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# A Review of Research on the Energy Performance of Green Buildings and its Relation to Occupancy

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**Abstract:** Buildings contribute 20 to 40% of the world's energy consumption, making the need to regulate and minimize their energy use a priority. Although green buildings appear to respond to this issue, there is little empirical evidence in the literature demonstrating their energy effectiveness and little consensus over their long-term energy performance. This study involved reviewing the literature on energy consumption in green buildings. It analyzed existing research based on its country of origin, year of publication, the type of building analyzed, the size of the sample of buildings studied, and the green building rating system used for certification. The study also used other parameters such as the availability of actual empirical energy data, the study period for which energy data was collected, and the frequency of the data collected. It also extended to analyzing the degree to which the effects of building occupancy on energy performance were considered in the literature. The review showed that approximately 50% of all studies reviewed were carried out in the US, with only three studies conducted in Canada. Although building samples considered were usually small, existing research investigated a variety of building types. Approximately a third of all studies focused on buildings certified using the Leadership in Energy and Environmental Design Rating system (LEED). Fifty-five percent of all studies considered study periods of two years or less, with a third focusing on analyzing energy data on a monthly basis. Although some studies suggested a strong correlation between occupancy and energy consumption, research in this area remains limited, highlighting the need for more studies on how building occupants' use of green buildings affects their energy performance. Although more than half of the studies reviewed demonstrated energy savings in green buildings, these results varied depending on the reference used for comparison. The goal of this research was to provide a general overview of green buildings' energy consumption as documented in the literature rather than the energy performance of specific green buildings. It highlights the limitations in current research stressing the need to streamline and standardize the methods used in future studies. Standardized research of green buildings' energy performance would ensure the generation of a coherent body of knowledge in the field for future researchers and industry practitioners.

## 1 Introduction

The rapid increase in energy use around the world raises concerns about the depletion of finite natural resources (Perez-Lombard et al. 2007) and the need to regulate this use across various industries, the building industry being the most important of all. This is because the building industry currently accounts for 20-40% of energy use worldwide (Issa et al. 2011). Although the energy crisis of the 1970s triggered several initiatives to promote green building design and construction (Hill et al. 2009), the actual surge in green buildings did not occur until the last two decades. Because of this recent surge, there is little research in the field demonstrating their actual energy effectiveness and little empirical energy data to account for it (Oates and Kenneth 2012).

Early reviews of this limited research reveal conflicting results about green buildings' energy performance (Oates and Kenneth 2012) prompting the need for researchers to reach consensus over their performance. There is also little empirical data about the role of occupants in regulating their buildings' energy efficiency (Turner 2006), making the need to analyze their impacts a priority. These reviews reflect most importantly the fragmented and disjointed nature of research in the field (Oates and Kenneth 2012), with studies conducted in isolation of each other, prompting the need for studies that provide benchmarks about green buildings' energy performance. These early limitations also highlight the need for a comprehensive, holistic literature review to determine the literature's strengths and limitations and identify opportunities for streamlining and steering the direction of future research in the field.

This study aims to conduct a comprehensive review of current research investigating energy consumption in green buildings. Its goal is to demonstrate current trends regarding green buildings' energy performance as opposed to the energy performance of specific green buildings Specific objectives involve: 1) reviewing current research based on a number of parameters such as its date of publication, country of origin, number of buildings analyzed in each study, and, 2) reviewing research focusing on the relationship between green building occupancy and energy performance. This paper aims to set the foundation for a study conducted by the Construction Engineering and Management Group at the University of Manitoba about the relationship between building occupancy and energy consumption in Manitoba's green school buildings.

This study provides a much-needed benchmark for researchers undertaking post-occupancy energy evaluations of green buildings. Because of its focus on research studies using empirical evidence to assess green buildings' energy consumption, the study would also be of interest to industry stakeholders looking to invest in these buildings because of their presumed energy-effectiveness.

## 2 Methodology

SCOPUS database was used to identify the literature investigating green buildings' energy performance. The key words "Green Buildings" and "Energy Performance" were used to identify research papers relevant to this study, resulting in an initial set of 773 research papers. These results were further narrowed down using the keyword "evaluation", limiting them to 220. The abstracts of these papers were skimmed through to determine those that will be included in the review. Papers were included if the research described focused on whole building performance evaluations and on investigating occupancy in relation to building energy performance. Papers were rejected if the research focused on the energy performance of one building element solely or failed to capture a whole building perspective. They were also rejected if post-occupancy evaluations of green buildings were conducted with no connection to energy performance. Additional papers were also identified through the citations of some of the selected papers for this study, resulting in a total of 29 reviewed research papers. These papers were analyzed according to the parameters identified in Table 2.

Table 2: Dimensions of research papers analyzed

| ***Parameters of study*** | ***Section*** | ***Associated Figures*** |
|---|---|---|
| Country of origin | 4.1 | Fig 1 |
| Year of publication | 4.2 | Fig 2 |
| Building sample size | 4.3 | Fig 3 |
| Building type | 4.4 | Fig 4 |
| Green rating system | 4.5 | Fig 5 |
| Study period | 4.6 | Fig 6 |
| Data collection frequency | 4.7 | Fig 7 |
| Data collection method | 4.8 | Fig 8 |
| Reference dataset | 4.9 | Fig 9 |
| Occupancy | 4.10 | N/A |

The review also involved analyzing research findings to determine the level of agreement or disagreement in the literature about the energy-efficiency of green buildings. For studies investigating occupancy, the review focused on identified the methods used to study its effects on green buildings' energy consumption.

## 3 Results and discussion

This section presents the results of the literature review with a discussion of them in the wider context of the literature investigated.

### 3.1 Country of origin

The review involved analyzing research studies based on their country of origin. Figure 1 shows how three countries seem to be taking the lead on this research. Approximately 50% of the studies analyzed were carried out in the United States (e.g. Menezes et al. 2011, Kats 2006). The United Kingdom came in second, with four studies overall. Only three studies were conducted in Canada (e.g. Issa et al. 2011, Diamond et al. 2011), highlighting the need for more research on Canadian green buildings. While reasons behind these observations were not investigated, the US' leading research position could be related to it being one of the earliest adopters of green building standards. The distribution of research papers per country of origin could also be correlated to the size of the green building industry in every country, providing a potential explanation for why some countries might have been underrepresented in the literature.

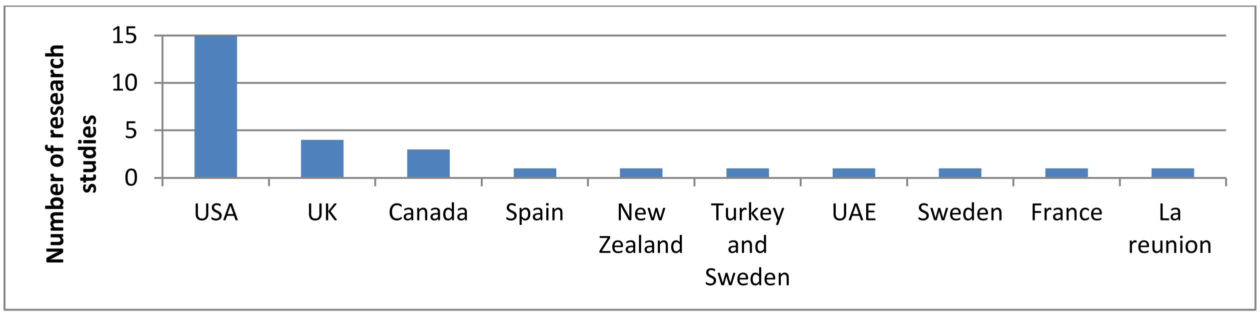


Fig 1: Distribution of research studies per country of origin

### 3.2 Year of publication

The reviewed papers were also analyzed per year of publication. Figure 2 shows how research on green buildings' energy performance has been growing in recent years. This growth could be related to the rate of adoption of green building practices, with research increasing as the number of existing green buildings available for analysis increases (Turner and Frankel 2008). The lack of actual, documented energy data in the early 2000s might also explain the smaller number of studies published at that time. Despite this being a potential problem today; the growth of the green building industry in the future should enable analyses of more green buildings and larger energy datasets, and thus provide opportunities for more comprehensive energy evaluations of these buildings.

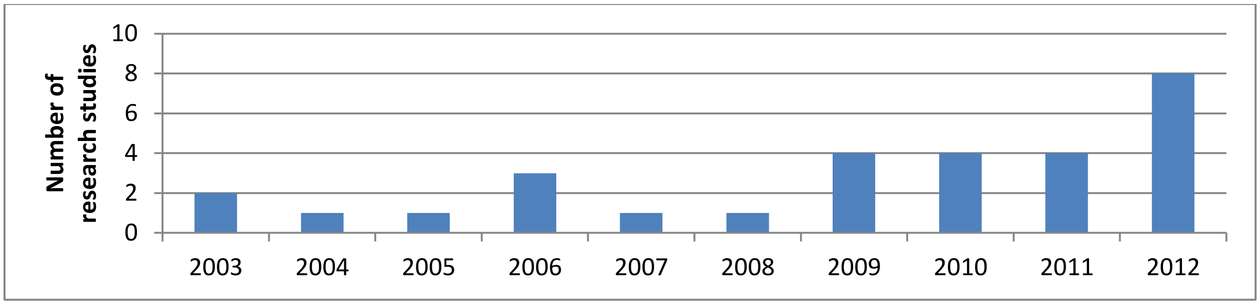


Fig 2: Distribution of research studies per year of publication

### 3.3 Building sample size

The small samples used in most studies present an important limitation that makes it difficult to generate statistically significant results. Figure 3 shows how approximately 55% of reviewed research used sample sizes of less than 10 buildings (e.g. Scofield 2002, Byrd 2012, Brunklaus et al. 2010). Only 3 studies used samples of more than 90 buildings (e.g. Turner and Frankel 2008, Newsham et al. 2009, Scofield 2009). Turner and Frankel (2008) investigated a total of 121 green buildings, making this the largest study by far in the field. While there is a need for larger green building samples to enable more meaningful conclusions, one barrier to doing so might have to do with the lack of actual energy data (Flanagan et al. 2005). Building owners might also be unwilling to take part in these studies for fear for their public image, should their buildings prove to be underperforming.

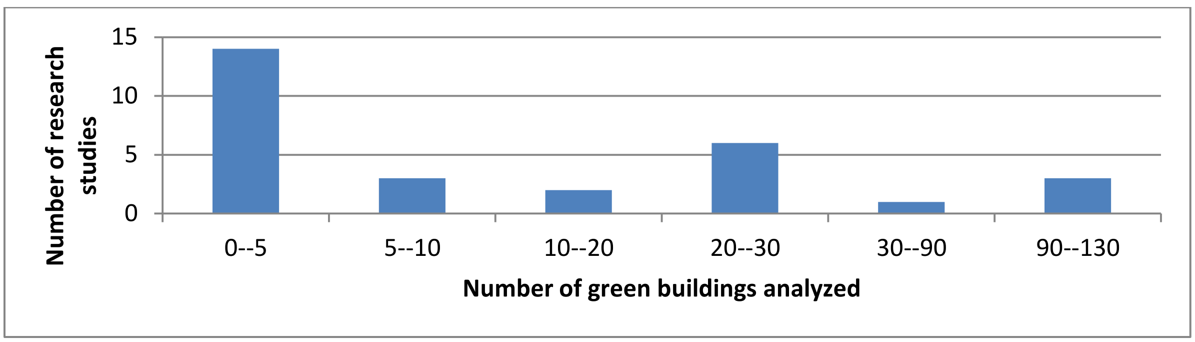


Fig 3: Distribution of research studies per buildings sample size

### 3.4 Building type

Studies were categorized according to the type of buildings investigated. As shown in Figure 4, nine investigated samples of different types of buildings (e.g. Oates and Kenneth 2012, Diamond et al. 2011, Scofield 2009), while the remaining studies focused on one specific type (e.g. Issa et al. 2011, Zhu et al. 2009, Robertson and Higgins 2012). Of those studies, six focused on residential buildings (e.g. Gill et al. 2010), another six focused on academic buildings (Robertson and Higgins 2012), and five focused on commercial buildings (Byrd 2012). Even though focusing on one type of building enables more accurate analyses of the energy efficiency of this specific type, the evaluation of different types of green buildings in one study is also needed to enable meaningful comparisons of these various types. Balancing single-type versus multi-type building research is also needed to identify the sectors and industries that are the largest consumers of energy.

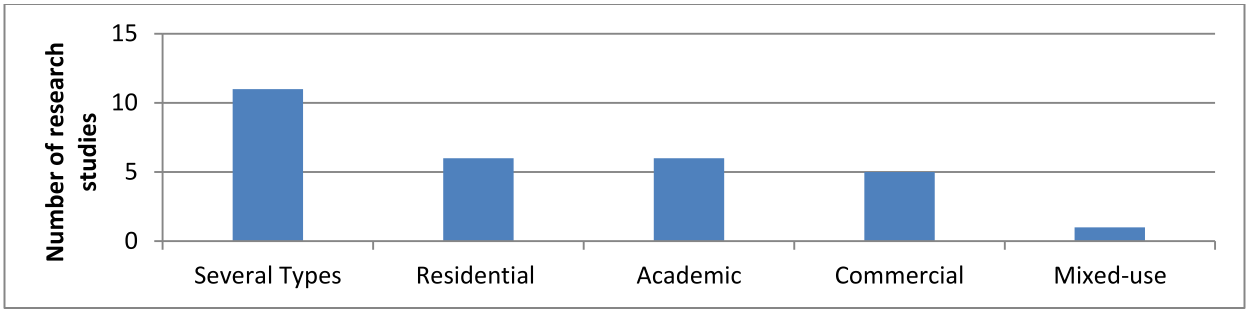


Fig 4: Distribution of research studies per building type

### 3.5 Green rating system

Nine of the identified research studies analyzed Leadership in Energy and Environmental Design (LEED) buildings (e.g. Beauregard et al. 2011, Issa et al. 2011, Kats 2006), bringing the total number of LEED buildings analyzed in these studies to 352. Figure 5 shows the breakdown of these buildings per certification level. Most of the identified LEED buildings were either Certified or LEED Silver buildings. As the number of Platinum buildings constructed to date tends to be small in comparison with other LEED buildings, only ten were Platinum buildings, highlighting the need for more research on them.

The review showed there was little focus on other green buildings rating systems. From the twenty nine studies identified, only one (Gill et al. 2010) analyzed UK EcoHomes buildings. Another (Byrd 2012) assessed a building certified by the New Zealand Excellence green rating system. The remaining studies (e.g. Zhu et al. 2009 and Brunklaus et al. 2010) focused on buildings with green features but not accredited to any specific standards. These results stress the need to consider buildings using other rating systems to enable cross-system comparisons and investigate the effects of every system's requirements on overall building energy consumption.

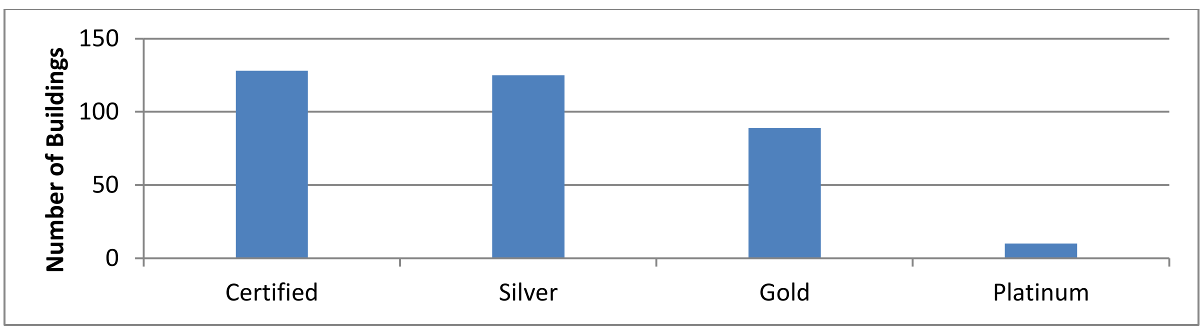


Fig 5: Distribution of LEED buildings investigated in the literature per certification level

### 3.6 Study period

The identified research studies were classified according to the study period over which buildings' energy data was collected. As depicted in Figure 6, 55% of all studies had study periods of two years or less (e.g. Robertson and Higgins 2012, Byrd 2012). Therefore, only six of the reviewed research studies were able to use statistics to test the statistical significance of their findings (e.g. Menassa et al. 2011, Issa et al. 2011, Li et al. 2006). The remaining studies analyzed energy data over two to five years or did not specify the length of their study periods. These short study periods could be due to the relative recent promotion of these buildings and the short time periods they have been operating for. As time progresses and green buildings are available for longer, researchers should be able to collect energy data spanning longer time periods and overcome this existing limitation.

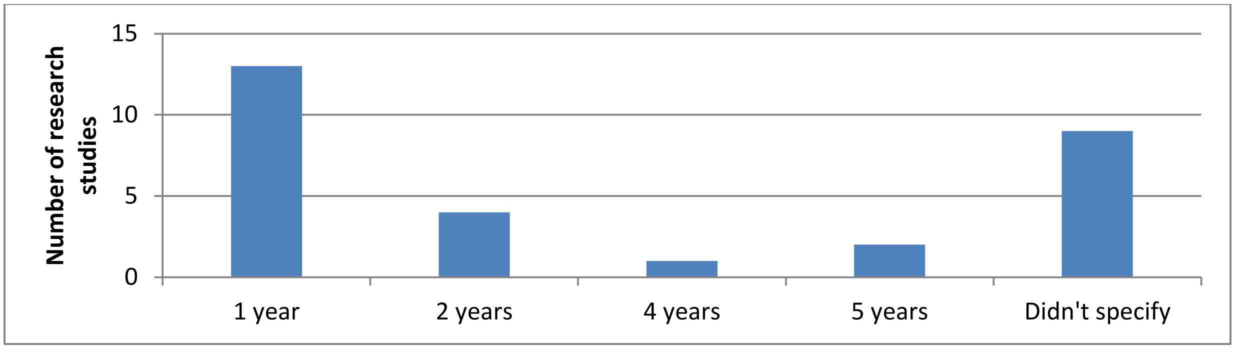


Fig 6: Distribution of research studies per study period

### 3.7 Data collection frequency

The frequency of the data collected was also investigated in each of the studies reviewed. As shown in Figure 7, 10 of the identified studies collected energy data on a monthly basis. Another eight used frequencies varying from semi-annually to minutely whereas the remaining eleven did not specify the frequency of their data. While the use of monthly data seems most common as energy tends to be incurred on a monthly basis in practice, there is still a need to analyze daily, seasonal and annual variations in energy to capture all patterns of change in green buildings' energy levels.

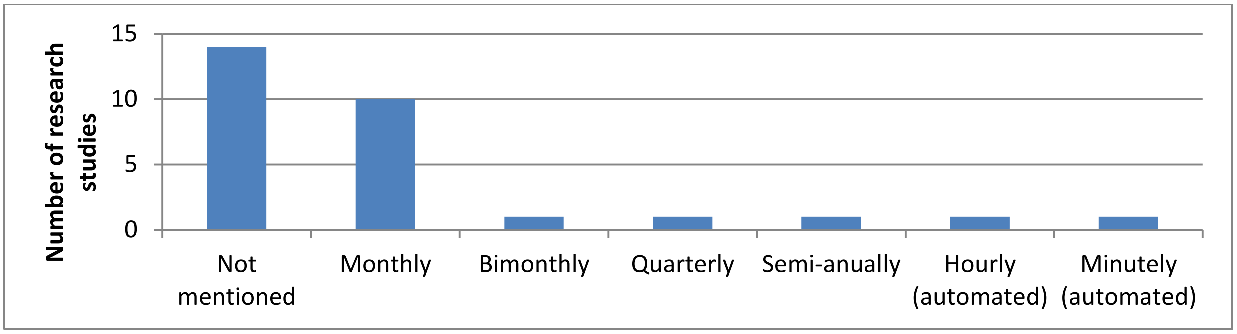


Fig 7: Distribution of research studies per data collection frequency

### 3.8 Data collection method

As shown in Figure 8, research studies collected energy consumption data using a variety of methods. Not surprisingly, the majority used data from utility bills (e.g. Oates and Kenneth 2012, Diamond et al. 2011). Five installed individual meters in each of the buildings analyzed to ensure readings that were reflective of actual energy consumption (e.g. Zhu et al. 2009, Li et al. 2006). Another eleven studies did not indicate their own data collection methods, raising concerns about their accuracy (e.g. Torcellini et al. 2006, Kats 2006). Three studies used second-hand data (e.g. Brunklaus et al. 2010, Scofield 2009, Newsham et al. 2009), relying on data collected by Adalberth et al. (2001) and Turner and Frankel (2008). While the use of the older data was justified in this particular case, there are tremendous risks associated with doing so as the accuracy of any post-occupancy evaluation study is primarily dependant on the accuracy of its data (Flanagan et al. 2005).

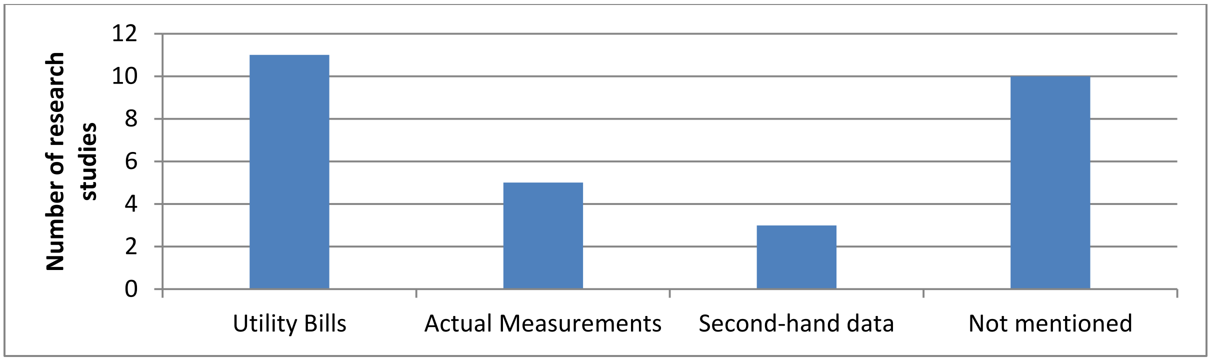

Fig 8: Distribution of research studies per data collection method

### 3.9 Reference dataset

Green buildings' energy performance was determined by comparing their energy consumption data to some other reference data. This reference data varied from one study to another, as shown in figure 9, with some studies occasionally using more than one reference for comparison. Seventeen of the identified studies used energy consumption data of similar conventional buildings for comparison (e.g. Menassa et al. 2011, Issa et al. 2011). Five studies used the national and regional energy consumption averages for commercial buildings provided by the US Commercial Building Energy Consumption Survey (CBECS) as their reference (e.g. Scofield 2002, Newsham et al. 2009), while eleven used design simulations for energy consumption (e.g. Diamond et al. 2011, Beauregard et al. 2011). Some other studies used the same building energy data prior to its energy retrofitting (e.g. Li et al. 2006, Hill et al. 2009)

The reference dataset used by these studies is an important dimension to capture as different datasets can lead to different conclusions for the same study. For example, the average energy consumption of LEED buildings in Arizona was found to be lower than the national average for similar conventional ones (Oates and Kenneth 2012). However, that same average was found to be higher than that of the conventional buildings in the CBECS in comparable climates (Oates and Kenneth 2012). In addition, that same sample performed worse than predicted using modelled energy simulations (Oates and Kenneth 2012). Menassa et al. (2011) showed that while some green buildings consumed less energy than their conventional counterparts, the whole sample was found in general to be less energy-efficient than that of conventional buildings. Scofield (2002) found that even though green buildings' actual energy performance exceeded the one predicted using modelled energy simulations, this performance was still lower than that of some existing similar conventional buildings.

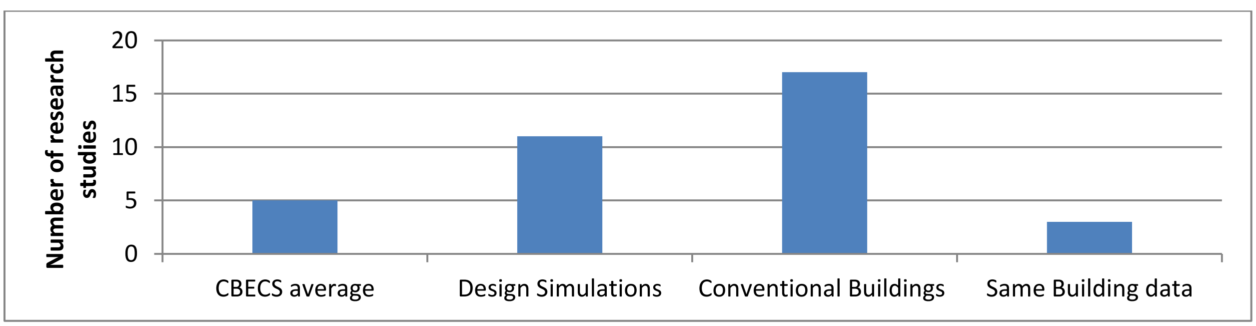

Fig 9: Distribution of research studies per reference dataset used for comparison

### 3.10 Research results

Another important observation is that research results varied widely from one study to another, reflecting a lack of consensus among researchers about green buildings' energy efficiency. A common finding in many studies (Menassa et al. 2011, Diamond et al. 2011 and Newsham et al. 2009) was that the number of LEED points achieved in the energy category did not correlate with the amount of energy consumed by green buildings. Another was that although green buildings consumed less gas and less energy overall than similar conventional buildings, their electricity consumption was higher than conventional buildings' (e.g. Issa et al. 2011, Robertson and Higgins 2012, Menassa et al. 2011). A third finding was that even though most green buildings consumed less energy than their conventional counterparts, a number of larger ones consumed more energy on average (Turner and Frankel 2008), resulting in a sample that consumed more energy overall than the national average (Scofield 2009).

Overall, 17 studies (e.g. Thiers and Peuportier 2011, Kats et al. 2003, Torcellini et al. 2006) concluded that green buildings performed better than predicted or better than other comparable conventional buildings. Seven (e.g. Newsham et al. 2009, Scofield 2002, Scofield 2009) found green buildings did not necessarily perform better than conventional ones, with some in fact performing worse. Other studies, especially those considering occupancy, could not make solid conclusions about their buildings' energy performance (e.g. Menassa et al. 2011, Turner and Frankel 2008). While such variations in research findings are not uncommon, there are many reasons to why this might be the case. Differing problems, goals, methodologies, and outcomes from one study to the other create a host of factors and conditions that lead to differing results. Even though this study has identified some of those factors, researchers need to make a concerted effort to identify them all to investigate the impact of each on final results.

### 3.11 Occupancy

The wide variation in research findings prompts the need to investigate how occupants use green buildings, and how this usage affects their energy consumption. Only seven of the total 29 papers reviewed investigated this aspect.

Four of these studies (Beauregard et al. 2011, Turner 2006, Turner and Frankel 2008, Lenoir et al. 2012) used surveys and face-to-face interviews to do so. Gill et al. (2010) surveyed building occupants' use of personal controls of heating, ventilation and air conditioning and utilized the Theory of Planned Behavior (TPB) to quantify this behaviour and correlate it with measured energy data. It concluded that occupant behaviour explained a total of 51%, 37% and 11% of the variations in a building's heat, electricity and water consumption respectively (Gill et al. 2010).

Other studies relied on more detailed measurement techniques. For example, Menezes et al. (2011) compiled energy data from plug monitors that gave half-hour usage profile of individual computing devices such as computers and printers, and correlated that with the recorded number of occupants at half-hour intervals. The study found a strong correlation between occupants' use of these devices and overall electricity consumption (Menezes et al. 2011). Byrd (2012) relied on the use of blinds in an office building as an indicator of occupancy, with the use of blinds during daytime suggesting an increase in artificial lighting and thus in electricity consumption. The study demonstrated that the use of blinds by building occupants was directly correlated to the building's overall energy consumption (Byrd 2012).

Unfortunately, current research lacks standard performance indicators and evaluation methods to account for the effects of occupants on energy consumption. One possible reason is that human behaviour is difficult to analyze, let alone quantify and measure (Menezes et al. 2011). This makes the need to develop, validate and standardize these indicators and methods a priority to better quantify and measure these aspects.

## 4 Conclusion

Despite its rapid growth, the green building sector is still in its early stages. Providing empirical evidence to the energy efficiency of green buildings during this early period of adoption is critical, thus the importance of research in the field. Reviewing this research to identify its strengths and limitations is also critical, as failure to do so can slow the growth of the green building sector in the near future (Oates and Kenneth 2012).

This literature review was limited by its inability to account for specific aspects such as the age of the buildings investigated and the criteria used to select the building samples in these studies due to a lack of information about them in the papers reviewed. These aspects would have had an impact on the results and as such, they need to be studied carefully. Moreover, although the review attempted to include all the available research, it is possible that some studies may have not been identified. The goal was to demonstrate the current trends in green buildings' energy performance as opposed to the performance of specific green buildings.

The literature review revealed the importance of increasing Canadian capacity to undertake more post-occupancy evaluations of green buildings as research in the field seems to be severely limited in Canada. There is a need for research that would analyze larger building samples, over longer study periods and using actual empirical evidence. There is also a need for larger-scale studies that would evaluate buildings across various regions, in various climates and of different types to provide broader conclusions that can be generalized to larger populations. Although there are no preferences with respect to the frequency of the data analyzed and the reference datasets green buildings should be compared against, it is important that these aspects are standardized as much as possible in future research. Standardizing research methods should facilitate establishing benchmarks about green buildings' energy performance: a priority given the current state of the literature.

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