LOW CARBON LIVING CRC

Do green-rated office buildings save operational energy?

Rapid review of comparative evidence

Milestone Report Activity3

SP0008e1

V1.0

Authors	Malgorzata Lagisz[1,2], Gihan Samarasinghe[2], Shinichi Nakagawa[3], Anir Kumar Upadhyay[4], Faustino De La Peña Suarez[5], Paul Twomey[6] [1] Faculty of Built Environment, Evolution and Ecology Research Centre and School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, New South Wales 2052, Australia m.nakagawa-lagisz@unsw.edu.au [2] School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, New South Wales 2052, Australia; g.samarasinghe@unsw.edu.au [3] Evolution and Ecology Research Centre and School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, New South Wales 2052, Australia; s.nakagawa@unsw.edu.au [4] Faculty of Built Environment, University of New South Wales, Sydney, New South Wales 2052, Australia; anir.upadhyay@unsw.edu.au [5] Faculty of Built Environment, Evolution and Ecology Research Centre and School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, New South Wales 2052, Australia; faustinodelapena@gmail.com [6] CRC for Low Carbon Living, University of New South Wales, Sydney, New South Wales 2052, Australia; p.twomey@unsw.edu.au
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The author(s) confirm(s) that this document has been reviewed and approved by the project's steering committee and by its program leader. These reviewers evaluated its:

- originality
- methodology
- rigour
- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2007),

and provided constructive feedback which was considered and addressed by the author(s).

Abbreviations and Acronyms

BREEAM – Building Research Establishment Environmental Assessment Method

CI – Confidence Intervals for point estimates

EUI – Energy Usage Intensity is expresses a building's energy use as a function of its size or other characteristics, typically expressed as energy (measured in kBtu or GJ) per square foot (total gross floor area of the building) per year

GFA – Gross Floor Area is the total building area (square footage) within the exterior walls of the building

LEED – Leadership in Energy and Environmental Design

lnRR – log response ratio, effect size calculated as the natural logarithm of the ratio between two means

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Executive Summary

Background

It is commonly assumed that buildings certified as "green" or "energy efficient" can save energy at operational stage, especially the buildings that achieved highest certification levels using green rating tools. However, literature shows that not all highly rated buildings consume less energy at operational stage (Oates et al. 2012). The differences in the estimates of energy savings may stem from the methodological quality of the studies comparing certified buildings with other buildings, especially the choice of the comparator group and indicators of energy performance.

Objectives

We aimed to locate and summarise peer-reviewed published empirical evidence for the energy efficiency of new green-rated office buildings. Additionally, we collected information on the time and resources needed to perform this rapid review.

Data sources

Data sources included Scopus, Web of Science and Google Scholar, and snowballing from the included full-text studies.

Study eligibility criteria

We included peer-reviewed studies published in English after 2007 and comparing green-rated buildings to equivalent non-certified buildings.

Study appraisal and synthesis methods

We qualitatively summarised studies that fulfilled our inclusion criteria. We also performed quantitative synthesis via meta-analysis of the effect sizes calculated from comparisons between the mean energy intensity usage of certified and no-certified office buildings. The analyses were performed for the building-weighted and area-weighted site energy usage intensity (EUI) estimates.

Results

We included six peer-reviewed studies that fulfilled our inclusion criteria. All studies were performed in the U.S.A. and comparing LEED-certified buildings with sets of matched non-certified buildings. **Quantitative summary using meta-analysis indicated on average better performance for building-weighted EUI, but no difference between certified and non-certified office buildings in area-weighted EUI.**

Limitations

Only peer-reviewed academic literature in English was included in this review. The search was not fully comprehensive (e.g., specialist databases were not searched), so some relevant studies might have been omitted.

Conclusions and implications

Overall, the evidence was inconclusive as to whether green rated office buildings save operational energy. After initially identifying over 2600 potentially relevant studies, only six studies met the eligibility criteria of this review. This small number of studies limited the statistical power of the analysis.

The results were not robust across the choice of statistical models and method of calculating energy usage intensity. Only one of the four methods of data synthesis resulted in statistically significant difference (indicating an 11% energy saving on average).

The results highlight the need for further research and trials in this space. In improving the selection of matching buildings for this type of analysis, such work could fruitfully interact with the ongoing research agenda on understanding and predicting the energy performance of buildings.

Further systematic review research could also consider the value of including datasets potentially available from the grey literature (reports, theses), as well as non-English literature. Such an approach, although more time consuming, would likely result in a larger and more balanced data set for analyses providing stronger evidence base for drawing conclusions, although care should be taken to assess risk of bias of the estimates.

Registration

The protocol for this review has been preregistered using free Open Science Framework system at *https://osf.io/d49r3/.*

Amendments to the protocol

Non peer-reviewed publications were excluded from the review due to the limited time available. The data items extracted from included papers were modified to better reflect the similarities and differences in the study contents. In particular, we used a different unit of EUI [$kBtu/ft^2/year$], due to all studies being performed in the United States of America. Some of the planned data items (size range of the buildings, occupation duration) were not reported in all or most of the included studies. Data analyses were limited due to the small number of included papers. Only one study separately reported values for the highest-rated buildings.

Introduction

Rationale

Today, a great deal of effort is conducted all over the world in achieving energy efficiency and other sustainable development goals in the building industry. Part of such efforts have been the introduction of various green building rating systems, where a building (or collection of buildings) is graded on a number of measures of best practice in environmental design and management. The sum of the points awarded across these measures determines a level of certification (e.g., Silver, Gold, or Platinum). Prominent examples over the last three decades include Leadership in Energy and Environmental Design (LEED) in the U.S.A., Building Research Establishment Environmental Assessment Method (BREEAM) in the U.K., and Green Star in Australia. Participation is such schemes is usually voluntary.

While most building ratings systems cover a number of environmental issues such as energy, materials, water, emissions and indoor environmental quality, the energy consumption is often used for comparing building performance. Thus, in this review we focus on energy consumption, looking specifically at office buildings.

For many years it has been generally assumed that green rated office buildings do indeed save energy. However, the evidence used to support such claims has often not been based on post-occupancy building energy performance, but rather on energy consumption estimates at design stage, where baseline comparisons may be easily biased by optimistic designer forecasts (Scofield 2013).

This rapid review looks for the research that has adopted more rigorous standards, namely studies that use actual operational energy performance data that allow the comparison of rating certified buildings with sets of matched non-certified buildings.

The rapid review method used in this report allows gathering information on specific research topic relatively quickly, in comparison to full systematic review (Haby et al., 2016). Seeking out and bringing together the highest standard studies allows us to identify scientifically robust results and draw more confident conclusions about the efficacy of green rating building schemes in reducing operational energy.

Objectives

- The main objective of this rapid review was to identify and organise recent peer-reviewed empirical evidence for the energy efficiency of new (not retrofitted) green-rated office buildings. We also aimed to quantify the overall effect size, assess the sources of discrepancies in the existing peer-reviewed literature on the topic.
- The secondary objective of this project was to assess the time and resources needed to perform a rapid review on a topic related to the built environment. Thus, information relevant to the review team's structure, review timeline and associated workloads are also included in this report.

Metrics for comparison

Energy Usage Intensity (EUI) is a derived measurement to represent energy performance of buildings. EUI is calculated by dividing energy usage by the gross floor area of a building (final EUI units are MJ/m^2/year or kBtu/ft^2/year). When calculating mean EUI for a group of buildings, two different approaches of averaging can be followed: (1) building-weighted mean EUI:

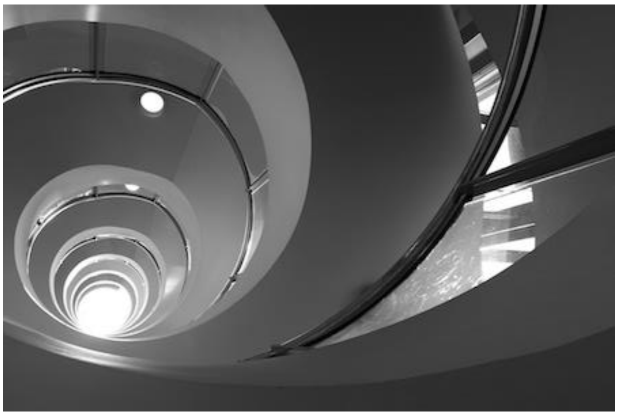
$$\text{EUI} = \frac{\sum_{i=1}^{N} EUI_i}{N},$$

and (2) area-weighted mean EUI:

$$\text{EUI} = \frac{\sum_{i=1}^{N} (EUI_i \times A_i)}{\sum_{i=1}^{N} A_i},$$

where for a group of N buildings having individual gross-areas of $\{A_1,\ A_2, \ldots \ldots\ A_N\}$, individual EUI values are $\{EUI_1,\ EUI_2, \ldots \ldots\ EUI_N\}$.

The building-weighted EUI above is a simple averaging of individual EUI values regardless of the gross-area contribution. Therefore it downplays the effect of large buildings on the total energy consumption of the building stock, since large buildings usually have larger EUI than small buildings (Scofield 2013). Area-weighted EUI is the recommended averaging method for comparison of energy consumption of groups of building, as outlined in *ANSI/ASHRAE/IES Standard 90.1-2013 Determination of Energy Savings, page 64*.



Methods

Eligibility criteria

The following study characteristics were used as inclusion criteria for the review:

1. Studies published in peer-reviewed academic journals
2. Studies published in English
3. Studies published after 2007
4. Studies on office buildings located in developed countries, such as: Australia, New Zealand, U.S.A., Canada and countries from European Union
5. Studies on buildings rated using following schemes: LEED, Green Star (Au/NZ), BREEAM, CASBEE and NABERS
6. Studies comparing rated buildings to a set of equivalent non-certified buildings (similar size, location, age, etc.; not national baselines or building standards)
7. Comparisons are performed for operational buildings (post occupancy) that were not retrofitted
8. Comparisons are made in terms of site energy usage, such as energy usage per unit of gross or conditioned floor area (MJ/m^2/year or kBtu/ft^2/year) and/or per occupant basis (MJ/FTE or kBtu/FTE) (i.e. site load, not net energy).
9. Full text available

Information sources

1. Search engines of Scopus, Web of Science and Google Scholar
2. Snowballing (forward and backward reference screening) from the included studies using Scopus search engine and database

Literature search and study records

To construct search strings, we used combinations of keywords and phrases related to the certification and building type:

Search string for SCOPUS (search date 22/06/2018):

TITLE-ABS-KEY ((office OR workspac*) AND (certif* OR "rated" OR "rating" OR "leed" OR "breeam" OR "Green Star" OR "naebers") AND (energ* OR electricity*)) AND PUBYEAR > 2007 AND (LIMIT-TO (LANGUAGE , "English ")* **[657 hits]**

Search string for Web of Science (search date 22/06/2018):

(TS=((office OR workspac*) AND (certif* OR rated OR rating OR "leed" OR "breeam" OR "Green Star" OR "naebers") AND (energ* OR electricity*) NOT (residential OR retrofit* OR health* OR simulat* OR model*))) AND LANGUAGE: (English)*

Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=2008-2018 **[413 hits]**

Records from Scopus and Web of Science electronic databases were exported to Mendeley reference management software. Two reviewers (GS, FS) independently screened de-duplicated records (titles, abstracts, keywords) using Rayyan platform (Ouzzani et al., 2016) to identify relevant studies using a pre-defined decision tree reflecting the eligibility criteria described in the previous section.

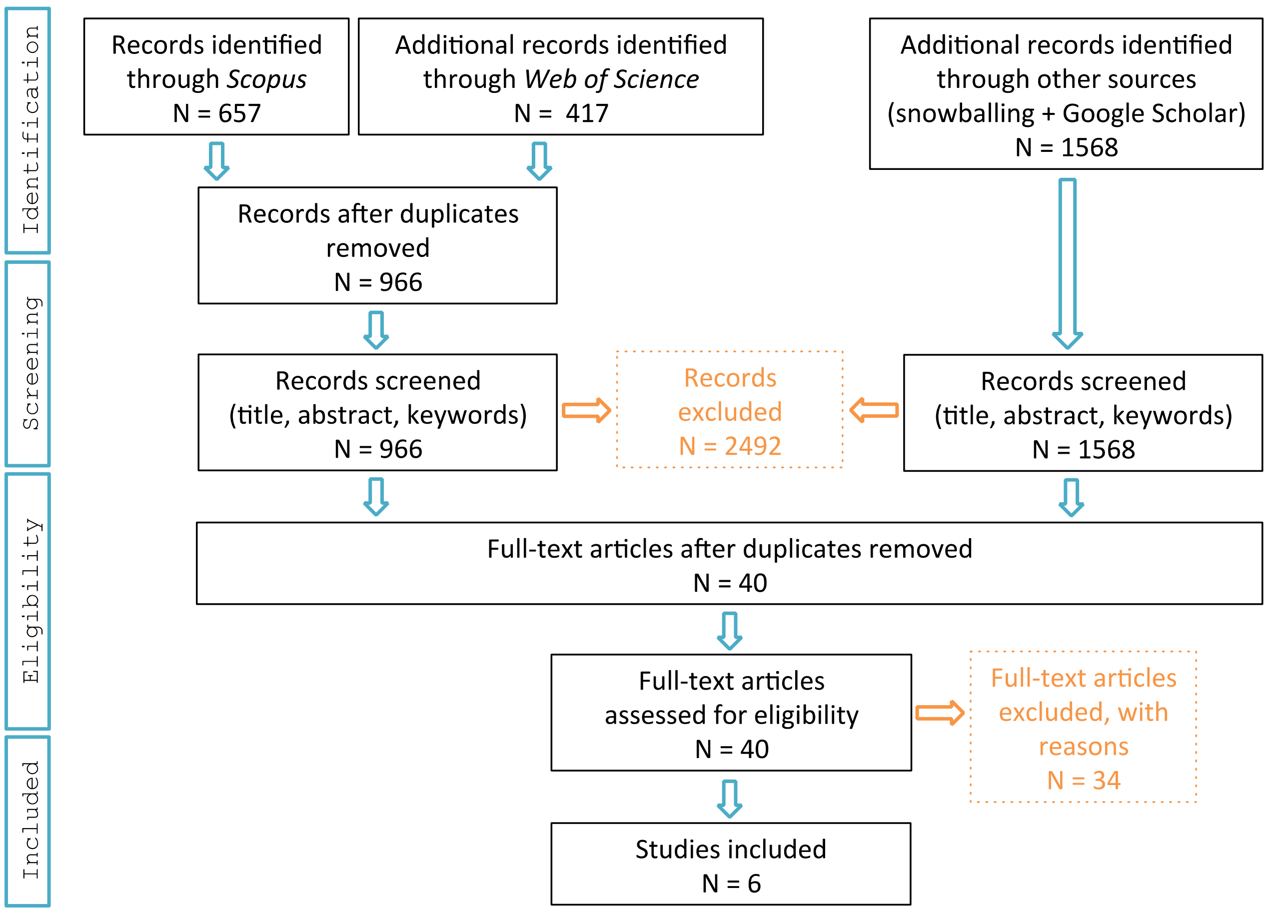
Full papers were retrieved for studies deemed potentially relevant. Two reviewers (FS, GS) independently performed screening of full papers using same criteria for the titles and abstracts, with a third reviewer (ML) resolving any disagreements and checking the final list of included studies and their coding (i.e. data extraction) with another reviewer (AU). Studies deemed suitable for inclusion were then used to perform additional snowballing searches (i.e. forward and backward reference screening, as described above).

In addition, a Google Scholar search was conducted using the following search string:

certified|rated|star|LEED|BREEAM|CASBEE|NABERS occupational|occupancy|performance electricity|energy|load comparative|comparison "office buildings" **[27,900 hits]**

One reviewer (ML) screened the results of this Google Scholar search by looking at the top 60 hits from each year between 2008 and 2018 (660 hits screened in total, 12/07/2018). Finally, ML performed snowballing (i.e. forward and backward reference searches) for the already included reviews and other relevant reviews on the topic (11-14/07/2018, Scopus database, 908 non-unique references screened). The overview of the search and screening process is presented in Figure 1.

Figure 1. PRISMA diagram of the search and screening process



Data items

We extracted the following characteristics for each included study: first author and year of publication, full study reference, main topic, study location (country), type of certification scheme assessed (LEED, GreenStar AU/NZ, BREEAM, CASBEE, NABERS), number of certified buildings from which data was collected, declared sources of study funding and potential conflicts of interests. Table 1 presents the main extracted variables and their values / codes (also used in Table 2 in the Results section). Data extraction was performed by one reviewer (GS, with help from FS) and checked by other reviewers (ML, AU). For each study, we have also recorded overall conclusions and extracted information on the comparisons made between certified and non-certified buildings. This information included additional details on study location (location state and city), certification type, certification level and year for certified buildings, sample sizes, buildings total floor area (gsf = Gross Square Feet, in ft^2), mean and standard deviation of building-weighted EUI [kBtu/ft^2/year], mean and standard deviation of area-weighted EUI (kBtu/ft^2/year), data table or figure number in the original paper. Where data was missing on any of these variables, we attempted to contact the study authors by email asking for information or clarification. As on 28/08/2018, we did not receive any response to our requests. We also looked for the data on the age, occupancy type and period of the compared buildings, but we did not find such data reported in any of the included studies.

Table 1. List of the main study variables extracted and coded for the included studies, with relevant values

Study variable	Description
First Author_year	Key (ID) of the article is created by concatenating the last name of the first author and the year published
Reference	Full publication reference information, including title of the article
Main topic	Main topic addressed in the article
Study location	Country in which compared buildings are located
Certification	Type of certification scheme considered in the study
N certified buildings	Number of certified buildings for which data is reported in the study
Study funding	Funding sources declared in the article
Conflict of interests	Conflicts of interests declared in the article

Outcomes and prioritisation

The main outcome of interest was the comparison of the total energy usage intensity per year between the certified buildings and similar non-certified buildings, with particular interest in the buildings that achieved highest certification levels (gold, platinum, etc., as relevant). We prioritised extraction of data on energy performance measures expressed as actual mean (and standard deviation) energy use on a floor area, and did not extract energy usage (EUI) data per occupant basis, since no such data was reported in the included studies.

Risk of bias of individual studies

We recorded information on study funding sources and conflict of interest statements from the included studies. We also collected information allowing us to assess whether the compared buildings are equivalent in terms of size, age, location/climate, use (operational characteristics), etc., if such information was reported. We attempted to contact the study authors for the missing information. We coded the way the average estimates take into account building size or other potentially confounding variables. We also noted other details and any concerns related to data collection or analysis. We did not find in the included papers information on whether buildings used in analyses were selected randomly or were "self-selected" (building owners agreeing to provide necessary data). Collected information was used for the overall assessment of the methodological quality of the included studies.

Data Synthesis

A qualitative summary is provided in the form of tables and narrative description of the patterns observed in the included studies. Quantitative synthesis (meta-analysis) was performed on the quantitative data extracted from the 6 included studies. When a study reported more than one comparison between certified and non-certified buildings, with partially overlapping subsets of buildings, we selected one comparison that was comparing most similar sets of certified and non-certified buildings in terms of type, size and location. In particular, from the study of Newsham_2009 we chose comparison with conservative climate zone matching and unique pairing, for study by Scofield_2013 we chose comparison of all certified buildings to office buildings in New York City.

Where data was not reported as mean and standard deviations for the groups of certified or non-certified buildings, but the data was reported for individual buildings (Menassa_2012, Tilton_2014), we used this information to calculate means and standard deviations of the groups of certified and matching non-certified buildings. We imputed missing standard deviations of the mean EUI values reported in Oates_2012 by using values from Scofield_2009, which reports similar mean EUI values.

We used log response ratio (*lnRR*) as our effect size, suitable for small sample sizes (Friedrich et al., 2008; Hedges, 1999). This effect size represents the natural logarithm of the ratio between the mean energy usage in the non-certified buildings to the mean energy usage in the certified buildings:

$$lnRR = \ln(\frac{\bar{x}_E}{\bar{x}_C})$$

with the sampling variance:

$$se^2{}_{lnRR} = \frac{sd_C^2}{n_C\,\bar{x}_C^2} + \frac{sd_E^2}{n_E\,\bar{x}_E^2}$$

where $\bar{x}_C$ and $\bar{x}_E$ are the sample means of the control group (*C – certified buildings*) and experimental group (*E – non-certified buildings*), respectively, s_C and s_E are the standard deviations of the two groups, n_C and n_E are the sample sizes of the two compared groups.

Positive values of lnRR indicate lower energy usage in the certified buildings than in non-certified buildings.

The overall meta-analytical estimates of mean values of *lnRR* across studies were also expressed as percentage difference in EUI between the two groups of buildings.

Table 2. List and the main characteristics of the included studies

First Author_year	Reference	Main topic	Study location	Certification	N certified office buildings	Study funding	Conflict of interests
Menassa_2012	Menassa, C., Mangasarian, S., El Asmar, M., & Kirar, C. (2012). Energy consumption evaluation of U.S. Navy LEED-certified buildings. Journal of Performance of Constructed Facilities, 26(1), 46–53. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000218	Measures and analyses energy consumption of 11 LEED-certified buildings vs. similar non-certified buildings.	USA	LEED	2	Construction Engineering and Management graduate students at the University of Wisconsin-Madison, USA	Not declared
Newsham_2009	Newsham, G. R., Mancini, S., & Birt, B. J. (2009). Do LEED-certified buildings save energy? Yes, but... Energy and Buildings, 41(8), 897–905. https://doi.org/10.1016/j.enbuild.2009.03.014	Compares Total energy use intensity (EUI) of LEED-certified vs. non-LEED commercial buildings (including office buildings).	USA	LEED	21	Program of Energy Research and Development, administered by Natural Resources Canada	Not declared
Oates_2012	Oates, D., & Sullivan, K. T. (2012). Postoccupancy energy consumption survey of Arizona's Leed new construction population. Journal of Construction Engineering and Management, 138(6), 742–750. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000478	Compares energy performance of LEED-certified buildings non-LEED buildings (including office buildings) and national average values.	USA	LEED	5	Not declared	Not declared
Scofield_2009	Scofield, J. H. (2009). Do LEED-certified buildings save energy? Not really... Energy and Buildings, 41(12), 1386–1390. https://doi.org/10.1016/j.enbuild.2009.08.006	Compares energy usage and savings of LEED-certified vs. non-LEED buildings.	USA	LEED	35	Not declared	Not declared
Scofield_2013	Scofield, J. H. (2013). Efficacy of LEED-certification in reducing energy consumption and greenhouse gas emission for large New York City office buildings. Energy and Buildings, 67, 517–524. https://doi.org/10.1016/j.enbuild.2013.08.032	Compares greenhouse gas emission values of LEED-certified New York office buildings vs. non-LEED office buildings.	USA	LEED	21	Not declared	Not declared
Tilton_2014	Tilton, C., & El Asmar, M. (2014). Assessing LEED versus Non-LEED energy consumption for a university campus in North America: A preliminary study. In ICSI 2014: Creating Infrastructure for a Sustainable World - Proceedings of the 2014 International Conference on Sustainable Infrastructure (pp. 1071–1076). https://doi.org/10.1061/9780784478745.101	Compares energy usage values of LEED-certified vs. non-LEED student housings, office buildings and research facilities in a university campus in North America.	USA	LEED	2	Not declared	Not declared

Table 3. Overview of the quantitative data extracted from the included studies

N – sample size, EUI – Energy Usage Intensity [kBtu/ft²/year], NA – not available

Study_ID	Comparison description	**Certified buildings**				**Non-Certified buildings**				Data sources
		N	Total area [ft²]	Building-weighted EUI [mean ± SD]	Area-weighted EUI [mean ± SD]	N	Total area [ft²]	Building-weighted EUI [mean ± SD]	Area-weighted EUI [mean ± SD]	
Menassa_2012	LEED-rated silver and gold U.S. Navy administration office vs. CBECS data for similarly functional buildings	2	54243	48.4 ± 25.8	55.5 ± 16.8	2	14955	93.6 ± 277.2	112.7 ± 146.7	Individual data from Table 1 and Table 3 in the original paper.
Newsham_2009	LEED certified U.S.A. office buildings, pairwise-matched, unique paring, conservative climate zone matching	21	NA	70.2 ± 28.2	NA	21	NA	111.5 ± 60.6	NA	Data from Table 6 in the original paper.
Oates_2012	LEED certified U.S.A. office buildings vs. non-rated buildings from CBECS	5	1448059	NA	73.5 ± 3.4	10	12208000	NA	72.6 ± 8.4	Data from Table 4 and Table 5 in the original paper. Imputed SD values using the values from Scofield_2009, which has similar mean values.
Scofield_2009	LEED certified U.S.A. office buildings vs. non-rated buildings from CBECS selected using liberal matching with non-unique paring	35	5303460	67.8 ± 4.2	77.1 ± 3.4	27	5196100	97 ± 8.7	80.7 ± 8.4	Data from Table 2 in the original paper.
Scofield_2013	LEED certified+ buildings vs. office buildings in New York city	21	21600000	98 ± 5.9	106 ± 6.5	953	308000000	97 ± 2.0	103 ± 1.7	Data from Table 1 and Table 2 in the original paper.
Tilton_2014	LEED certified+ university office buildings vs. non-certified university office buildings	2	NA	91.7 ± 27.7	NA	6	NA	88.6 ± 27.6	NA	EUI calculated from data extracted from Figure 2 for individual buildings.

Table 4. Summary of conclusions for the included studies

First Author_year	Study conclusions	Comments
Menassa_2012	Nine out of 11 LEED-certified USN buildings of mixed type did not achieve the expected energy consumption savings of 30%. Most of the certified buildings consumed more energy than matched CBECS buildings. The authors found no evidence that buildings with higher certification levels perform better than these with the lower certification levels. There was also weak relationship between the number of energy credits and performance.	For our analyses we only used data from 2 office-type buildings from this paper (buildings nr 6 and 9 in Tables 1 and 2). One of these two office buildings performed 14.66% better in terms of electricity usage than similar non-certified building, while the other one performed 127.75% worse (reflected in large standard deviation of the mean estimate).
Newsham_2009	On average, LEED-certified commercial buildings used 18-39% less energy per floor area than matched non-certified buildings. However, there was large variation among the buildings, with 28-35% actually showing higher energy usage. Certified office buildings on average were found to consume 38-44% less energy than non-certified buildings. There was no effect of certification level or number of energy credits awarded to individual certified buildings across the whole dataset.	For our analyses we only used data for the 35 office buildings, out of 100 commercial buildings. In the original paper four different comparisons were performed for the office building subsets using various matching strategies (Table 6). For our main analyses we prioritized comparison using conservative climate zone matching and unique pairing of the buildings.
Oates_2012	Overall, a mix of Arizona LEED NC rated buildings performed slightly better than comparable CBECS buildings within comparable climates in terms of site EUIs, however, the results varied by building type and size. The 10 office buildings in this dataset were concluded to be 1% less efficient than comparable zone 5 CBECS buildings in terms of site EUI. The paper indicates that facility management deficiencies within LEED buildings can contribute to the underperformance of many rated buildings.	For our analyses we only used data on the comparison between office buildings in Arizona climate zone 5 LEED NC Certified and comparable non-rated CBECS buildings (GSF and climate zone adjusted), basing on the data presented in Tables 4 and 5 and imputed missing values of standard deviations.
Scofield_2009	Building-weighted comparisons show significant energy savings in certified buildings relatively to non-certified buildings, while area-weighted means comparisons show no difference. The authors conclude that while small offices are more likely to be more energy efficient, the effect of big energy-inefficient office buildings results in the total energy consumption of the certified buildings to be similar to that of non-certified buildings.	Non-rated buildings from CBECS database were selected using liberal matching with non-unique paring for comparisons. For our analyses we used site-energy (case A) data from Table 2.
Scofield_2013	The authors conclude that the 21 certified large office buildings located in New York are not more energy efficient than the similar non-certified office buildings. However, when they analysed the subset of gold-certified buildings they found 20% better performance. The authors perform additional comparisons of certified buildings versus four other subsets of non-certified buildings from CBECS.	For our analyses we extracted data from Tables 1 and 2. We prioritised comparison of all LEED certified office buildings vs. office buildings in New York city.
Tilton_2014	Preliminary conclusions of the presented analyses indicate no difference in energy usage between certified and non-certified university office buildings. The authors suggest looking at the factors that influence energy consumption, such as building usage intensity and number of certification points.	For our analyses we used data from two LEED certified (silver and gold) university office buildings vs. two non-certified university office buildings extracted from Figure 2.

We performed all statistical analyses using R package *metaphor* v2.0-0 (Viechtbauer, 2010) in R environment version 3.3.3 (2017-03-06). We run both fixed-effect and random-effects meta-analytic models (standard basic models in meta-analytic research).

Meta-analytic models were run on calculated effect sizes using data for all certified buildings, regardless of their level of certification. We were not able to run meta-analyses comparing buildings with highest certification levels to non-certified buildings, because only one study (Scofield_2009) provided separate data for highest (gold) rated buildings. Since the energy usage intensity was reported either as building-weighted EUI [kBtu/ft^2/year] or area-weighted EUI [kBtu/ft^2/year], or as both, we performed two analyses with these alternative measures of building energy usage, as available.

We report mean effect sizes as our point meta-analytic estimates and their 95% Confidence Intervals (CI). We considered the point effect estimates statistically significant when their CI did not cross zero. R code and data files are available at *https://github.com/mlagisz/MA_building_certification*.

Meta-bias(es)

Our data set comprised only six studies: for our two main meta-analytical models (for building-weighted EUI and area-weighted EUI), we had only 5 and 4 data points available, respectively. Thus, it was not possible to formally assess publication bias using funnel plots and Eggers regression.

RESULTS

Overview of the included studies

The final study list included six studies published between 2009 and 2014 that fulfilled our inclusion criteria. Table 2 provides an overview of these studies, including publication details, main topic, location, types of certification scheme, number of certified buildings considered, funding and conflict of interests.

All studies were performed in the U.S.A. and comparing LEED-certified buildings with non-certified buildings (Table 2). Table 3 contains a summary of the extracted data, while Figure 2 illustrates available data in terms of the numbers of compared certified and non-certified buildings, their average floor area, building-weighted and area-weighed energy usage intensity. Table 4 provides a short description of conclusions drawn by the authors of each included study.

Quantitative summary

Overall, the included studies were inconclusive as whether certified buildings use less energy than non-certified buildings, and suggest that the answer may depend how the mean values per building group are calculated.

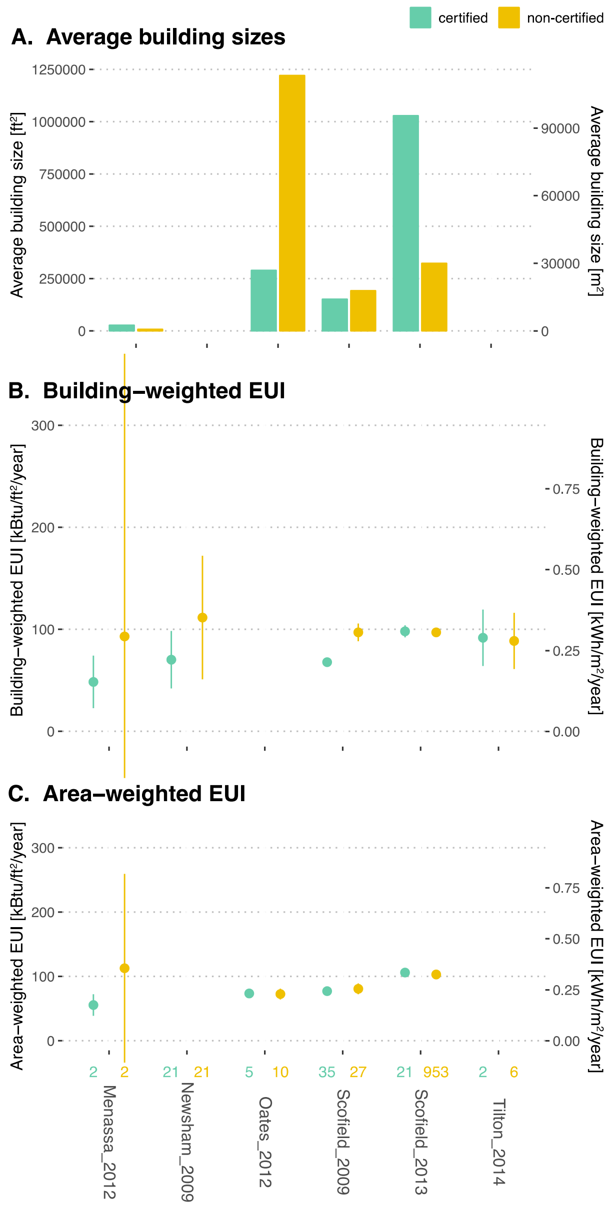


Figure 2. Visual data summary.

Key values are shown for certified (green) and non-certified (orange) office buildings from the six included original studies. Numbers at the bottom of the graph (above study IDs) indicate number of buildings per each compared group.

A. Average area of included buildings calculated as their total area divided by the numbers of office buildings in a group (total area data was not reported in Newsham_2009 and Tilton_2014).

B. Mean (point) and standard deviation (whiskers) building-weighted energy usage intensity of included office buildings (relevant values were not reported in Oates_2012).

C. Mean (point) and standard deviation (whiskers) area-weighted energy usage intensity of included office buildings (relevant values were not reported in Newsham_2009 and Tilton_2014).

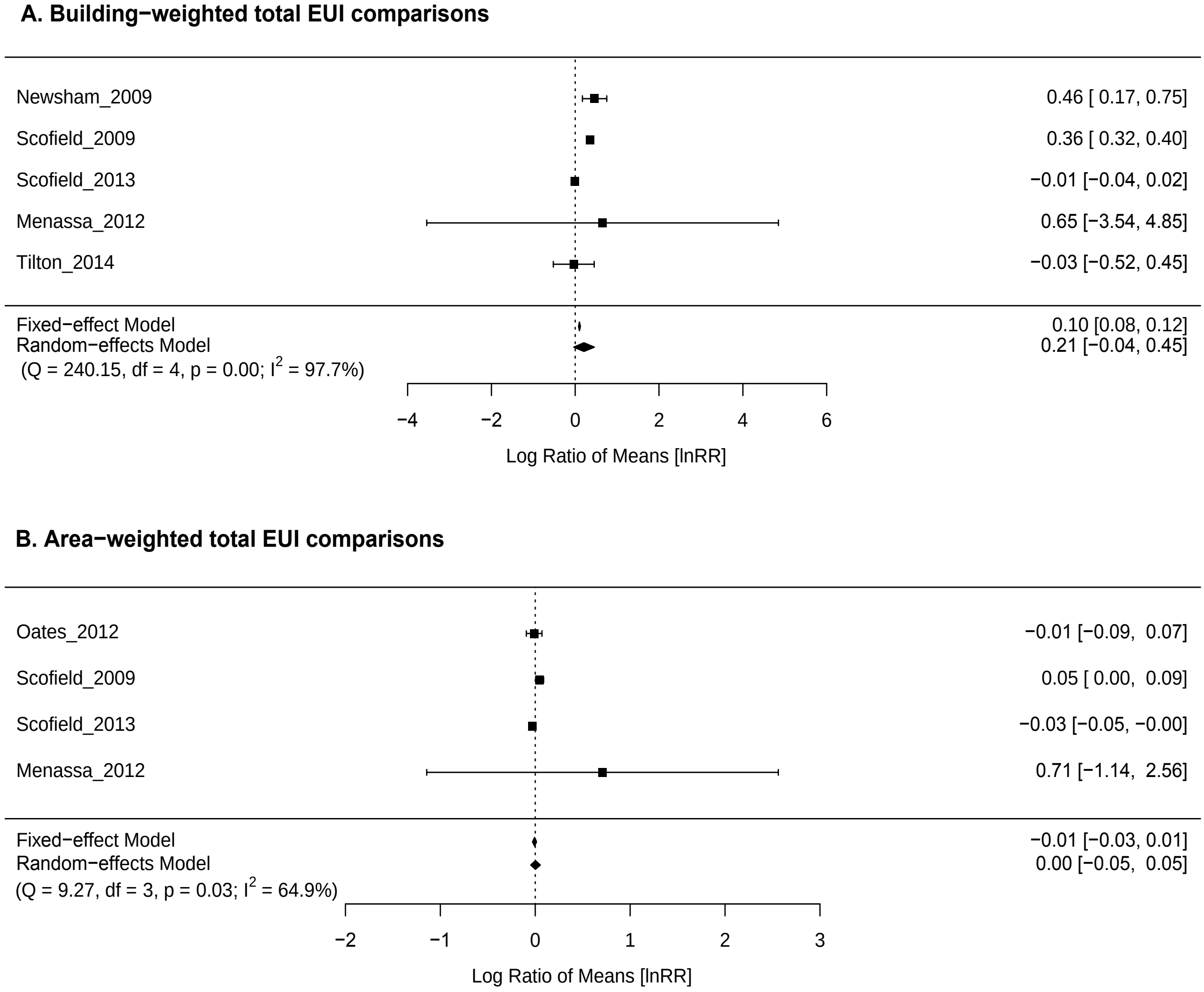


Figure 3. Results of a meta-analysis

Meta-analytical means for the building-weighted EUI, based on effect sizes from 5 studies, indicated 11% (fixed-effect model) and 23% (random-effects model) less energy consumption per unit of area in the certified buildings relatively to the non-certified buildings (Figure 2 A). However, this second estimate (23%) was statistically not different from zero (i.e. there is no statistically significant difference at 95% confidence level between the two groups of buildings).

Meta-analytical mean for the area-weighted EUI was based on effect sizes from only 4 studies and clearly showed no difference in energy consumption per unit of area in the certified buildings relatively to the non-certified buildings. (-0.8% in fixed-effect and 0.2% in random-effects model) (Figure 2 B).

Quality, risk of bias and confidence in cumulative evidence

The included studies ranged from preliminary works with small sample sizes (two certified buildings; Menassa_2012; Tilton_2014) to extensive and in-depth analyses on relatively large data sets (Newsham_2009; Scofield_2013). Notably, Menassa_2012 included two office buildings with starkly different energy performances relatively to the matched buildings, which resulted in large variance for the point estimate from this study.

None of the studies reported or considered in their analyses information on variables such as building occupancy, usage patterns, selection bias, etc., which could help explain variation observed in the aggregated data set. Other details, particularly these related to risk of bias was often missing, e.g., statements on study funding or potential conflicts of interests (Table 2). Thus, there is clearly scope for improving reporting quality of the original studies, including more details and providing easy and open access to the raw data for re-analyses.

Overview of the excluded studies

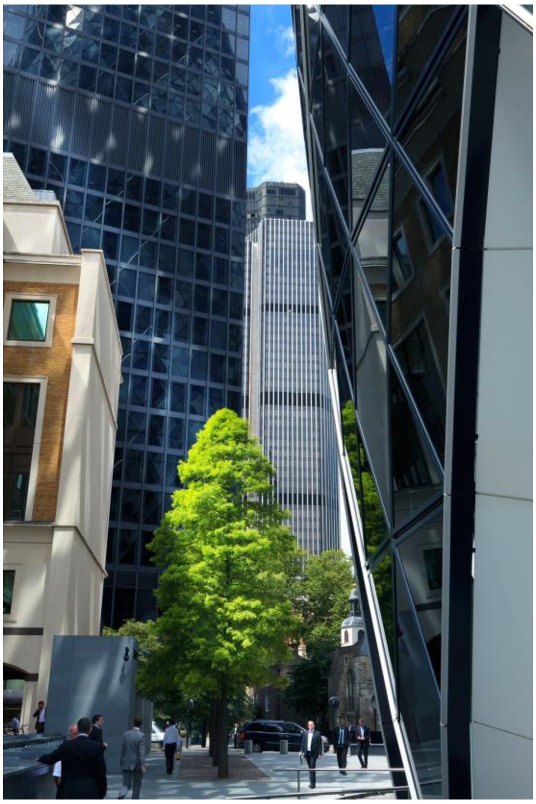
Table S2 presents the list of studied excluded after full-text screening, alongside the reasons for exclusion. Most of these studies were excluded because they either described performance of a single building, did not focus specifically on office buildings (or presented a data for a office-buildings subset in an extractable format), did not compare the buildings in terms of energy usage intensity, only compared certified buildings to national standards or baseline values, only reviewed certification schemes or design practices, etc. Nevertheless, some of the excluded papers can still provide useful insights that are relevant to how the buildings are certified or assessed for their energy usage or how better energy efficiency can be achieved in the office buildings.

Review Limitations

Our literature search was not fully comprehensive and some relevant papers might have been missed. We included only peer-reviewed studies. Thus, we did not include grey literature (e.g., theses, reports, reviews of technology or case studies) that could potentially provide additional data. We only included studies published in English.

Limited number of included studies and small numbers of buildings considered in some of the included studies can influence the reliability of the conclusions drawn form this review. Finally, some of the information necessary for assessing study quality and risk of bias was not reported in the original papers.

Our data set is restricted to six studies on buildings located in the U.S.A. and assessed under LEED schemes. Because of this, one should not extend our conclusions to the buildings in other countries and to other certification schemes.



Summary and conclusions

In this rapid review, we drew on primary literature to determine whether there is evidence that on average green-certified office buildings are more energy efficient than similar non-certified office buildings, especially for the high levels of certification. Given that designing for reduced energy consumption is a significant element of building rating schemes, one would expect to see evidence for such reductions.

After initially identifying over 2600 potential relevant studies, the search and screening process resulted in only six studies that met the pre-defined eligibility criteria. All these studies were located in the U.S.A and were, therefore, examining the effectiveness of the LEED rating scheme. Unfortunately, we were unable to conduct any comparison or aggregation with other rating schemes such as Green Star, BREEAM, CASBEE and NABERS in other countries.

The number of certified office buildings used in the analyses was small and ranged from two (in two studies) to 35. Five of the studies provided data on building-weighted mean EUI and four studies on area-weighted mean EUI.

The conclusions of the six included studies ranged from the certified buildings performing worse, similarly or much better than the non-certified buildings in terms of energy usage intensity. Two papers noted the high variation in performance among the included certified buildings, and weak or no relationship with the certification level or number of energy credits (Menassa_2012, Newsham_2009). One study (Scofield_2013) found 20% better performance in a subset of gold-certified buildings.

When aggregating the results in a meta-analysis for each EUI calculation method, we found similarly mixed results. Two meta-analytical means for the building-weighted EUI, based on effect sizes from 5 studies, indicated 11% and 23% (the latter statistically non-significant) less energy consumption per unit of area in the certified buildings relatively to the non-certified buildings. However, two meta-analytical means for the area-weighted EUI, based on effect sizes from 4 studies, showed no difference in energy consumption.

We chose not to limit the analysis to one particular set of data aggregation techniques, since there does not currently appear to be a consensus on the most suitable choices and it would have reduced the size of available data even further. The lack of robustness in the results across the different analysis techniques was undoubtedly in part due to the small number of available studies that reported relevant data.

Of course, even finding solid evidence as to positive energy savings from implementing green building rating schemes would be only one element towards concluding whether such schemes are economic. A full cost-benefit analysis would be required to answer this. Conversely, negative evidence on energy savings would not necessarily condemn green rating schemes, as there are many other potential benefits from such schemes including savings in materials, water and waste, and higher productivity and increased occupant health and productivity.

The results of our review have highlighted the need for further research and trials in this space. In improving the selection of matching buildings for this type of analysis, this work could fruitfully interact with the ongoing research agenda on understanding and predicting the energy performance of buildings (including how it is affected by building codes and rating schemes). This is a notoriously complex area, affected by numerous variables such as ambient weather conditions, building structure and characteristics, types of lighting and HVAC systems, occupancy numbers & hours and other behaviours. The literature is well aware of the frequently observed gap between predicted energy performance and observed energy outcomes and is seeking to identify the causes of this gap (Zhao and Magoulès, 2012). Such work could be valuable for matched-building analyses of the type examined in this review.

Further systematic review research could also consider the value of including data sets potentially available from the grey literature (reports, theses), as well as non-English literature. Such an approach, although more time consuming, would likely result in a larger and more balanced data set for analyses, providing stronger evidence base for drawing conclusions on the performance of green-rated office buildings.

Resources, workload and timeline

Figure 4. Review team members

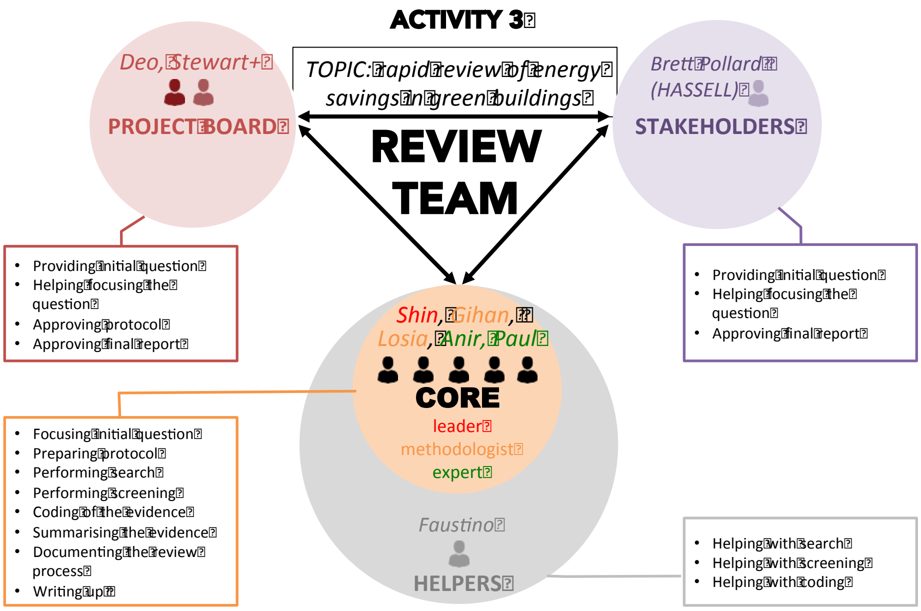


Figure 5. Review timeline

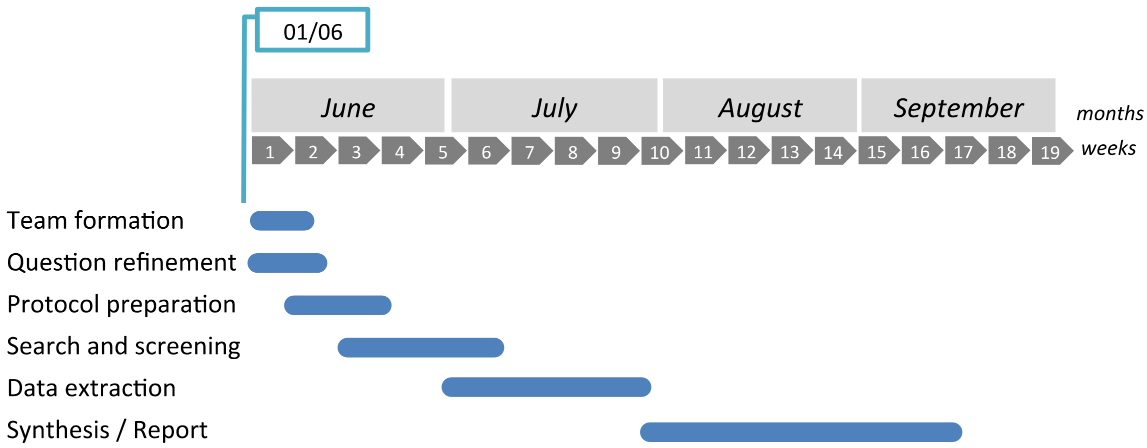


Table 5. Workloads (in hours) of the team members for each main review stage

Review Stage	ML	GS	FS	SN	PT	AU	Total	Comments
Team formation	2	2		1		1	6	
Question refinement	3	3		1		1	8	
Protocol preparation	6	1		1		1	9	
Search and screening	9	26	8	1			44	
Data extraction	5	25	5			2	37	
Synthesis / Report	24	2		4	10	7	47	
Total	**49**	**59**	**13**	**8**	**10**	**12**	**151**	

Supplementary Information

Table S1. Table of snowballing results

Snowballing from: First Author_year	Snowballing from: Title	N citing papers screened	N cited papers screened	N total screened	N papers selected for checking full-text
Cooperman_2010	Cooperman, A., Dieckmann, J., & Brodrick, J. (2010). Building energy labels. ASHRAE Journal, 52(11), 54–56.	0	14	14	0
Elliott_2011	Elliott, J., & Guggemos, A. (2011). Validating electric use intensity in multi-use buildings. Journal of Facilities Management, 9(1), 52–63.	1	9	10	0
Menassa_2012	Menassa, C., Mangasarian, S., El Asmar, M., & Kirar, C. (2012). Energy consumption evaluation of U.S. Navy LEED-certified buildings. Journal of Performance of Constructed Facilities, 26(1), 46–53.	34	22	56	4
Newsham_2009	Newsham, G. R., Mancini, S., & Birt, B. J. (2009). Do LEED-certified buildings save energy? Yes, but... Energy and Buildings, 41(8), 897–905.	249	17	266	4
Oates_2012	Oates, D., & Sullivan, K. T. (2012). Postoccupancy energy consumption survey of Arizona's Leed new construction population. Journal of Construction Engineering and Management, 138(6), 742–750.	19	17	36	0
Scofield_2009	Scofield, J. H. (2009). Do LEED-certified buildings save energy? Not really... Energy and Buildings, 41(12), 1386–1390.	145	8	153	4
Scofield_2013	Scofield, J. H. (2013). Efficacy of LEED-certification in reducing energy consumption and greenhouse gas emission for large New York City office buildings. Energy and Buildings, 67, 517–524.	64	25	89	1
Tilton_2014	Tilton, C., & El Asmar, M. (2014). Assessing LEED versus Non-LEED energy consumption	1	5	6	0

	for a university campus in North America: A preliminary study. In ICSI 2014: Creating Infrastructure for a Sustainable World - Proceedings of the 2014 International Conference on Sustainable Infrastructure (pp. 1071–1076).				
Doan_2017	Doan, D.T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ghaffarianhoseini, A., John Tookey, J. (2017). A critical comparison of green building rating systems. Building and Environment 123: 243-260	137	15	152	0
Li_2017	Li, Y., Chen, X., Wang, X., Xu, Y., Chen, P. (2017). A review of studies on green building assessment methods by comparative analysis. Energy and Buildings 146: 152-159.	46	10	56	0
Shan_2018	Shan, M., Hwang, B. (2018). Green building rating systems: Global reviews of practices and research efforts. Sustainable Cities and Society 29: 172-180.	69	1	70	0
Total:		765	143	872	13

Table S2. Table of the excluded studies at the full-text screening stage, with reasons

First Author_year	Reference	PDF available	Reason for exclusion
Agdas_2015	Agdas, D., Srinivasan, R. S., Frost, K., & Masters, F. J. (2015). Energy use assessment of educational buildings: Toward a campus-wide sustainable energy policy. Sustainable Cities and Society, 17, 15–21. https://doi.org/10.1016/j.scs.2015.03.001	yes	Analysis of energy usage of 10 LEED-certified buildings and 14 non-LEED certified buildings within a university in US. Office buildings are not specifically selected.
Altomonte_2013	Altomonte, S., & Schiavon, S. (2013). Occupant satisfaction in LEED and non-LEED certified buildings. Building and Environment, 68, 66–76. https://doi.org/10.1016/j.buildenv.2013.06.008	yes	Only draws data related to indoor environment effects on occupant satisfaction.
Altomonte_2017	Altomonte, S., Saadouni, S., Kent, M. G., & Schiavon, S. (2017). Satisfaction with indoor environmental quality in BREEAM and non-BREEAM certified office buildings. Architectural Science Review, 60(4), 343–355. https://doi.org/10.1080/00038628.2017.1336983	yes	Only draws data related to indoor environment quality and surveys on occupant satisfaction
Bannister_2017	Bannister, P., & Zhang, H. (2017). Load Resilience in High Performance Buildings. In Procedia Engineering (Vol. 180, pp. 261–271). https://doi.org/10.1016/j.proeng.2017.04.185	yes	Only focuses on occupancy of NABERS rated buildings.
Birchall_2008	Birchall, S. J., & Tinker, J. A. (2008). A post occupancy evaluation of a BREEAM " excellent " rated office building in the UK. Building, (Bre 2009), 683–690.	yes	Focuses on in-use performance of a 'green' office building located in the UK that was awarded a BREEAM 'Excellent' rating of 87.55%.
Byrd_2011	Byrd, H., & Leardini, P. (2011). Green buildings: Issues for New Zealand. Procedia Engineering, 21, 481–488. https://doi.org/10.1016/j.proeng.2011.11.2041	yes	Discusses on several aspects that needs to be addressed in building rating tools for New Zealand.
Chokor_2016_a	Chokor, A., El Asmar, M., Tilton, C., & Srour, I. (2016). Dual Assessment Framework to Evaluate LEED-Certified Facilities' Occupant Satisfaction and Energy Performance : Macro and Micro Approaches. Journal of Architectural Engineering, 22(4). https://doi.org/10.1061/(ASCE)AE.1943-5568.0000186.	yes	Energy consumption data of LEED-certified buildings within Arizona State University are compared to their counterparts. Office buildings are not specifically selected.
Chokor_2016_b	Chokor A, El Asmar M. A novel modeling approach to assess the electricity consumption of LEED-certified research buildings using big data predictive methods. InConstruction Research Congress 2016 2016 (pp. 1040-1049).	yes	Seven years of energy metering information of 5 LEED-certified facilities and 13 non-LEED facilities within a university campus are analysed. Office buildings are not specifically selected.
Chokor_2017	Chokor, A., & El Asmar, M. (2017). Data-Driven Approach to Investigate the Energy Consumption of LEED-Certified Research Buildings in Climate Zone 2B. Journal of Energy Engineering, 143(2), 5016006. https://doi.org/10.1061/(ASCE)EY.1943-7897.0000405	yes	Energy metering data for 5 LEED-certified facilities and 13 non-LEED facilities within a university campus are analysed. Office buildings are not specifically selected.

Cooperman_2010	Cooperman, A., Dieckmann, J., & Brodrick, J. (2010). Building energy labels. ASHRAE Journal, 52(11), 54–56.	yes	Provides comparative average energy usage and CO2 emission values for ENERGY STAR or LEED rated building vs. non-rated buildings. However comparison group is not specifically selected to match rated buildings, and also percentage energy consumption only is compared.
Dobiás_2014	Dobiás, J., & Macek, D. (2014). Leadership in Energy and Environmental Design (LEED) and its impact on building operational expenditures. Procedia Engineering, 85, 132–139. https://doi.org/10.1016/j.proeng.2014.10.537	yes	Operational costs of LEED-certified buildings only, are analysed.
Egan_2012	Egan, A. M. (2012). Occupancy of Australian office buildings: How accurate are typical assumptions used in energy performance simulation and what is the impact of inaccuracy. In ASHRAE Transactions (Vol. 118, pp. 217–224). Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84865047549&partnerID=40&md5=b81b3fc019aab62c90f7cdd56d7bd2ce	yes	Focuses on occupancy of NABERS rated buildings.
Eisenstein_2017	Eisenstein, W., Fuertes, G., Kaam, S., Seigel, K., Arens, E., & Mozingo, L. (2017). Climate co-benefits of green building standards: water, waste and transportation. Building Research and Information, 45(8), 828–844. https://doi.org/10.1080/09613218.2016.1204519	yes	Only water usage and greenhouse gas emission of LEED-certified buildings are compared to baseline buildings.
Elliott_2011	Elliott, J., & Guggemos, A. (2011). Validating electric use intensity in multi-use buildings. Journal of Facilities Management, 9(1), 52–63. https://doi.org/10.1108/14725961111105727	yes	Compares energy usages of one LEED and ENERGY STAR rated high school building against one non-rated high school building. Office buildings are not specifically selected
Gabe_2016	Gabe, J. (2016). Successful greenhouse gas mitigation in existing Australian office buildings. Building Research and Information, 44(2), 160–174. https://doi.org/10.1080/09613218.2014.979034	yes	Energy usage and greenhouse gas emission of Australian NABERS rated building only, are assessed.
Gómez_2014	Gómez, P., Moore, B., & Regojo, C. (2014). Miami dade county moving forward, sustainable buildings program. Strategic Planning for Energy and the Environment, 33(3), 48–60. https://doi.org/10.1080/10485236.2014.10781521	yes	Only discusses about design processes of sustainable buildings.
Heidarinejad_2014	Heidarinejad, M., Dahlhausen, M., McMahon, S., Pyke, C., & Srebric, J. (2014). Cluster analysis of simulated energy use for LEED certified U.S. office buildings. Energy and Buildings, 85, 86–97. https://doi.org/10.1016/j.enbuild.2014.09.017	yes	Only analyses the energy usage patterns of LEED certified buildings, no comparison is included.
Hossaini_2013	Hossaini, N., & Hewage, K. (2013). Emergy-based Sustainability Rating System for Canadian Construction Projects. Emergy Synthesis 7, 2012,	yes	Discusses about current building rating systems available for

	159–166.		Canada.
Keeton_2010	Keeton, J. M. (2010). The road to platinum using the usgbc's leed-eb® green building rating system to retrofit the U.S. Environmental protection agency's region 10 park place office building. Journal of Green Building, 5(2), 55–75. https://doi.org/10.3992/jgb.5.2.55	yes	Analysis of single LEED platinum rated building.
Khosrowpour_2016	Khosrowpour, A., Duzener, T., Taylor, J. E., Perdomo-Rivera, J. L., Gonzáles-Quevedo, A., del Puerto, C. L., … Molina-Bas, O. I. (2016). Meta-Analysis of Eco-Feedback-Induced Occupant Energy Efficiency Benchmarked with Standard Building Energy Rating Systems. In Construction Research Congress 2016: Old and New Construction Technologies Converge in Historic San Juan - Proceedings of the 2016 Construction Research Congress, CRC 2016 (pp. 1192–1201). https://doi.org/10.1061/9780784479827.120	yes	This includes a literature review of residential and commercial feedback of different building types, and a meta-analysis of LEED guided energy efficiency of the same building types.
Kim_2008	Kim, J., Augenbroe, G., & Suh, H. (2008). COMPARATIVE STUDY OF THE LEED AND ISO-CEN BUILDING ENERGY PERFORMANCE RATING METHODS College of Architecture , Georgia Institute of Technology , Atlanta , GA , US POSCO Engineering & Construction , Korea.	yes	Correlation of energy usages and LEED-EAc1 and EPC rating system parameters are analysed for rated buildings only.
Kim_2017	Kim, J., Hyun, J.-Y., Chong, W. K., & Ariaratnam, S. (2017). Understanding the effects of environmental factors on building energy efficiency designs and credits. Journal of Engineering, Design and Technology, 15(3), 270–285. https://doi.org/10.1108/JEDT-12-2015-0082	yes	Studies the correlation between actual energy usage vs. LEED certification standards using data from 3 LEED certified university buildings.
Lessard_2017	Lessard, Y., Anand, C., Blanchet, P., Frenette, C., & Amor, B. (2017). LEED v4: Where Are We Now? Critical Assessment through the LCA of an Office Building Using a Low Impact Energy Consumption Mix. Journal of Industrial Ecology, 0(0), 1–12. https://doi.org/10.1111/jiec.12647	yes	Focuses on environmental facts and material contributions facts of LEED rating system.
Li_2014	Li, C., Hong, T., & Yan, D. (2014). An insight into actual energy use and its drivers in high-performance buildings. Applied Energy, 131, 394–410. https://doi.org/10.1016/j.apenergy.2014.06.032	yes	Energy efficiency of high-rated U.S., EU, and China–Pacific region office buildings are analysed, but not compared against non-rated buildings.
Menadue_2014	Menadue, V., Soebarto, V., & Williamson, T. (2014). Perceived and actual thermal conditions: Case studies of green-rated and conventional office buildings in the City of Adelaide. Architectural Science Review, 57(4), 303–319. https://doi.org/10.1080/00038628.2014.986433	yes	Focuses on temperature and relative humidity and occupant satisfaction of the buildings.
Miller_2008	Miller, N., Spivey, J., & Florance, A. (2008). Does green pay off? Journal of Real Estate Portfolio Management, 14(4), 385–399. https://doi.org/10.5555/repm.14.4.m5g300025p233u24	yes	Paper analyses the rental prices and values of LEED certified vs. non-rated buildings.

Newell_2014	Newell, G., MacFarlane, J., & Walker, R. (2014). Assessing energy rating premiums in the performance of green office buildings in Australia. Journal of Property Investment and Finance, 32(4), 352–370. https://doi.org/10.1108/JPIF-10-2013-0061	yes	Analyses property value-related measurements of buildings in Sydney and Canberra with different NEBERS ratings.
Ouf_2013	Ouf, M.M., Issa, M.H., Polyzois, D. 2013 A review of research on the energy performance of green buildings and its relation to occupancy Proceedings, Annual Conference - Canadian Society for Civil Engineering 1(January), pp. 690-699	no	No PDF
Pan_2013	Pan, J., Jain, R., Biswas, P., Wang, W., Addepalli, S., & Paul, S. (2013). Toward an Energy-Proportional Building prospect: Evaluation and analysis of the energy consumption in a green building testbed. In 2013 IEEE Energytech, Energytech 2013. https://doi.org/10.1109/EnergyTech.2013.6645358	yes	Performs energy monitoring, modelling and evaluation of single LEED-gold-certified building.
Papadopoulos_2017	Papadopoulos, S., Bonczak, B., & Kontokosta, C. E. (2017). Spatial and geographic patterns of building energy performance: A cross-city comparative analysis of large-scale data. In International Conference on Sustainable Infrastructure 2017: Technology - Proceedings of the International Conference on Sustainable Infrastructure 2017 (pp. 336–348). https://doi.org/10.1061/9780784481219.030	yes	Analyses and compares energy usage data of 2791 buildings in 5 US cities.
Perepelitza_2015	Perepelitza, M., Petterson, L., & Turpin, K. (2015). Performance validation case study: Federal office building with an integrated facade. Journal of Building Physics, 39(6), 542–569. https://doi.org/10.1177/1744259115611871	yes	Provides a discussion on design aspects for LEED platinum standard.
Pritchard_2017	Pritchard, R., & Kelly, S. (2017). Realising operational energy performance in non-domestic buildings: Lessons learnt from initiatives applied in Cambridge. Sustainability (Switzerland), 9(8). https://doi.org/10.3390/su9081345	yes	Presents a case study of a single building to justify its BREEAM, BRUKL and EPBD ratings.
Reichardt_2014	Reichardt, A. (2014). Operating Expenses and the Rent Premium of Energy Star and LEED Certified Buildings in the Central and Eastern US. JOURNAL OF REAL ESTATE FINANCE AND ECONOMICS, 49(3), 413–433. https://doi.org/10.1007/s11146-013-9442-z	yes	Statistical data are presented to analyse whether certified buildings have lower operating expenses compared to conventional buildings. No energy usage comparison is provided.

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