part L Conservation of Fuel and Energy: Dwellings
15	Italy	8	1	Italian National Code
16	Japan	3	2	Japan Energy Conservation Standard, CASBEE
17	Korea	4	1	Building Design Code for Energy Saving
18	Luxemburg	0	1	Règlement grand-ducal modifié du 30 novembre 2007 concernant la performance énergétique des bâtiments d'habitation.
19	Lithuania	0	1	Technical Regulation of Construction
20	Malaysia	4	1	Energy Efficiency Standard
21	Netherlands	9	1	Bouwbesluit 2012
22	New Zeeland	2	1	H1 Energy Efficiency
23	Norway	2	1	The Planning and Building Act
24	Poland	1	1	Technical regulations: Energy Savings and Thermal insulation
25	Portugal	1	1	RCCTE
26	Russia	0	1	Thermal Performance of Buildings
27	Slovak Republic	0	1	Act No. 555-2005 Coll. on energy performance of buildings
28	South Africa	0	1	South Africa Building Energy Code
29	Spain	11	1	CET
30	Sweden	4	1	Boverket's
31	Switzerland	57	4	Mu Ken, Minergie– A, Minergie – P, Minergie - Eco
32	Sudan	1	0	N/a
33	Tunisia	0	1	Thermal building regulation

34	Turkey	0	1	Bep-TR (Regulation of energy performance of buildings)
35	Taiwan	1	3	Residential and Non-residential building energy standards, Energy Labeling Program, Green Building Evaluation System
36	UK	17	3	Part L, Breem, Code for Sustainable Homes
37	US	37	2	IECC, LEED
38	United Arab Emirates	1	0	N/a