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ORIGINAL ARTICLE

Defining zero carbon and zero energy homes from a performance-based regulatory perspective

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Abstract The development of a framework for defining net zero energy and net zero carbon homes has seen significant progress over the past decade. With anthropogenic climate change the principal driver, numerous governments are moving to regulate homes at or near a net zero energy or net zero carbon performance level. What has been missing in the literature is a discussion of how the basic principles of performance-based building regulation will shape the definition. The very nature of performance-based regulation as a legally contestable instrument shapes and limits the content of a regulatory definition. This paper examines the recent literature on zero energy and zero carbon building definition frameworks, explores the key characteristics of performance-based standards and determines practical definitions that could be adopted within performance-based building codes.

Keywords Zero energy · Zero carbon · Residential building · Energy efficiency · Performance-based regulation

Introduction

Global concern for anthropogenic greenhouse gas emissions has led governments in Europe, North America, Australia and Asia to consider regulating building energy and carbon equivalent emission performance at levels approximating net zero energy or net zero carbon (Kapsalaki and Leal 2011; Department of Climate Change and Energy Efficiency 2010). In the UK, the national government has set the regulatory path to their definition of net zero carbon for new dwellings by 2016 with an explicit goal of reducing national carbon emissions (Department of Communities and Local Government 2006); in Europe, the EU Directive on the Energy Performance of Buildings ties improved building energy performance directly with international commitments to addressing climate change and specifies that by the end of 2020, all new buildings shall be 'nearly zero energy buildings' and the US Department of Energy has communicated a strategic goal of 'marketable zero energy homes in 2020' (Sartori et al. 2012). In Australia, policy makers driven by the need to reduce domestic contributions to global greenhouse gas emissions have suggested the need for a pathway to net zero carbon buildings by 2020 (Department of Climate Change and Energy Efficiency 2010).

While this policy fervour rages, many academics have proposed definitions for net zero energy and net zero carbon homes (see for example Torcellini et al. 2006; Laustsen 2008; Riedy et al. 2011; Voss et al. 2011; Sartori et al. 2012). To confuse the matter further, numerous case studies have been published with alternative definitions and calculation boundaries (see for example Chow 2008; Newton and Tucker 2009; Wang et al. 2009; Hoque 2010; Bambrook et al. 2011; Ferrante and Cascella 2011; Leckner and Zmeureanu 2011). To promote a clearer and more consistent approach to defining these buildings, the International Energy Agency established a specific project to 'develop a

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common understanding of a harmonised international definitions framework' (International Energy Agency 2010).

Some definitions have been discussed from the perspective of their application in building regulation (Hernandez and Kenny 2008; Marszal et al. 2010; Riedy et al. 2011; Chalfoun et al. 2011; Buildings Performance Institute Europe 2011). Hernandez and Kenny (2008) argue that a life cycle approach is necessary for building codes to deliver the best energy and carbon outcome, Marszal et al. (2010) describe the differences between their proposed regulatory definition of net zero energy and the current building energy codes in six European nations, Chalfoun et al. (2011) describe the process used to develop a draft net zero energy code for the City of Tucson and Riedy et al. (2011) suggest their definition has potential application in Australian building regulation. A report from the Buildings Performance Institute Europe has examined a raft of voluntary and mandatory building standards used in Europe and highlight the challenges of moving to nearly zero energy buildings (Buildings Performance Institute Europe 2011). These discussions appear to be driven by the desire to achieve significant carbon reductions above that of existing codes without recognising the limitations caused by the specific nature of building codes as legal instruments or the characteristics of performance-based building codes or performance-based compliance paths offered in building codes used in many developed and developing nations.

Missing from the debate has been an exploration about how the basic principles of legally enforceable performance-based building regulation will shape the definition and influence the potential energy and carbon outcome.

The research question addressed by this paper is: how do the characteristics of performance-based regulatory instruments used to determine the minimum energy and carbon performance of buildings and the limitations associated with creating a robust and verifiable standard shape the definition of net zero energy and net zero carbon buildings that can be applied in regulatory standards?

To answer the research question, this paper (a) identifies the primary characteristics of legally contestable regulatory instruments and, in particular, the characteristics of performance-based building codes; (b) analyses the key boundary issues used to define net zero energy and net zero carbon homes against those characteristics and (c) uses this analysis to determine the elements of a definition for net zero energy and net zero carbon homes.

By addressing this key gap in the literature, this paper proposes practical regulatory definitions for both net zero energy and net zero carbon homes appropriate for application in performance-based building regulation.

Background

The application of energy-efficient and renewable energy technologies in buildings is not a new phenomenon as thermal insulation and solar energy have been utilised to improve thermal comfort for several millennia and solar energy has been used for water heating for more than a century (Butti and Perlin 1980). During the twentieth century, scientific research played a vital role in demonstrating the potential for energy-efficient and renewable energy technologies to reduce the energy and greenhouse gas emission impact of buildings, with many well-known examples such as the Massachusetts Institute of Technology series of solar passive houses which commenced in the 1930s, the University of Delaware's 'Solar One' built in 1973, the Freiburg Solar House built in 1992 and BedZED, which was completed in 2002 as the first attempt at a large-scale residential zero energy development (Boer 2001).

Recently, the increasing availability and affordability of renewable technologies has encouraged building practitioners and researchers to explore the potential to create homes that have little or no impact on net anthropogenic greenhouse gas emissions. Examples of dwellings claiming to be net zero carbon or net zero energy are appearing on a number of continents (Land Management Corporation 2011; AusZEH 2010; Rijal and Stevenson April 2010; Hoque 2010; Research for Energy Optimized Building 2013). A research group within the International Energy Agency's "Towards Net Zero Energy Solar Buildings" project has mapped almost 300 net zero energy and energy-plus buildings worldwide (Research for Energy Optimized Building 2013). Case studies detailing technical aspects of individual or small groups of net zero carbon and net zero energy homes have been documented for many nations and climates (Ferrante and Cascella 2011; Hoque 2010; Newton and Tucker 2009; Leckner and Zmeureanu 2011; Bambrook et al. 2011; Chow 2008; Miller and Buys 2012; Wang et al. 2009). Chow (2008) applied a life cycle assessment methodology to examine the carbon impact of a proposed zero carbon home in the UK; Newton and Tucker (2009) explored the feasibility of reaching near zero carbon performance for four different building types in Melbourne, Australia; Wang et al. (2009) considered the feasibility of net zero energy homes in Cardiff, Wales; Hoque (2010) contrasted two different design strategies for homes in North-Eastern USA; Ferrante and Cascella (2011) explore strategies to reach a zero energy balance for a home in Southern Italy; Leckner and Zmeureanu (2011) examined various technical options for a net zero energy home in Montreal, Canada; Bambrook et al. (2011) modelled options for reaching net zero energy for a detached home in Sydney, Australia and Miller and Buys (2012) examined the performance of near zero energy homes in Queensland, Australia. In each case, the authors have applied different methodologies or have constructed different calculation boundaries to determine the relative energy and/or carbon impact.

In parallel, the promotion of alternative low-energy standards, terms and labels such as ‘passive house’, ‘energy-neutral’ and Minergie have played a role encouraging innovation diffusion and industry development in various markets (Hall 2012; Mlecnik 2012). Similarly, international collaborative exercises such as the International Energy Agency’s Solar Heating and Cooling Programme Task 28 have promoted energy-efficient and sustainable solar housing.

Progress towards highly energy-efficient appliances and lighting, plus reductions in the cost of renewable technologies, has combined with government sustainable development policies to deliver ever larger-scale developments approaching a net zero energy or net zero carbon performance level (Saman 2010; Heinze and Voss 2009; Kansara and Ridley 2012).

The rapidly growing number of exemplar buildings and environmentally sustainable developments demonstrating industry’s capability to deliver low-energy and low-carbon emission housing has given governments the confidence to propose building energy regulation at levels approximating net zero energy or net zero carbon (Lovell 2009).

Performance-based building regulation

New homes, like all products, are shaped by the complex interaction of economic, political, technical and professional influences (Bijker and Law 1992). Social, economic and technical influences (such as the cultural institutions that shape communities; the technology norms applied by industry, tax systems and economic incentives that encourage investment; organisational artefacts such as regulations and the education and training of industry and community participants) all play a part in shaping both the physical building and the energy behaviour of the building users (Guy 2006).

Most developed countries and many developing countries regulate the energy and/or carbon equivalent emission performance of buildings (Janda 2008; Iwaro and Mwasha 2010). In a survey of building energy regulations for 80 countries, Janda (2008) found that 39 nations had mandatory codes, a further 20 had voluntary codes and 12 others had proposed the introduction of codes.

New building construction is usually subject to two regulatory systems: (a) planning regulation—which focuses on how the proposed *use of the land* will impact the surrounding community and (b) building regulation—which focuses on how the proposed *building* will impact the potential users and the wider community. Planning schemes consider issues such as visual amenity, noise pollution, solar access, traffic, heritage and environmental impacts due to the type of use requested for the land; whilst building regulations consider the design, construction and expected ongoing performance of the building from the perspectives of health, safety, amenity and sustainability (Australian Building Codes Board 2006; Australian Greenhouse Office 1999).

While the energy and carbon impact of a building is influenced by many factors such as the commissioning and maintenance of building energy systems, the quality of construction and the behaviour of the building users, from a regulatory perspective only a few factors are usually influenced by planning regulations (including solar access and the use of renewable energy systems in heritage zones), with the majority of factors influenced by building design and construction aspects covered by building energy regulation.

Many nations use performance-based building codes rather than prescriptive codes or offer a performance-based compliance path to regulate building design, construction and alteration (Meacham et al. 2005). The performance-based system provides increased flexibility and the opportunity for lower-cost solutions by allowing suitably qualified persons to follow any reasonable path to demonstrate compliance to the published objective (Meacham et al. 2005; Foliente et al. 1998).

The structural hierarchy of performance-based building codes typically starts with (1) the Objective, describing the social aim; (2) the Functional Statement, which sets out how the objective will be met; (3) the Performance Requirement, which outlines suitable performance expectations; and (4) Building Solutions, which describes specific approved assessment/verification methods (Foliente 2000; Meacham 2009; Oleszkiewicz 1994).

For example, The Energy Efficiency part of the Building Code of Australia communicates the Objective as "to reduce greenhouse gas emissions"; the Functional Statement highlights that the objective is achieved by "efficiently using energy" for domestic services; the Performance Requirement provides separate performance targets for thermal comfort and other domestic services (such as water heating, lighting, etc.) and the Verification Methods level indicates acceptable construction practice, building energy tools, calculation methods and alternative solutions.

Building regulations are limited in nature by being legally contestable instruments, confined to objective issues which can be verified by recognised methods (Meacham 2009). Meacham (2009), reporting on the principles and experiences of performance-based building regulatory systems, describes the need for regulatory requirements to be clearly identified, articulated, quantified and supported by verification methods for demonstrating compliance—'Ultimately, this ability to quantify performance criteria and connect them to specific verification methods is essential, as it serves as the basis for testing, design and evaluation.'

The characteristics of verification methods are similarly impacted by the requirements of legally contestable instruments. When examining the application of building energy rating systems, used as a verification method within regulatory instruments, Hernandez and Kenny (2011) listed the key system characteristics to be robustness, transparency, reproducibility, sufficient accuracy, timeliness and low cost. These verification method characteristics ensure the efficiency and robustness of the compliance approval process.

For performance-based building regulatory systems, the building approval process is conducted by the building control authority or designate (i.e. building surveyor, building control official or building certifier), with assessment conducted by an independent suitably qualified person who is responsible for making an informed decision based on a transparent verification process (Meacham 2009).

Given the legal status of building regulations, the nature of the associated building approval process, the principles for performance-based regulation and the characteristics needed for verification methods, it can be argued that each building energy or carbon performance requirement must:

- be quantified
- be transparent
- be relatively simple and cost-effective to evaluate
- specify verification methods
- be certifiable as compliant by a suitably qualified person

Continuing this argument, the delivery of a net zero energy or net zero carbon standard through a performance-based building regulatory instrument therefore places constraints on the calculation methodology and boundaries. Using the principles established above, the performance requirements for net zero energy or net zero carbon homes must be transparent and quantified (have clearly communicated outcomes), verifiable (clearly communicated verification methodologies) and certifiable (readily and repeatedly testable by a suitably qualified person).

Boundary issues

The energy or carbon emission performance of a building is determined by the boundaries used in the calculation. The most comprehensive reviews on the boundaries used to define net zero energy and net zero carbon homes are found in Marszal et al. (2011), Riedy et al. (2011) and Sartori et al. (2012). Each of the reviews places greater emphasis on specific boundary issues but is broadly consistent on the range of boundary issues discussed. Table 1 provides a summary of the key boundary issues discussed by each research team.

While there is reasonable consistency across the review papers with each covering most issues, there are notable differences. For example, Riedy et al. (2011) and Sartori et al. (2012) highlight spatial dimensions by discussing the impact of the scale of development [i.e. number of buildings] on the definition of net

Table 1 Coverage of boundary issues

	Marszal et al.	Riedy et al.	Sartori et al.
Metric	X	X	X
Balancing period	X	X	X
Balance type	X		X
Energy use coverage	X	X	X
Generation type	X	X	X
Generation location	X	X	X
Grid connection	X	X	X
Minimum energy efficiency	X	X	X
Additional specific performance	X	X	X
Spatial boundary		X	X
Verification method		X	X

zero energy, but the issue is not covered by Marszal et al. (2011). Sartori et al. (2012) note that individual buildings within a development may not meet a net zero energy performance level, but a collective of buildings may reach the standard.

Riedy et al. (2011) and Sartori et al. (2012) discuss the impact of verification methods as a boundary issue and in particular highlight the issue of measured versus modelled calculation methods for energy use and generation.

Marszal et al. (2011) and Sartori et al. (2012) discuss balancing type as a key boundary issue, particularly as it impacts the use of low-carbon generation technologies such as combined heat and power systems, but this issue is not highlighted by Riedy et al. (2011).

Each review acknowledges that any useful definition of net zero carbon or net zero energy homes used for building regulation will need to address the key boundary issues. What is missing from the discussion is the relationship between the boundary issues and the characteristics of performance-based building regulation. Does the very nature of legally contestable performance-based regulation shape the way each boundary issue is addressed in a definition of net zero energy or net zero carbon used for the purpose of regulation?

Regulatory constraints to boundaries

By examining each of the boundary issues identified in Section "Boundary issues" against the principles for legally contestable performance-based regulation, it is possible to determine an appropriate definition of net zero carbon homes that will be applicable within building regulatory instruments.

The metric

Primary energy and carbon equivalent emissions have been the most commonly applied metrics for zero energy and zero carbon building research, particularly for the later because reductions in carbon equivalent emissions is often the key goal of national climate change strategies (see Marszal et al. 2011; Riedy et al. 2011). Primary energy as the metric provides the most accurate assessment of the depletion of scarce energy resources and is, in cases without the distortion of nuclear power, sufficiently proportional to carbon equivalent emissions (Buildings Performance Institute Europe 2011).

Primary energy and carbon emission impacts are by nature constantly changing due to the fluctuating contribution of renewable sources to the local electricity grid, the conversion of energy in thermal power stations and energy transport losses. To apply these metrics and meet the basic principles of performance-based regulation, in particular the need to be transparent and the need for simple and cost-effective calculation methods, it will be necessary to assign primary energy flows and average greenhouse gas coefficients for each fuel type (electricity and gas) on a regular basis (e.g. annually). The Minergie-A label developed in Switzerland is an example of a voluntary zero energy building standard that incorporates a national weighting factor for primary energy (Hall 2012). The European Directive 2010/31/EU on the energy performance of buildings makes specific reference to primary energy to determine the energy impact of a building, requiring each member to detail calculation methodologies and assign primary energy conversion rates.

Applying average primary energy or carbon equivalent emission conversion rates is a useful mechanism for calculating approximate impacts, but is likely to misrepresent a building's actual impact because the hourly, daily and seasonal draw on the local electricity grid for a net zero energy or net zero carbon building is likely to be very different to the network-wide draw on renewable and non-renewable energy sources. Applying conversions rates beyond annual coefficients increases the quantity and complexity of calculations and would be contrary to the performance-based regulatory principle of requiring simple and cost-effective calculation. To illustrate this point: if we consider a home which generates electricity from solar photovoltaic panels, what is the primary energy value of the electricity generated as it replaces electricity that would otherwise be generated by some unknown source and that mix of sources is changing hourly, daily, seasonally and annually. The use of average primary energy factors or carbon equivalent emission conversion rates is likely to significantly misrepresent the actual impact of replacing that electricity during the specific periods of generation. This issue is magnified as we move to net zero energy and net zero carbon buildings which are designed to use very small total amounts of delivered energy with large daily and seasonal differences, drawing energy loads substantially different in profile to the average across the national or regional grid.

During a buildings' relatively long effective life, the primary energy coefficient is likely to significantly vary with changes in the mix of electricity generation technologies and changes in the efficiency of individual generation technologies. With many nations committed to lowering the carbon equivalent emission impact of their electricity grid through the increased use of renewable energy and other low-carbon energy sources, annual primary energy conversion factors for the grid are expected to significantly change over time.

In many nations, such as Australia, neither primary energy nor carbon emissions are typically calculated during the building design process or for building regulatory purpose and given the level of uncertainty associated with applying primary energy or carbon emission coefficients, the additional complexity may not outweigh the additional benefit. In this case, a delivered or site energy calculation provides an equally transparent regulatory solution. This does not rule out explicit policy goals requiring the use of primary energy as the metric but rather suggests metrics other than primary energy may also be viable within a performance-based building energy regulatory test.

Energy delivered to, or generated at, a dwelling is measured and priced by the local energy utility and is of direct economic relevance to the building user (household). But once energy generation occurs onsite, the delivered energy number hides the amount consumed directly from the onsite generation source and hides the relative efficiency of the energy used.

The total site energy expected to be used to maintain thermal comfort, provide lighting, hot water and operate other energy systems in a building can be (a) modelled by well-understood building energy assessment tools based on the laws of physics combined with published assumptions and local weather data or (b) be calculated through test methodologies published within international standards. This means that total site energy use as the metric will both provide reasonable energy performance disclosure and meet the basic principles of performance-based regulation.

Riedy et al. (2011) argue that a carbon emission metric would be the most appropriate if the primary object of the building energy regulation is to reduce net carbon emissions, but typically building energy regulation is designed to deliver multiple policy goals including energy security, peak energy reduction, reduced greenhouse gas emissions, economic efficiency, health and safety and social equity, and therefore a purely carbon-based metric may be restrictive. For example, the Regulation Impact Statement (Australian Building Codes Board 2009) for the move to 6 Star residential buildings in Australia discusses a range of policy outcomes such as increased energy efficiency, reduced energy demand, reduced peak energy demand and the need to address market barriers to the uptake of energy efficient technologies as well as the primary goal of addressing climate change through reduced building energy-related greenhouse gas emissions.

In Europe, where primary energy calculations are well supported by published primary energy calculation methods and conversion coefficients, primary energy is a viable metric. For other countries, given the very low amounts of energy needed for zero energy and zero carbon homes and the level of uncertainty regarding accurate primary energy conversion factors, a quantified energy performance requirement, based on the net balance of site energy used and locally generated energy with a clearly articulated assessment (verification) method or methods, allowing simple compliance testing, may be the most suitable approach for a performance-based building regulatory instrument.

Balancing period

The balancing period for net zero energy and net zero carbon buildings is commonly either monthly or annual assessments (Riedy et al. 2011). To meet the building regulatory characteristics of being quantified, transparent and simple to calculate, either of those approaches is valid. Problems can arise if the calculation period is extended further into the future.

Under many regulatory systems, a building can only be occupied following certification by a suitably qualified person that it meets building regulatory requirements at a point in time. To meet the characteristics of transparency and cost-effectiveness, energy use or carbon impact assessments must be calculated according to likely energy use based on known properties of materials and systems installed or highly likely to be installed, expected number of users and their use pattern, physical laws and a transparent set of user behaviour and climate assumptions.

The further into the future the energy use is modelled, the less confident the model becomes due to uncertainties in likely future behaviours, technology availability and performance, and climate conditions. Given expectations of global and regional climate change and the long economic life of buildings, the need for certainty and simplicity in regulation creates a conundrum. Residential buildings often have an effective economic life in excess of 50 years (Australian Bureau of Statistics 2001) and climate science predicts significant global and regional climate change during that period (CSIRO 2007) when combined with high levels of uncertainty regarding global action to reduce anthropogenic greenhouse gas emissions: should buildings be regulated according to historic climate data (high certainty) or predicted future climate (lower certainty)? Economic tests used by governments to evaluate regulation discount the value of future activity and place greater value on more recent and therefore more certain events. Given the need for simplicity and transparency, for building regulatory purpose, building environmental performance is best modelled for a period very close to the date of regulatory assessment, employing a typical building use pattern known at that time. This does not prevent the use of immediate–future climate files constructed to represent highly likely weather patterns.

Balancing type

The balancing approach can be based on two netting processes: (a) netting energy generated against energy load or (b) netting energy exported against energy imported with the netting period [i.e. monthly or annual] providing additional variation (Sartori et al. 2012).

From a regulatory perspective, because codes are required to be simple and cost-effective to calculate, option (a) is the most viable option as both the expected energy load and energy generation calculations are relatively easy to calculate using well-understood verification methods. Option (b) requires the calculation of expected self-consumption of energy generated onsite, which would be difficult to predict at a high resolution (short time periods) and at low resolution, relies on the same calculation of energy load and generation used in option (a).

The process of netting energy generated against energy load on an annual basis may hide large seasonal variations with requisite impacts on the local energy networks. Where this is expected to be an issue, it would be possible to require monthly netting calculations with maximum allowable differences, thus requiring a better sub-seasonal balance of generation and load.

Energy use coverage

There are two key issues regarding the coverage of energy within a definition of net zero energy or net zero carbon: firstly, the extent of the life cycle of the building energy use is measured and secondly, the extent of the occupant's lifestyle energy impacts to be covered.

While operational energy consumption is typically the dominant energy impact for residential buildings, as the building and the associated systems become more energy efficient, the energy embodied in the materials becomes relatively more important (Blengini and Di Carlo 2010; Sartori and Hestnes 2007). Looking at the issue from a resource-constraint or resource-efficiency perspective, the planet has a finite quantity of non-renewable resources to construct and operate the energy systems in buildings (Srinivasan et al. 2012). The best outcome for energy conservation and greenhouse gas emission reduction through a building regulatory instrument is to incorporate all relevant impacts from the building life cycle (Hernandez and Kenny 2011; Szalay 2007; Casals 2006; Australian Greenhouse Office 1999). The Australian Greenhouse Office (1999) investigating the building energy regulatory options for the Building Code of Australia notes 'Thus a complete assessment of the greenhouse gas impact of buildings must ultimately include embodied and operating energy on a life cycle basis'. Alternatively, Srinivasan et al. (2012) suggest the use of emergy analysis, an environmental accounting procedure based on energy flows, to fully incorporate all relevant impacts.

Life cycle and emergy assessments are resource intensive and require significant databases quantifying the environmental impact of materials (Srinivasan et al. 2012; Blengini and Di Carlo 2010). Blengini and Di Carlo (2010) point out that a full life cycle carbon or energy impact assessment requires a detailed and time-consuming examination of the carbon and/or energy intensity for each product covering sourcing, manufacturing, transportation, construction, operational and deconstructing processes across the economic life of the building and therefore is not commonly used in the design of buildings or for building regulatory purpose. To speed up the process, life cycle assessment tools and, similarly, emergy analysis draw on inventories of impact assessments for building materials and building systems.

The widespread use of an impact inventory places great faith in the database to ensure a 'level playing field' for all building materials and systems (Australian Greenhouse Office 2006). The Australian Greenhouse Office (2006) found, in relation to the development and use of a life cycle inventory, that stakeholders emphasised the need for transparency, fairness, accuracy, comprehensiveness and availability and found five key requirements:

- That databases and tools be developed and maintained by a credible neutral party or parties
- That the methodology and boundaries be clearly defined and transparent and in harmony with international practice and standards
- That all industry sectors be invited to provide and review data
- That the information be available for use across the industry
- That the outputs tie into existing rating tools for market recognition

Incorporating a life cycle assessment methodology, utilising a life cycle impact inventory, within a regulatory instrument means that the assessment process will need to satisfy not only the key conditions above, but others relating to industry's capacity to deliver consistent outputs. A more complete list of requirements would include:

- Transparency—an agreed and detailed methodology should be established within recognised standards (i.e. ISO) requiring sufficient thoroughness of calculation
- Fairness—all materials must be treated fairly and according to the best available science
- Consistency—the boundaries for impact calculation should be identical for all materials and defined by published standards
- Comprehensiveness—all materials likely to be used in a home must be included
- Availability—the inventory should be readily available to all users
- Regional validity—impacts should be calculable at the location of material use, where transport impacts are likely to be large
- Tools—affordable calculation tools, giving equivalent outputs, should be readily available in the market
- Industry development—suitable training materials and courses should be available to ensure consistent outputs

Creating and maintaining a publicly available inventory that satisfies those conditions is no easy task. For example, the Building Products Innovation Council (2011), with Australian Government funding, has produced a building products life cycle inventory. This inventory uses weighted average impacts, provided by each product manufacturing industry, using impact boundaries determined by that industry. The lack of consistency in the calculation methodology used by each industry, the lack of involvement by some industries, and the lack of localised (regional) information means that the inventory does not facilitate a like-with-like site-specific comparison of all building products. The lack of regional scale information means that products transported many kilometres, produced by that industry's worst process, rate the same as locally produced products by that industry's best available process.

The consequent uncertainty in the results is currently a major limiting factor for the use of a life cycle assessment methodology in building energy regulation (Hernandez and Kenny 2011, 2008). Hernandez and Kenny (2008) suggest a simplified life cycle methodology based on limiting the calculation of embodied energy to only the differential between the proposed design and a base building will limit the amount of calculation and uncertainty. While this approach appears to have merit, even limiting the number of products required for analysis does not remove product-specific or location-specific uncertainty. Without a sufficiently comprehensive inventory and tools that can calculate impacts accurately according to the development location, a high level of uncertainty will remain.

Once sufficiently comprehensive and rigorous inventories are readily available and used within building energy assessment tools, a full life cycle or similar approach would provide the most appropriate route to assess a net zero carbon home. Until that time, only an operational energy calculation will meet the requirements for inclusion in performance-based regulation by being readily measurable, having reliable verification methods and certifiable by a suitably qualified person.

Occupants use energy for a variety of activities associated with buildings, including transport to and from that building, activities within the property boundary but not in the building and activities that occur within the building. Building regulation is limited to those activities associated with the design, construction and operation of a building on a specific site and hence can only include those activities occurring within the limits of the property boundary and may be verified onsite or through the use of predictive building assessment tools. Householder activities that largely occur offsite or outside the building such as private transportation or food production are not covered by building regulation.

The compliance testing process involving an expert certifier inspecting the building prior to habitation places limits on the specific technology that can be included. Technologies that form the structure or are built into or attached to a building to provide essential energy services of thermal comfort, lighting, cooking and water heating can be included in regulatory tests. Each of these energy services may require assumed occupant behaviour and assumed system efficiency to calculate likely average energy use.

Other energy using technologies that are brought to the building by the occupants' post-certification cannot easily be included in a regulatory test, although the expected energy use of an average household may be included in the balancing equation (energy use vs. generation) using standardised behaviour and system efficiency assumptions. For example, although white goods such as refrigerators, washing machines and clothes dryers; home office equipment such as computers and printers; and home entertainment equipment such as televisions, set top boxes and audio equipment are typically not installed in a building by the developers and therefore cannot be assessed directly by the certifier, these energy use activities occur wholly within the property as regular household actions and may be included in the balancing equation if all assumptions are transparent and the calculation methodology is consistent for all developers.

In regions such as Europe and countries such as Australia, electrical appliances and equipment are subject to extensive energy performance labelling regulation and minimum energy performance standards, representing significant policy action to reduce the energy and carbon equivalent emission impact of white goods, home entertainment and other appliances.

But with general plug loads covering energy services such as refrigeration, laundry, home office and home entertainment representing approximately one quarter of operational energy use and the fastest-growing end use (Department of the Environment Water Heritage and the Arts 2008), by transparently quantifying the expected energy use associated with these services, this large energy and carbon impact can be incorporated into the net zero energy or net zero carbon regulatory test.

Type of energy generation

The energy available for use in a particular building or development can come from the local energy grid, generated onsite by renewable or non-renewable sources or be reclaimed from otherwise waste energy such as heat from co-generation, tri-generation or an industrial process. The type of generation as well as the amount of generation will determine whether a building reaches a net zero energy or net zero carbon standard. For a net zero energy building, the amount generated onsite would need to equal or exceed the expected energy load of the building. Utilising low-carbon energy sources such as combined heat and power and renewable energy can assist with reducing greenhouse gas emissions by reducing the energy otherwise needed from the local grid to meet all energy services but to reach a net zero carbon operational impact, an amount of energy equal or greater than the remaining load for the building must be supplied by renewable sources. Local consideration of renewable energy sources will be required. For example, combined heat and power systems fed by biofuels and wood pellets may be considered renewable technologies where those fuels could be demonstrated to be locally sustainable across the building's effective life.

Under a regulatory instrument, to be readily measurable and certifiable by a suitably qualified person, any local energy generation must have a predictable expected supply. This means that for a net zero carbon regulatory standard, local generation of energy offsetting demand must include renewable energy technologies with predictable expected annual performance. The production of electricity from wind turbines in an urban environment is highly influenced by local conditions and is difficult to predict. A comprehensive study of the potential for micro-wind technology in Australia found that the complex terrain of urban areas create unpredictable wind patterns at a micro-level, making the wind energy production virtually impossible to model with reasonable accuracy (Webb 2007). Similarly, a trial of domestic scale wind turbines in the UK found that building-mounted systems, typical of that applied in an urban setting, had inadequate wind speed and produced lower than expected energy results due to the impact of local obstructions such as trees and buildings (Energy Saving Trust 2009).

Technologies such as solar thermal and solar photovoltaic, micro-hydro, combined heat and power systems fed by biofuels, wood pellets, etc. and ground loop heat pumps produce relatively predictable annual quantities of low or zero carbon energy and are therefore appropriate for inclusion in calculation methods.

Location of energy generation

Building regulation is limited to those activities associated with the design, construction and operation of the building, and hence, can only include those materials used, or activities occurring, within the limits of the property boundary which can be verified by a building certifier. The contribution of energy generation systems established offsite and not exclusively connected to the building poses significant uncertainty and are problematic for inclusion in building regulatory calculations (McLeod et al. 2012). McLeod et al. (2012) note two main problems associated with offsite generation: (a) additionality and (b) permanence. During compliance checking processes, it may not be possible to determine whether the offsite renewable or non-renewable energy technologies offer additional energy to that which would have occurred due to a separate policy instrument and the compliance process cannot determine the likelihood of that offsite system remaining connected after the completion of the building.

Larger-scale energy generation systems that exclusively serve a multi-unit residential development created under a single development application, but may be located away from the units but within the development boundary, may be included if the whole development is assessed together for regulatory purpose. This typically occurs for apartment buildings where a collection of residential units, sometimes spread across separate buildings, is considered as a single development.

Grid connection

Buildings can be connected to various local energy networks, typically for electricity, thermal energy, and heating fuels such as natural gas. Apart from the need to balance energy generated with that used by the building (covered in Section "Balancing type") and the location issues of additionality and permanence (covered in Section "Location of energy generation"), there are no other specific regulatory issues relating to the need to connect with local energy networks.

Minimum energy efficiency and other specific requirements

A building that balances high levels of energy use with an abundance of onsite generation wastes scarce resources and would likely be contrary to the policy objective of net zero energy or net zero carbon building regulation. Authors including Torcellini et al. (2006), Riedy et al. (2011) and Voss et al. (2011) make reference to the need for any definition to encourage the efficient use of energy first and then have that energy balanced by onsite generation.

Given that performance-based regulation must be quantified, transparent, relatively simple and cost-effective to evaluate and be testable by a suitably qualified person, a simple minimum energy efficiency test or set of tests associated with the calculation of the total energy load of the building would be appropriate.

As noted in Section "Balancing period", although a building may reach a net zero energy or net zero carbon standard, large seasonal variations in the balance of energy load and generation may lead to significant impacts on the local energy networks. To be consistent with the characteristics of performance-based regulation, any additional requirements will need to have transparent, simple and cost-effective tests. In this case, the division of an annual test into monthly or seasonal sub-tests to ensure stresses are not passed to the energy network would be reasonable.

Specific performance targets for energy efficiency or other related requirements could be incorporated into either level 3 'the Performance Requirement' or level 4 'Building Solutions' of the performance-based regulation hierarchy.

Spatial boundary

Should net zero energy or net zero carbon calculations be tested on single or multiple buildings, which may or may not have direct energy links through local networks? Building regulation is limited to those activities associated with the design, construction and operation of the building or buildings of a single development application and hence, can only include those materials used, or activities occurring, within the limits of the property boundary which can be verified by a building certifier. Consistent with the examination of generation location in Section "Location of energy generation", this approach does not prevent the consideration of a cluster of buildings or the development of local energy networks, where they are the subject of a single regulatory application.

Verification method

A building's energy impact can be determined from measured actual energy use or modelled expected energy use based on assumptions such as climate, construction quality, fit-out, and occupant behaviour. The building approval process is conducted prior to a building's occupancy and use; therefore, it would be difficult to require a test of measured performance.

The modelled expected energy use method is typically applied for performance-based building energy regulation, often through energy rating systems. For example, in Australia, the Nationwide House Energy Rating System is used as a compliance path and in the UK, the Standard Assessment Procedure and more recently the Code for Sustainable Homes has been used to test compliance with the energy provisions of the building code. This verification method requires the performance requirements to be quantified, transparent and the tests able to be conducted cost-effectively by a suitably qualified person.

Going beyond net zero carbon or energy performance

Whilst creating ecologically sustainable buildings that provide their own ecosystem services for waste management, food production and other services may be ecologically sound and morally justifiable under certain value sets; building regulation defines only the minimum onsite performance that is measurable and testable by a suitably qualified person before a building can be approved for habitation. Hence, many environmental impacts are likely to be outside the scope of building regulation.

Processes that deal with air and water purification onsite may be within the scope of building regulation but as the environmental deliberation of this research is restricted to the energy and carbon impact of residential buildings, consideration of other air and water quality issues is outside the scope of the proposed regulatory definition.

Going beyond net energy or net carbon performance through the deliberate generation of renewable energy in excess of that required for the operation of energy systems in the home may be ecologically advantageous, but it would be difficult to determine what level of excess is reasonable for a minimum standard. In addition, it is likely that energy and carbon impacts that occur offsite and are not related to the building and associated energy systems are better addressed locally to minimise transmission losses or optimise economic efficiencies of scale.

Descriptors and definitions

Many terms have been used by researchers to describe super-low building energy and greenhouse gas emission performance such as autonomous house, energy-independent house, net zero energy house, net zero carbon house, carbon-neutral, carbon-positive, hybrid buildings, net zero source energy, net zero energy costs and net zero energy emissions (Marszal and Heiselberg 2009; Voss et al. 2011; Hernandez and Kenny 2010; Kapsalaki and Leal 2011; Marszal et al. 2011; Riedy et al. 2011; Torcellini et al. 2006; Laustsen 2008; Newton and Tucker 2009; Sartori et al. 2012). Conceptual confusion has led the International Energy Agency to establish a specific project to 'develop a common understanding of a harmonised international definitions framework' (International Energy Agency 2010).

Just as there are many descriptors used to communicate nuances between zero energy, zero carbon homes and other similar super low-impact homes, there are also many definitions published in the literature that capture the boundary conditions being applied by particular authors or organisations (see for example Laustsen 2008; Newton and Tucker 2009; Riedy et al. 2011, Buildings Performance Institute Europe 2011; Voss et al. 2011). For example, Buildings Performance Institute Europe (2011) lists numerous definitions for low-energy buildings used in Europe, although most of those definitions are not intended to produce net zero energy or net zero carbon buildings.

To examine how the boundary issues have been applied in published definitions, a small sample of net zero energy and net zero carbon building definitions are analysed in greater detail. Laustsen (2008) presents a set of definitions for four types of low-impact buildings: net zero energy buildings, stand-alone zero energy buildings, plus energy buildings and zero carbon buildings. Defining the latter, Laustsen states:

> Zero Carbon Buildings are buildings that over a year do not use energy that entails carbon dioxide emission. Over the year, these buildings are carbon neutral or positive in the term that they produce enough CO_2 free energy to supply themselves with energy.

This definition allows the netting of generated renewable energy against the energy delivered to the home over a 12-month period; when the former is equal to or larger than the later, the building is described as zero carbon. Although not explicit in the definition, Laustsen argues that zero carbon buildings can use electricity produced by offsite CO_2 free sources such as large windmills, nuclear power and solar photovoltaic systems. As noted in Section "Regulatory constraints to boundaries", offsite generation is not usually viable within performance-based building regulation. This zero carbon definition makes no reference to the energy efficiency of the building and may lead to wastage of scarce resources.

Laustsen's definition of net zero energy buildings places the emphasis on local generation, rather than zero carbon emission generation, although separately stating that zero energy buildings should get their energy from renewable sources. Laustsen's net zero energy definition states:

> 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 grids. 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.

Laustsen's net zero energy definition makes no reference to the efficiency of energy use, but rather relies on the economics of energy generation to discourage energy wastage. This definition centres the calculation on the balance of imported and exported energy and thus avoids complications related to the primary energy efficiency or carbon intensity of fuels.

Newton and Tucker (2009) also define four classes of a building's energy performance: net zero energy buildings, carbon neutral buildings, zero carbon buildings and hybrid buildings. Their zero carbon building definition states:

> Zero carbon building: uses carbon free energy over the entire year, sufficient in quantity to supply all household energy needs (both dwelling operations and appliances to match any lifestyle). Connection to the grid is primarily in order to supply energy that is surplus to household needs, and for periods of emergency supply when local energy systems may be inoperable.

Newton and Tucker's definition of a zero carbon building varies significantly from that of Laustsen by stating that the building uses carbon-free energy over the entire year rather than a net balance for the required period. The balance type changes from Laustsen's import/export netting to a load/generation calculation. No reference is given to the efficient use of energy. Given the seasonal and daily variation of both renewable energy supply and household energy demand, such a standard would require a significant renewable energy system and/or local energy storage. Their definition of a carbon-neutral building (see below) more closely matches Laustsen's zero carbon building definition:

> Carbon neutral building: generates sufficient surplus CO_2-e free energy over the course of a year that balances any purchase of grid energy (primarily fossil-fuel-based). This recognises the fact that a single dwelling/household may be unable or unwilling to generate sufficient CO_2-e free energy to be classed as zero carbon;

This definition facilitates a simple energy import/export balance equation but makes no reference to the location of renewable energy sources, nor any reference to the efficient use of energy. Newton and Tucker add the concept of hybrid buildings (see below), establishing the metric as site energy, the life cycle impact limited to operational energy, the balancing energy from both low-emission and renewable local sources, the system grid connected and the timeframe of annual calculation. No reference to energy efficiency is incorporated in the definition. This definition is designed to be more flexible than previous zero carbon definitions and moves away from carbon as the metric by allowing a simple site measurement of energy used and generated.

> Hybrid buildings: residential buildings that have the capacity to supply, in total, the annual operating energy requirements of their occupants by utilising locally generated (low or zero emission) energy sources. Operating energy includes energy for heating, cooling, lighting and domestic appliances (built-in and plug-in). At times when energy is generated surplus to its occupants' immediate demands, energy is supplied to the grid and if the dwelling is unable to generate sufficient energy for autonomous operation, energy is received back from the grid.

Riedy et al. (2011) take a different approach making reference to the United Nations Environment Program common metric framework for defining emissions:

> A zero carbon building is one that has no net annual Scope 1 and 2 emissions from operation of building incorporated services. Building-incorporated services include all energy demands or sources that are part of the building fabric at the time of delivery, such as the thermal envelope (and associated heating and cooling demand), water heater, built-in cooking appliances, fixed lighting, shared infrastructure and installed renewable energy generation. Zero carbon buildings must meet specified standards for energy efficiency and on-site generation. Compliance is based on modelling and/or monitoring of greenhouse gas emissions in kg CO_2-e/m^2/year.

This definition establishes the metric as carbon calculated from primary energy, the life cycle impact limited to a subset of operational energy services, the balancing energy from onsite renewables and the timeframe of annual calculation. The balancing type is modelled (expected) energy use netted against expected zero carbon energy generation. No reference is given to grid connection, which facilitates flexibility across autonomous and grid connected buildings. Their definition emphasises the importance of energy efficiency and the need for onsite generation. By restricting the coverage to a sub-set of energy end uses, approximately one quarter of typical energy end-use is not addressed. This means that under this definition, on average, a zero carbon home will still receive a sizable energy bill and have an annual carbon impact.

Voss et al. (2011) define a zero energy building as:

> An energy-efficient building which in combination with the public electricity grid meets its total annual primary energy demand, as determined by monthly balancing, by the primary energy credit for electricity surpluses fed into the grid. The electricity generated on-site is used primarily to meet the building's own energy demand.

This definition establishes the metric as primary energy balanced at the supply interface, the life cycle impact limited to operational energy, the balancing energy from onsite generation, the system grid connected and the timeframe of annual calculation from monthly reconciliations. Voss et al. recognise the complication of using primary energy as the metric due to the need for regionally specific conversion factors, but argue that the use of primary energy provides better credit for fuels such as biomass. Voss et al. propose that the entire energy use associated with the building should be balanced by onsite generation with the calculation based on published user profiles and appliance efficiency standards.

The various definitions above provide an excellent basis to discuss net zero energy or net zero carbon homes, yet none of the definitions examined above would completely satisfy the needs of a performance-based building energy regulation, as determined by the analysis of the key boundary issues in Section "Regulatory constraints to boundaries".

Other researchers reviewing the spectrum of published definitions such as Torcellini et al. (2006) and Marszal et al. (2011) avoid providing a single definitive response. Torcellini et al. (2006) instead presents a value judgement on what a definition should be trying to achieve, arguing that the calculation methodology should encourage energy efficiency and then encourage local renewable energy sources to match demand.

International experience of regulatory definition

Many countries have established mandatory or voluntary building energy codes that deliver highly energy efficient and low-carbon emission homes (Buildings Performance Institute Europe 2011; Janda 2008). Buildings Performance Institute Europe (2011) provide a comprehensive list of European voluntary and mandatory building energy codes that seek to deliver low energy, low carbon emission or near zero energy building performance, pointing to the similarities and differences between the treatment of building codes by various nations. Many of these 'nearly zero energy' codes are voluntary instruments that are used to market best practice and therefore are not subject to the same level of legal contestability as mandated regulations but as nations move to align their building regulations with European Directive 2010/31/EU by mandating higher performance, these 'nearly zero energy' codes will become subject to full legal contestability.

The first instance of regulatory consideration of the net zero carbon home concept occurred in 2006 when the UK government became the first national government to suggest that building regulations be increased to net zero carbon by 2016 (Department of Communities and Local Government 2007, 2006). Due to devolution of power to regional authorities, the zero carbon standard would only apply to England, although the Welsh government has also determined that Welsh building regulations would have a similar performance goal (Tweed and McLeod 2008).

The UK Department of Communities and Local Government (2006) provided an initial definition based on the practical reality of energy use in residential buildings:

> For a new home to be genuinely zero carbon it will need to deliver zero carbon (net over the year) for all energy use in the home – cooking, washing and electronic entertainment appliances as well as space heating, cooling, ventilation, lighting and hot water. This will require renewable or very low carbon energy in addition to high levels of insulation, etc. Again it could be at the development or building level.

This definition established the metric as the carbon impact of primary energy, the life cycle impact limited to operational energy, the balancing type load/generation, the balancing energy from both low-emission and renewable sources within the development, the system grid connected and the timeframe of annual calculation. But with a change of government in 2010 came a change of the boundary conditions with the new Minister for Housing (Shapps 2011) announcing:

> that the regulatory threshold for zero carbon should be set to cover only those emissions which are within the scope of the Building Regulations, such as those from heating, ventilation, hot water, fixed lighting and building services.

This statement reduces the span of the operational energy calculation by eliminating the energy used for lifestyle activities such as home office and home entertainment and reflected concern from industry on the relative cost of solar technologies, the practical limitations of onsite solar collection areas and the relative low level of incident solar radiation in England (Zero Carbon Hub 2011). Given the large energy and carbon impact of plug loads excluded by the new definition, homes built to this standard will be significantly less than net zero carbon in operation. Other changes included reference to potential carbon offsetting through yet to be defined 'allowable solutions'.

Critics of the UK government approach have argued that the proposed boundaries will deliver inadequate environmental outcomes by limiting the life-cycle extent, sub-optimal economic outcomes by requiring on-site renewables, will impact on housing affordability and present an unrealistic timetable for industry (Chow 2008; Skaar 2008; Sujana et al. 2009; Williams 2009; McLeod et al. 2012; Greenwood 2012). McLeod et al. (2012) also points to potential problems associated with carbon offsetting through 'allowable solutions' whereby the impact of appliances is no longer considered, but credit may be given for installing high performance appliances, even though additionality cannot be determined. This carbon offsetting scenario also means that actions associated with appliances which have an effective life of 10–20 years can be substituted for building fabric actions which could have an effective life of 60–100 years.

The European Union requires member states ensure that all newly constructed buildings be 'nearly net zero energy' by 2020 and that the energy needs to a significant extent be met from renewable sources (European Commission 2010; Schimschar et al. 2011). The European approach applies an operational energy equation using a primary energy metric and specifies that the renewable energy sources should be onsite or nearby. A number of national governments within Europe have developed detailed road maps describing their path to nearly zero energy buildings (Jagemar et al. 2011) and have reported their national plans to the EU Commission;

however, by early 2013, Denmark was the only national government to have their 'nearly net zero energy' definition and plan officially approved (Buildings Performance Institute Europe 2013). Buildings Performance Institute Europe (2013) provide more detail on the various approaches being developed by European Union member states within national building codes to achieve the 'nearly zero energy' requirement. Additionally, the Buildings Performance Institute Europe (2011) report identifies 10 challenges facing a practical definition that can be applied in national building energy codes, many of which align with the boundary issues raised in Section "Boundary issues".

The proposed definition

While the definitions analysed in Sections "Descriptors and definitions" and "International experience of regulatory definition" provide an excellent basis to discuss net zero energy or net zero carbon homes, those definitions either would not completely satisfy the needs of a legally contestable performance-based building energy regulation or would have insufficient coverage of total building energy use to be considered fully net zero energy or net zero carbon.

The examination of various boundary and metric issues in Section "Regulatory constraints to boundaries" highlights the constraints placed on a definition by the nature and characteristics of performance-based building regulation. Recognising these constraints, a practical net zero energy definition that could be incorporated into either a level 2 'Functional Statement' or level 3 'the Performance Requirement' of the performance-based regulation hierarchy would be:

> A net zero energy building is an energy efficient building that generates sufficient energy on-site over the course of a year to supply all expected on-site energy services for the building users.

Similarly, a practical net zero carbon definition that could be incorporated into a performance-based building regulation would be:

> A net zero carbon building is an energy efficient building that generates sufficient CO_2-e free energy on-site over the course of a year to supply all expected on-site energy services for the building users.

These definitions incorporate several key points: (a) the policy outcome is a greenhouse gas emission reduction yet the regulatory measurable metric can be either site energy or primary energy, (b) energy must be generated onsite to be verified by the building certifier, (c) the period of measurement is annual, (d) the calculation methodology considers modelled (expected) energy needs for an average building user associated with that building type in the local climate and (e) energy must be efficiently used.

These definitions are transparent (clearly communicated outcomes), measurable (allows for a clear measurement methodology) and testable (readily and repeatedly calculable by a suitably qualified person).

Flexibility is facilitated by allowing the details of the calculation methodology, including the energy model assumptions, to be developed to suit local energy assessment practices and tools. For example, the phrase 'all expected onsite energy services' should be determined locally according to the standard industry practice for installing energy systems and technologies and the assumptions of internal heat loads and user behaviour incorporated into local energy performance assessment schemes. This approach also allows the calculation methodology to incorporate primary energy coefficients to suit local preferences (e.g. European Union member states) or site energy where primary energy calculations are not commonly applied in building energy performance regulation.

The phrase 'all expected onsite energy services' signals that onsite plug loads including laundry, refrigeration, home office and home entertainment should be included in the net energy equation. This will rely on locally developed models of energy use behaviour with requisite relationships such as plug load energy use per floor area.

The phrase 'energy efficient building' highlights the need to ensure that onsite generation is not over-sized to compensate for poor efficiency. Given the social objective of net zero energy and net zero carbon homes is to reduce the greenhouse gas emission impact of residential buildings, an explicit reference to the efficient use of resources is an appropriate inclusion and is likely to reduce some of the daily and seasonal impacts of building energy load and generation on the local energy network.

The reference to 'CO_2-e free' energy for the net zero carbon definition does not limit the range of generation technologies to those exclusively CO_2 free, but rather states that the net sum shall deliver equal or greater

CO_2-free energy to that used to provide onsite energy services.

The requirement of 'onsite' energy generation does not limit technology to that which can be attached to a single building. In the case of larger multi-building or multi-unit developments, community scale generation technologies within the physical boundary of the development is possible where compliance testing is conducted collectively for the total development.

The optional use of site energy as the metric and expected energy use versus expected energy generation as the balancing type avoids complications with primary energy weighting factors, particularly as each building constructed to the standard will directly impact the level of local renewable energy contribution to the network. In cases where minimum renewable energy targets exist for the local energy network, all renewable energy generation associated with net zero energy or net zero carbon buildings should be included in the target to avoid double counting across policies.

As discussed in Section "Energy use coverage", once sufficiently comprehensive and rigorous inventories are readily available and used within building energy assessment tools, a full life cycle or similar approach would provide more comprehensive approach to reduce the energy and carbon emission impact of buildings within a performance-based building regulation. At that point, the definitions of net zero energy and net zero carbon would need to be altered to reflect the addition of material- and construction-related energy use and the process of allocating impacts to an annual assessment will need to made transparent through verification methods.

Limitations of definition

While the examination of the literature and the proposed definition in this paper explicitly deal with residential buildings, it is likely that the concepts that underpin defining net zero energy and net zero carbon from a performance-based building regulatory perspective are equally valid for non-residential buildings. Further research will be required to establish this potential.

The proposed definition does not explicitly set sub-system performance standards, but rather refers to the efficient use of energy. Building thermal comfort has a strong relationship with human health, with researchers (Saniotis and Bi 2009; Bi et al. 2011; Hansen et al. 2008; Vaneckova et al. 2008; Nitschke et al. 2007) arguing that for groups, both young and old, without ready access to thermally comfortable buildings, extreme weather events such as heat waves significantly increase human mortality and morbidity and increase demand on an already overloaded health systems. This important relationship between thermal comfort and human health could provide a case for minimum sub-system performance standards to be incorporated in level 3 'the Performance Requirement' or level 4 'Building Solutions' of the performance-based regulation hierarchy.

Similarly, the argument for resource efficiency signalled by the term 'energy efficiency' could trigger a case for sub-system standards. For example, a resource efficiency consideration could reduce the size of the renewable energy system by optimising the level of building energy efficiency through specific sub-system performance standards.

The location, scale and efficiency of the renewable technology have important economic implications. Larger-scale renewable energy systems, free from overshadowing or the urban setting constraints related to noise, visual pollution or other urban setting issues, can often produce renewable energy at a lower cost than systems restricted by the size, orientation and situation of the building or development site. At the same time, transmission losses are higher according to the distance generation that occurs from the building. The proposed definition, by requiring the renewable to be located onsite, most likely in a highly urban setting, impacts the scale, type and efficiency of the system, and therefore may not lead to the generation of renewable energy at the lowest cost.

It should be noted that given the variability of household behaviour, the application of the proposed definition will not guarantee that each house in each year will deliver a net zero carbon operational performance. The intention of the standard is to deliver, on average across the stock of new homes, a net zero carbon operational performance.

Flexibility built into the application of the proposed definition, in particular allowing the calculation methodology, energy model assumptions, and the concept of 'expected onsite energy services' to be developed to suit local energy assessment practices and tools, means that the standard may not be identical in all regions, although the net zero energy or carbon intent is consistent. This may limit the ability to compare building performance between regions that use different energy performance assessment tools.

The regulatory limitation of requiring onsite or on-development generation will impact the feasibility of applying the proposed net zero energy or net zero carbon definition in all climates and for all building types and situations. Household energy demand, particularly for maintaining human thermal comfort, varies according to climate (Schipper et al. 1985), the electricity generation output for solar technologies varies according to local climate and latitude (Geoscience Australia and ABARE 2010) and technology efficiency (Razykov et al. 2011) and the roof area available for solar technologies varies with building type and urban environment (Zero Carbon Hub 2011). The combination of these issues may mean that the net zero carbon standard is not practical or cost-effective in some climates or latitudes with lower incident solar radiation or on some building types where the collection area may be relatively low for the number of dwelling units (e.g. apartment towers). This does not highlight a problem with the definition, but rather points to issues associated with the applicability of the standard in some climates and construction locations with current technology. This problem is likely to be reduced over time as technology efficiencies improve to both reduce demand and increase solar related renewable supply or may be solved using an alternative set of low-carbon and renewable technologies (e.g. tri-generation with biomass fuel or fuel cell technology).

This paper addresses the definitions of net zero energy and net zero carbon homes from the perspective of the characteristics of performance-based building standards used in regulatory instruments and does not consider issues relating to the economic, environmental or social consequences of applying the definitions in any particular climate or national situation.

Conclusion

The need of governments to address the greenhouse gas emission impact of buildings has led many to regulate the energy efficiency of homes. Some governments are moving to regulate housing energy performance at levels equivalent to, or near, net zero energy or net zero carbon.

Significant progress has been made in establishing a suitable framework to describe the concepts of net zero carbon and net zero energy buildings but no definition had been determined from the constraints associated with legally contestable performance-based building codes.

This paper has found that the nature of regulation and the principles and characteristics of performance-based building codes mean that any regulatory definition of net zero energy or net zero carbon homes:

- must allow the performance outcome to be quantified
- should facilitate simple, transparent and cost-effective verification methods
- the performance should be readily certifiable as compliant by suitably qualified person

These characteristics place significant limits on the way key boundary issues are addressed in the definition.

After examination of each of the key boundary issues against the principles and characteristics of performance-based building regulation, new definitions are proposed. These definitions provide practical yet flexible solutions, appropriate for adoption in local performance-based building codes and standards.

These proposed definitions have not been designed to address broader economic, social or environmental issues related to buildings, nor will the definitions be applicable to every residential building type or extreme local climate.

These definitions are designed to be applied in performance-based building energy regulations covering mainstream housing for the explicit objective of reducing building energy related greenhouse gas emissions.

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