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# Clusters and exemplars of buildings towards zero carbon

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ABSTRACT

In addressing anthropogenic climate change many buildings worldwide have been designed and constructed towards zero carbon. However, their cross-context learning is largely constrained. The aim of this paper is thus to achieve a better understanding of the clusters and the energy strategy and performance of buildings towards zero carbon worldwide. The research was carried out through the combination of a two-step cluster analysis of several hundreds of low or zero carbon buildings and case studies of five exemplars. Five clusters of these buildings were revealed, which identified the gaps in the knowledge of high-rise buildings towards zero carbon and of decarbonizing the building stock. The results of the case studies of exemplars illustrate the systems integration of strategies for buildings' energy efficiency and energy generation and supply, but also indicate different concepts and calculating methodologies of 'zero carbon' or 'zero energy'. This inconsistency significantly hampers the benchmarking of buildings' energy performance and carbon reduction practices. Net-zero carbon, particularly net-zero energy, was found to be technically difficult to achieve over the one-year period of operation. The findings cast a shadow over the feasibility of achieving net zero carbon particularly for high-rise buildings due to geographic constraints for use of renewable energies, which encourages the exploration of emerging energy and carbon reduction technologies.



## 1. Introduction

The approach of zero carbon building has been promoted in many countries and regions as a government strategy for addressing anthropogenic climate change [1–3]. This promotion has made an essential contribution to the momentum of 'zero carbon buildings'; many have emerged worldwide and been reported through various channels. Markedly, the International Energy Agency's (IEA) Solar Heating & Cooling (SHC) Program Task 40 'Net Zero Energy Solar Buildings' has analyzed and reported the conceptual approaches of several hundreds of 'net zero-energy and energy-plus buildings' worldwide [4]; the Zero Carbon Hub's (ZCH) Building Profiles showcase 'zero carbon homes' at national level [5]; various researchers reported on individual or groups of projects of 'zero carbon buildings' [6,7]. From the worldwide promotion and reporting more 'zero carbon buildings' can be expected to be developed for future years. Cross-context learning of the past and existing practices is thus important, which however is largely constrained. Also, there have been increasing government and academic concerns about the gap between as-designed and as-built energy performance of buildings [8,9], which is being further explored and addressed by, e.g. the IEA-EBC Annex 66 'Definition and Simulation of Occupant Behavior in Buildings' that addresses the gap between simulation and measurement. However, there is a lack of study of the profiles, patterns and energy strategy and performance of 'zero carbon buildings'.

The aim of this paper is thus to achieve a better understanding of the clusters and the energy strategy and performance of buildings towards zero carbon worldwide. There are three research objectives: (1) to reveal the profiles and clusters of the buildings towards zero carbon; (2) to examine the energy strategy for building 'zero carbon'; and (3) to investigate the energy performance of exemplary 'zero carbon building' cases. The research was carried out through the combination of a two-step cluster analysis of several hundreds of low or zero carbon buildings and case studies of five exemplars that represent the clusters. Following this introduction the paper reviews the concept of 'zero carbon'. It then reveals five clusters of the buildings studied, followed by the examination of the energy strategy and investigation of the energy performance of exemplary building cases. The paper discusses the

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implications of the findings before conclusions are drawn.

## 2. The concept of 'zero carbon building'

Although research on buildings' energy and carbon emissions at least dates back to the 1940s [10], the concept of 'zero carbon building' was probably first formalized in 2006 in the UK Government's policy publication of seeking for a step-change in sustainable homebuilding practice [11]. This policy well signposts the start of governments' promotion for zero carbon buildings worldwide. There have emerged a number of other similar but different terms, often used interchangeably, which are mostly associated with their relevant policy frameworks, e.g. 'nearly zero-energy building' in the EU [12], 'zero emission building' in Australia [13,14], and 'net-zero energy buildings' in the US [15,16]. Some researchers have expanded the scope of the concept of 'zero carbon building' to also include the many other building energy and carbon relevant concepts/terms in their studies. For examples, the Concerted Action report [17] presents different terms under the banner "high performance buildings", which are used in European Union (EU) member states. They suggested that the many terms could broadly be categorized as referring to low energy consumption, low emissions or sustainable or green aspects. Riedy et al. [13] 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." Most of these terms are used in real-life projects of building towards zero carbon. The many terms, coupled with their associated policies, calculation methodologies and practices, make the concept of 'zero carbon' so complicated that the learning of the practices in different contexts becomes implicit and difficult.

## 3. Research method

This research was carried out through the combination of a two-step cluster analysis of low or zero carbon buildings and case studies of five exemplars. The cluster analysis identifies and examines the clusters of those buildings. The case studies elaborate the clusters drawing on exemplary building cases, examine the strategies for energy efficiency and energy generation and supply, and investigate the buildings' energy performance.

### 3.1. Selection of building cases for cluster analysis

Three considerations were taken for the selection of the low or zero carbon building cases for inclusion in this study. First, the keywords of 'net, nearly and/or lifecycle zero carbon' or 'zero energy building' were used to describe and report the cases. This consideration addresses the complexity of 'zero carbon' and its related concepts. Second, information on the selected building cases was obtainable from accessible sources or channels. Not many buildings were reported on their designed energy performance and carbon emissions, fewer with measured data. Those reported with relevant data often did not provide details of the scope of energy use and carbon emissions and their relevant calculation methodology. Third, the selection of the cases of low or zero carbon buildings aimed to represent a worldwide overview of the practices, rather than being constrained to any specific countries.

Several important sources were identified in the selection of building cases. First was the source in the form of Google maps view developed by the research group within the IEA's 'Towards Net Zero Energy Solar Buildings' Project [4]. This source analyses the conceptual approaches of 'net zero-energy and energy-plus buildings' worldwide as of June 2013 with a primary focus on Germany and the rest of Europe. This source presents basic project data illustrated and provides web-links to most of the projects included. Second was the 'Low Impact Housing' in the form of a website with search function that is the outcome of a survey of low impact houses in the world with a focus on North America [18]. The building profiles in this source were provided through a two-round survey with relevant professionals and professional organizations. Third was the source provided by the Zero Carbon Hub which is an independent non-profit public/private partnership, established to take day-to-day operational responsibility for coordinating the delivery of low and zero carbon new homes in the UK [5]. These sources were complemented by a wide search in public domains taking into account the three abovementioned considerations for building case selection. In total 600 buildings were selected, which together provide a reasonable representation of low or zero carbon buildings in the market.

### 3.2. Method of cluster analysis

The Statistical Package for the Social Sciences (SPSS) 'TwoStep Cluster' method was applied to reveal the clusters of the selected buildings. This method is designed to discriminate natural groups from a set of variables stabilizing the nearness criterion, with a hierarchical agglomerative clustering whose centers are far apart [19]. Compared to classical cluster analysis methods, SPSS 'TwoStep Cluster' can deal with both continuous and categorical attributes. Also, this method can automatically determine the optimal number of clusters. Likelihood was selected as the distance measure, which defines the normal density for continuous variables and the multinomial probability mass function for categorical variables. The cluster analysis involved two steps:

- Pre-clustering step: the data records were scanned one by one and the algorithm decided whether the current record could be added to one of the previously formed clusters or it started a new cluster, based on the distance criterion;
- Clustering step: the clustering stage had sub-clusters resulting from the pre-cluster step as input and grouped them into the optimal number of clusters. To determine which number of clusters was optimal, each of these cluster solutions was compared using Schwarz's Bayesian Information Criterion (BIC) as the clustering criterion. An optimal number of clusters will have a smaller value of the BIC, a reasonably large Ratio of BIC Changes and a large Ratio of Distance Measures.

Silhouette Coefficient [20], a measure of density of all the data in the cluster, was utilized to measure the goodness-of-fit of the outcome. This index combines both, cohesion (based on the average distances between all the objects in a cluster) and separation (based on the average distance of any object to all the other objects not contained in the same cluster), and can range between $-1$ and $+1$; values below 0 are indicative of inappropriate fit, between 0 and 0.2 are poor, between 0.2 and 0.5 are fair, and above 0.5 are good.

### 3.3. Selection of variables for cluster analysis

Although previous studies have examined the 'metrics' of zero energy buildings [21,22], the 'characteristics' of net zero energy buildings [23] and the 'system boundaries' of zero carbon buildings [7], no previous research has yet explicitly examined the variables of low or zero carbon buildings. This seems to be attributed to the many existent similar but different concepts relevant to building energy and carbon and their different policy contexts. It may also be due to the different methodologies for calculating the energy