Renewable and Sustainable Energy Reviews 37 (2014) 424–434

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

System boundaries of zero carbon buildings

Wei Pan *

Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong, China

A R T I C L E I N F O

Article history:
Received 20 January 2014
Received in revised form
14 April 2014
Accepted 3 May 2014

Keywords:
Zero carbon building
Zero energy
Carbon emission
System boundary

A B S T R A C T

Zero carbon building has been regarded as an important approach in reducing the carbon emissions associated with buildings. However, despite significant policy drivers, the uptake of this approach has been low. This paper examines the concepts and develops a theoretical model of the system boundaries of zero carbon buildings. Previous research is largely grounded in the net (nearly) zero carbon/energy parameter and focuses on buildings operations. However, there is increasing awareness of the need for lifecycle approaches to address carbon emissions and for boundaries to be defined to help elaborate the concept and guide research. The developed model covers eight types of boundaries, the policy timeframe, building lifecycle, geographic, climatic, stakeholder, sector, density and institutional boundaries. These boundaries are dynamic and interactive. It is concluded that zero carbon buildings should be regarded as complex socio-technical systems, but should not be exaggerated as surrogates for sustainable buildings. The findings are confirmed with case studies of five pioneering zero carbon buildings worldwide. The case studies demonstrate the great diversity and complexity of zero carbon building boundaries and assert that without the explicit specification of the boundaries, the comparison of cases in different contexts is like "comparing apples to pears."

Contents

* Tel.: +852 2859 2671.
E-mail address: wpan@hku.hk

http://dx.doi.org/10.1016/j.rser.2014.05.015
1364-0321/

1. Introduction

Buildings worldwide account for as much as 45% of the total energy consumption and carbon emissions [1], which indicates that buildings are the biggest contributor to anthropogenic climate change. Buildings have therefore been identified as offering the greatest opportunities for reducing carbon emissions [2]. Zero carbon building (ZCB) has been regarded as an important approach for reducing the carbon emissions associated with buildings and has attracted significant policy attention in many countries [3]. For example, the UK government has set ambitious targets to achieve "zero carbon" for new homes from 2016 [4, p. 15] and for non-domestic new buildings from 2019 [5, p. 7]. The recast of the Energy Performance in Buildings Directive (EPBD) of 2010 [6, p. 21] requests that the EU member states ensure that "by December 31, 2020, all new buildings are nearly zero energy buildings (ZEBs) and after December 31, 2018, new buildings occupied and owned by public authorities are nearly ZEBs." Similarly, in the US, the Energy Independence and Security Act of 2007 authorizes the Net-Zero Energy Commercial Building Initiative to support the goal of net zero energy for all new commercial buildings by 2030. It specifies a zero energy target for 50% of US commercial buildings by 2040 and net zero for all US commercial buildings by 2050 [7].

However, despite these significant policy drivers, the up-take of ZCB practices has been low. The total number of ZCBs and similar building schemes worldwide as of June 2013 was less than 300 [8]. Researchers have attempted to determine the contributing factors to the low up-take by examining ZCB and similar approaches (e.g., ZEB) in relation to their definitions (Torcellini et al. [9]; Hernandez and Kenny [10]; Sartori et al. [11]), calculation methodologies (Marszal et al. [12]), policies (McLeod et al. [13] and Kilbert and Fard [14]) and construction activities (Panagiotidou and Fuller [15]). These studies suggested that there are significant challenges preventing the up-take of ZCB. Pan [16] summarized the challenges as a lack of understanding of the ZCB principles, insufficient and inconsistent ZCB practices, unclear and uncertain ZCB policies and conflicting ZCB priorities in management. Underlying all of these challenges is a lack of knowledge of the theoretical grounds and boundaries of ZCB.

In addressing these gaps in knowledge, this paper contributes an innovative theoretical approach. ZCBs are regarded as complex socio-technical systems that cannot be effectively examined without explicitly defining their boundaries. This systems approach is essential, as all carbon reduction strategies involve political, economic, technical, social and behavioral factors [17] that connect multiple stakeholders such as practitioners, occupants and researchers. Although researchers have suggested systematically addressing the issues related to energy supply and demand and connecting the multiple stakeholders [18,19], the systems approach has seldom been made explicit in ZCB research. The aim of this paper is to develop a theoretical model of the system boundaries of ZCBs. Following the introduction, the paper critically reviews ZCB concepts and examines the theoretical grounds. It develops a theoretical model of the ZCB system boundaries and verifies the model using case studies of pioneering ZCBs across the world. The paper then discusses the implications of the developed model on future ZCB research, policy and practices.

2. ZCB concepts

Although the term ZCB is new, the concept builds on research into low carbon/energy buildings that dates back to the 1940s and has been growing in the last two decades [20]. The term ZCB is sometimes used interchangeably with many related but different terms.

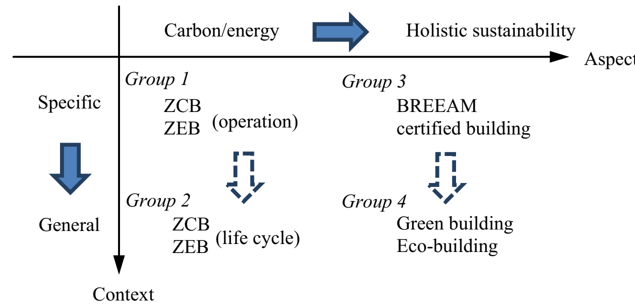

Fig. 1. Model of the categorized ZCB-related terms.

2.1. The terms describing ZCB

A survey carried out by Concerted Action in support of the EPBD in 2008 identified 17 different terms used across Europe to describe low or zero carbon and energy buildings [21]. This was expanded in a follow-up Concerted Action report [22] that presented 23 different terms for "high performance buildings" used in 14 EU member states. Erhorn and Erhorn-Kluttig [22, p. 3] commented that these terms could broadly be categorized as referring to

- "low energy consumption (low energy house, energy saving house, ultra-low energy house, 3-litre-house, zero heating energy house, zero energy house, plus energy house, very low energy house, energy self-sufficient house and energy autarkic house),
- low emissions (zero emission house, zero carbon house, emission-free house and carbon free house) or
- sustainable or green aspects (eco-buildings, green buildings, code for sustainable homes, bioclimatic house and climate: active house)."

Erhorn and Erhorn-Kluttig [22, p. 3] added, "One of the terms refers to a national standard (Lider A used in Spain), whereas two others refer to private organizations (passive houses) or public bodies (Building Research Establishment Environmental Assessment Method (BREEAM) buildings). Some of the terms for high performance buildings try to incorporate more than one of the mentioned issues (triple zero house and total quality planning and rating)."

Riedy et al. [23, p. iv], in their review of the definitions of "zero emission buildings," identified many similar terms in common use, such as "near zero energy; zero energy; zero net energy; passive house; energy plus; fossil fuel free; 100% renewable; zero carbon; net zero carbon; carbon neutral; climate neutral; climate positive and positive development." The Low Carbon Construction Innovation and Growth Team [24, p. 6] criticized that the shifting terminologies and the number of tools and methodologies that sometimes lead to quite different answers to the same questions have contributed a major barrier to the progress of achieving a low carbon future, "Carbon can sometimes mean carbon, sometimes carbon dioxide and sometimes a carbon dioxide equivalent, and the definition of zero carbon is far more complex than that rightly aspirational term might suggest." The ZCB concept is further complicated by concepts that take into account more parameters than carbon/energy and use special terms such as green building or eco-building, such as those listed by Erhorn and Erhorn-Kluttig [22].

The many terms in use depict a complicated profile of the concept of ZCB. This paper argues for a reduction in complexity by using two fundamental dimensions of the terms, the aspect being described and the context under discussion (Fig. 1). The paper categorizes the many ZCB-related terms into four groups:

Group 1	Carbon/energy-based terms within a specific context, divided into carbon emission-based, such