Energy & Buildings 226 (2020) 110367

Contents lists available at ScienceDirect

Energy & Buildings

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

# A review of data collection and analysis requirements for certified green buildings

Zakia Afroz *, H. Burak Gunay, William O'Brien

*Department of Civil and Environmental Engineering, Carleton University, Canada*

A R T I C L E I N F O

*Article history:*
Received 27 March 2020
Revised 25 June 2020
Accepted 2 August 2020
Available online 7 August 2020

*Keywords:*
Post-certification
Data infrastructure
Building performance
Monitoring requirement

A B S T R A C T

While the research community widely recognizes the importance of post-occupancy measurement of buildings to verify performance, requirements of green building certification schemes are highly varied. To assess the effectiveness of building certification schemes during the operation and maintenance stage of certified buildings, this paper critically reviews recent case studies that report on post-certification performance. The review of relevant case studies from the literature reveals some important findings in relation to the performance gap of certified buildings. Subsequently, major operation and maintenance-related building certification schemes are surveyed to reveal the underlying reasons behind this performance gap. Post-certification actions that require post-occupancy data collection and analysis are identified through this survey and compared to highlight their strengths and shortcomings and pinpoint the major discrepancies in data infrastructure and archiving practices that hinder certified buildings in performing according to their design intent. Lastly, suggestions are extracted which may shed light on the re-certification pathways.

© 2020 Elsevier B.V. All rights reserved.

**Contents**

1. Introduction . . . 2
   1.1. Background on green building certification schemes . . . 2
   1.2. Motivation and objectives. . . . 3
2. Methodology. . . . 4
   2.1. Identify recent case studies closely linked with building post-certification performance . . . 4
   2.2. Select and review building certification schemes . . . 4
3. Survey of existing case studies regarding post-certification performance . . . 4
4. Post-certification requirements of existing certification schemes. . . . 5
   4.1. LEED v4.1 O + M . . . 5
   4.2. BREEAM In-Use . . . 7
   4.3. Well v2. . . . 7
   4.4. Energy Star program . . . 7
   4.5. Boma best 3.0 . . . 7
   4.6. Green Star – performance. . . . 8
   4.7. Green Globes . . . 8
5. Energy metering and monitoring device requirements . . . 9
6. Discussion. . . . 9
   6.1. The performance of green-certified buildings from the context of surveyed case studies . . . 9
   6.2. Comparison of surveyed certification schemes in terms of data tracking requirements . . . 9
      6.2.1. Differences in post-certification requirements in terms of data tracking and their flexibility of options . . . 9
      6.2.2. Differences in energy metering and submetering requirements . . . 12
      6.2.3. Imbalance between site-level and user-level resource savings . . . 12

* Corresponding author.
*E-mail address:* afrozzakia@cunet.carleton.ca (Z. Afroz).

https://doi.org/10.1016/j.enbuild.2020.110367
0378-7788/© 2020 Elsevier B.V. All rights reserved.

6.2.4. Differences in energy meter-data tracking intervals . . . 13
6.2.5. Inconsistency between data submission interval and data recording period . . . 13
6.2.6. Differences in building-specific requirements and categorization. . . . 13
6.2.7. Differences in energy performance assessment approaches . . . 13
6.2.8. Differences in survey or audit requirements . . . 13
6.3. Recommendations . . . 14
7. Conclusions. . . . 15
Declaration of Competing Interest . . . 15
Acknowledgements . . . 15
Appendix A. . . . 15
Appendix B. . . . 20
Appendix C. Supplementary data . . . 21
References . . . 21

## 1. Introduction

Over recent years, environmental issues have become one of the greatest concerns of human beings. Climate change is predicted to be the greatest environmental threat and challenge of contemporary times [1]. This has resulted in the implementation of initiatives to monitor, and devise new solutions to limit our environmental impact [2]. The United Nations Environment Program for Sustainable Buildings and Construction reported that the building sector accounts for about 40% of the energy and 12% of the potable water use, 30% of the greenhouse gas emissions, and 40% of all solid waste production [3]. These figures reveal the need for sustainable alternatives for the design, construction, and operation of buildings. In this regard, green building design, maintenance, and operation hold prime importance in terms of sustainability and climate change.

It is worth noting that the term green building is often seen synonymous with sustainable building and high-performance building. The intent of green building design is to use less energy and water and reduce the life-cycle environmental impact on the environment and human health relative to typical buildings [4]. Green labels or green building certification programs can be considered an important tool to assure higher degrees of sustainability for the building sector. Wangel, et al. [5] states that building certification programs are simplified streamlined approaches to introduce sustainability aspects starting from the early stages of design. In addition, certification systems establish voluntary market drivers with the opportunity to benchmark and promote projects as 'sustainable'. Apart from sustainability issues, premium rental and sale prices awarded for adopting green building certification are important reasons for this increased popularity of certification schemes among the stakeholders [6]. Therefore, the aspirational benefits of these certification schemes are threefold: positive environmental effects in terms of less GHG emissions, cost-saving opportunities in terms of energy savings over time, and a publicly recognized environment-friendly profile that can largely aid in brand promotion [7]. However, aside from success in brand promotion for the stakeholders, the certification schemes often fail to deliver the projected benefits as promised. A building initially receives the certification based on its modelled performance. When the building becomes operational, it may not perform according to its design intent and this performance gap may increase over time because of the degradation of building performance. To tackle this situation, there should be suitable action-oriented strategies (such as strategies supporting detailed meter and submeter infrastructure and occupant feedback collection practices) in place to support identifying this performance gap through the implementation of advanced data analytics techniques and understanding the underlying reasons behind this mismatch. This can ultimately assist in addressing the identified issues and reveal the opportunities for improvements in a continuous cycle.

### 1.1. Background on green building certification schemes

Green building certification systems – such as Leadership in Energy and Environmental Design (LEED), the Building Research Establishment Environmental Assessment Method (BREEAM), Green Mark, and Green Star– are widely used to advocate the sustainability agenda in the design and operation of buildings. To date, there are more than 200 different green building certification schemes around the world, with an estimate of one million certified projects [8]. These certification schemes necessitate regular updates to cope with the ongoing demand for the performance improvement of buildings. Besides, it is crucial to closely monitor, maintain, and improve the performance of the certified buildings through post-certification actions to ensure the intended performance and environmental benefits. There is one critique in this regard: during design, developers receive points, and ultimately certification, even if the measures implemented do not result in any tangible environmental benefits during post-construction [9-11].

The term building performance has been defined by De Wilde [12] from three different perspectives: "*an engineering view of buildings as an object, a process view of building as a construction activity, and an arts view where performance involves the notions of form and appreciation. From an engineering point of view, building performance is referred to as how well a building performs the tasks or fulfils its functions*". Once a building becomes operational, it demands tracking of building performance to ensure that the building is performing according to its design intent. In this regard, the certification schemes can hold a strong position in assessing and evaluating the operational performance of existing buildings on an ongoing basis and demonstrate that certified buildings are performing as intended. It is worth noting that performance gap is often observed in these buildings which primarily refers to the over-consumption of energy as a proportion of the design energy demand rating [13].

It is worth noting that European buildings receiving Energy Performance Certificate (EPC) also experience the performance gap. Display Energy Certificate which is regarded as an important step to evaluate the performance of a building shows that there are often large variations between the actual metered energy use of buildings and energy use modelled for compliance purposes; this implies that there is a discrepancy observed in Energy Performance Certified buildings in terms of calculated energy use and targeted $CO_2$ emissions level [14].

Although several articles (e.g., [15,16]) highlight the energy performance achievements of certification schemes, most of them are based on design projections rather than actual measured energy performance. The calculation performed by MacNaughton, et al. [15] shows that significant environmental benefits were achieved by 20,000 buildings in six countries that were LEED-certified from 2000 to 2016. These calculated benefits were anticipated on an assumed reduction in fuel usage by these buildings as compared to conventional buildings in the same geographic areas. Specifically, it is assumed that each LEED building attains the percentage energy savings estimated by its design team and that these LEED buildings, on average, have the same fuel mix as other buildings in the same geographic area. More importantly, it is assumed that their projected performance does not decline over time. In reality, buildings' performance degrades over time as a result of deterioration of the envelope, changes/overrides to the operational sequences of major equipment, changes in the building energy systems' efficiency, and so on. Through critically reviewing existing literature associated with green buildings, Scofield and Cornell [17] reported that many of the LEED building studies inevitably suffer from selection bias as data are obtained voluntarily from cooperative building owners. Another problem reported in this study is the relevance of the baseline energy data to which the LEED data are being compared.

In contrast, a few studies (e.g., [18-22]) reported findings based on measured energy use data in certified buildings. These studies demonstrated that primary energy consumed by LEED-certified buildings, on average, is not considerably lower than that for conventional buildings, or in some cases (e.g., [21–23]) LEED-certified buildings demonstrated no source energy savings relative to similar conventional buildings. In line with these findings, Scofield and Cornell [17] reported that LEED certified buildings typically use less natural gas and other non-electric fuels on-site, but use more electricity. The off-site energy losses associated with the increased on-site electricity use nullify the on-site savings for the other fuels.

Similar findings were reported regarding comfort performance too. A few articles [24–27] compared occupant satisfaction in green-certified office buildings with conventional buildings and found that occupants in green-certified buildings report being more comfortable. On the contrary, some post-occupancy evaluation studies [28–30] demonstrated that, although indoor environmental quality (IEQ) ratings in green buildings were in general higher than their conventional counterparts, occupants expressed concerns regarding the usability of personal environmental control systems [28] and workstation designs [29,30]. Also, some other studies ([31–33]) reported that certified office buildings are not recognized as more comfortable and productive workplaces compared to their conventional counterparts.

To highlight these post-occupancy issues and to provide insights into green-certified buildings' energy and comfort performance, several papers [10,32,34,35] performed meta-analysis. For example, Khoshbakht, et al. [34] looked for evidence covering three aspects: IEQ, design, and facilities management. According to their survey results, the evidence on green buildings outperforming non-green counterparts is inconclusive. This finding is also supported by Geng, et al. [35]. The findings of their literature review showed that the energy performance and occupants' satisfaction level of green buildings were in general better than the conventional counterparts. However, the data representing occupants' satisfaction level collected from the U.S. did not support that inference. Also, a significant performance gap was found between the designed and operational energy consumption. Based on the analysis of a dataset featuring 11,243 responses from the occupants of 93 LEED certified buildings, Altomonte, et al. [32] identified the relationship between the points earned in the IEQ category and the satisfaction expressed by occupants with the qualities of their indoor environment. Their results showed that the achievement of a specific IEQ credit did not substantively increase satisfaction with the corresponding IEQ factor, and also, the rating level, and the product and version under which certification had been awarded, did not affect workplace satisfaction. de Wilde [10] critically reviewed related literature on the building energy performance gap and concluded that the performance gap can only be bridged by a broad, coordinated approach that brings together model validation and verification, improved data collection for predictions, better forecasting, and a change of industry practices. With regard to establishment of standard data infrastructure, Ahmad, et al. [36] presented the necessity of using detailed energy metering and submetering devices. This study reported that performance gap of existing buildings is poorly understood because of the lack of adequate energy submetering arrangements.

### 1.2. Motivation and objectives

It has been widely acknowledged in the literature (e.g., [37–41]) that continuous improvement of these certification schemes is crucial to address the ongoing demand for the performance improvement of buildings. However, these certification schemes can be more effective if the performance of these green-certified buildings can be closely monitored and controlled through post-certification actions. Despite active research being undertaken in the area of certification schemes of buildings, including post-occupancy evaluations, there is still a lack of studies addressing the issue of post-certification actions/requirements. This article provides an overview of different certification schemes widely recognized in North America, as well as others, highlighting various aspects of their post-certification actions. The strengths and weaknesses of these certification schemes in the context of their proposed data tracking requirements during the operational stage of certified buildings are explored through a comparative analysis. Also, this article presents detailed information on standard data infrastructures such as detailed meter and submeter infrastructure and occupant feedback collection practices prescribed by the certification programs. Some suggestions are extracted from this comparative study which may shed light on the re-certification pathways providing new possibilities to explore in terms of their effectiveness.

Through a literature survey, this research aims to address the following research questions:

- Are there any post-certification requirements that buildings need to achieve to maintain certification?[1]
- To what extent do these post-certification actions encourage or require data tracking on an ongoing basis?
- To what extent are post-certification actions capable of tracking the performance of green-certified buildings?
- How can these post-certification requirements be upgraded to the next level in terms of energy and comfort performance metrics?

This paper is organized as follows: Section 2 presents a methodological approach of this review. Recent case studies that report building post-certification performance are critically reviewed in Section 3. Section 4 presents a deep insight into different aspects of building post-certification actions directed by surveyed certification schemes. Section 5 discusses detailed meter and submeter infrastructure and occupant feedback collection practices proposed by various certification schemes. Section 6 summarizes and discusses the outcome of the review. Post-certification actions that require post-occupancy data collection and analysis are identified and compared to highlight their strengths and shortcomings. Also, recommendations are extracted for the standardization of data

[1] This research question is answered in the context of surveyed certification schemes.

infrastructure and archiving practices to enable data-driven building operation strategies in certified buildings. Lastly, a conclusion is drawn from the entire study in Section 7.

## 2. Methodology

The methodology of this study comprises of two parts as follows: identify recent case studies closely linked with building post-certification performance; and, select and review building certification schemes.

### *2.1. Identify recent case studies closely linked with building post-certification performance*

The review was conducted based on searching publication databases for journal and conference papers, dissertations, and technical reports from 2009 to 2019. The following databases were used: Web of Science, ScienceDirect, Scopus, and Google Scholar as the search engine. Search terms were combined with Boolean operators such as "OR" and "AND", parentheses, and query sets to cover extensive possible combinations in search engines. As search query all literature were included that satisfy: ("green label" OR "green building certification" OR "green certification" OR "building certification scheme" OR "building rating system") AND ("sustainable building" OR "sustainable energy" OR "certified building" OR "green building" OR "green office") AND ("energy performance" OR "energy saving" OR "energy efficiency" OR "energy use" OR "occupant satisfaction" OR "post-occupancy evaluation" OR "occupant comfort" OR "indoor environment" OR "thermal comfort" OR "user perception survey"). A precise combination of keywords was explored further on a trial and error basis. A further refinement to the search query was performed by subjectively identifying five of the most relevant papers associated with the performance of green-certified buildings and pinpointing a combination of keywords that represent those papers. The primary objective of following this systematic literature survey technique is to locate all the relevant literature that discusses post-certification performance of buildings. Finally, identified documents were assessed individually by reading the full text. Only documents concerning case studies of green-certified buildings are included in this study.

### *2.2. Select and review building certification schemes*

To identify the green building certifications used in this study, the following steps were carried out:

1. Search for building certification schemes widely used in North America by exploring relevant scientific peer-reviewed literature, reference books, and on the Internet.
2. Search for one or two international certification schemes not included in initial search based on world recognition – at least in three countries. This provides a reference point for projects outside North America.
3. Access the official websites of the identified green building certifications and download associated technical manuals that represent the most current versions of the schemes released within the past two years. Also, look for immediate previous versions of the schemes.
4. Search for information in the following areas:
   a. Post-occupancy data collection requirements and actions needed to retain the certification status
   b. Energy metering and monitoring requirements
5. Analyse all related documents downloaded from official websites of those certification schemes to ensure the breadth and depth of coverage.

Through this review process, post-certification actions that require post-occupancy data collection and analysis are identified and compared to highlight their strengths and shortcomings. For instance, we critically reviewed the certification schemes in terms of data tracking requirements and categorized them based on the flexibility of options. An important objective of this survey is to explore energy metering and submetering requirements from site to zone level prescribed by the certification schemes. To this end energy flowing into a building is divided into four distinct energy segments and data infrastructure requirements at each level is evaluated.

Additionally, this analysis attempts to interpret the reasons behind the design and measured performance gap in certified buildings based on the reviewed case studies and their respective certification schemes. Lastly, recommendations are developed for the certification schemes and developing projects associated with standardization of data infrastructure and archiving practices.

## 3. Survey of existing case studies regarding post-certification performance

To assess whether post-certification actions can enable green buildings to achieve the savings anticipated at the design phase, it is worthwhile to review case studies that report building post-certification performance. In this section, relevant case studies [7,22,23,27,42–46] are critically reviewed to understand the performance of green-certified buildings in three categories: occupant satisfaction, IEQ, and energy and GHG emissions.

While a number of case studies [7,42–44] concentrated on evaluating post-occupancy comfort performance, their context and research findings differs. Note that most of these case studies consider multiple buildings in their building performance evaluation studies. The results presented by Pastore and Andersen [7] show that although in most cases observed environmental factors complied with the norm prescriptions, the indoor conditions never attained the 80% satisfaction threshold by the users. Temperature and air quality appeared as the most critical factors, with satisfaction rates not exceeding 50% in three out of the four case studies. To reveal whether green certified buildings perform better than non-green-rated buildings in terms of occupant satisfaction, Menadue, et al. [42] assessed the perceived and actual thermal, visual and aural comfort, and also, health and productivity metrics through post-occupancy evaluation and found that green-rated buildings exhibit equal and, in some cases, lower occupant satisfaction of internal thermal conditions. Armitage, et al. [43] examined management and employee perceptions of their experiences of working in a green-certified workplace and assessed the effectiveness of the green features that enabled the certification credits. This research showed that there was an inconsistency between the views of management who see greater benefits of the green workplace than their employees. Ponterosso, et al. [44] studied the physically monitored thermal environment within the office floor of the building and compared these measurements with occupants' perception of comfort. The results demonstrated the importance of apparently small details to the level of comfort experienced by occupants.

Newsham, et al. [27] and Ravindu, et al. [45] concentrated on evaluating if green buildings possess better indoor environmental conditions compared with conventional buildings. Newsham, et al. [27] reported that green buildings exhibited improved indoor environment performance compared with similar conventional buildings in terms of environmental satisfaction, satisfaction with thermal conditions, satisfaction with a view to the outside, aesthetic appearance, less disturbance from HVAC noise, workplace image, night-time sleep quality, mood, physical symptoms, and a reduced number of airborne particulates. Conversely, Ravindu, et al. [45] showed that thermal comfort, ventilation, and ability to control indoor environment of the studied green factory were comparatively less satisfactory than a conventional factory. The study proposes the need for an equilibrium between energy efficiency and IEQ measures and climate responsive design for green buildings.

A few case studies [22,23,47] evaluated or compared the energy performance of certified buildings with similar conventional buildings. Scofield and Doane [22] performed an extensive meta-analysis in 2015 incorporating 132 LEED-certified Chicago properties to identify whether LEED-certified buildings use less energy than similar conventional buildings in Chicago. It was concluded that LEED-certified buildings use no less source energy than similar buildings that are not LEED-certified. Moreover, it was found that LEED-certified schools use 17% more source energy than conventional schools. Similarly, in an earlier study Scofield [23] analyzed 2011 benchmarking data for 21 LEED office buildings in New York City (NYC) and found no difference from other NYC office buildings in terms of their gross site and source energy use intensity (EUI) and greenhouse gas (GHG) emissions. Their results showed that a subset of the LEED buildings certified at the Gold level outperformed other NYC office buildings by 20% even though this finding was not observed by the 45 LEED Gold buildings in the Chicago study [22]. However, LEED Silver and Certified office buildings under-performed relative other NYC office buildings. It was summarized that the average Energy Star (ES) Score for the LEED buildings was 78, 10 pts higher than that for all NYC office buildings, raising questions regarding validity and interpretation of ES scores. Zhou [47] revealed the energy performance discrepancies between the modelled results and field performance, investigated possible causes and sought practical solutions. The assessment showed that only two out of the ten buildings achieved their preliminary high-performance goals. The other eight buildings sustained an offset of energy consumption from a minimum of 22% to a maximum of 282% compared to design performance (predicted by the energy models used in certification). The most common concerns were the unexpected inefficiency of air source heat pumps and occupant behaviours such as leaving windows open in winter.

Table 1 presents a summary of the surveyed case studies in terms of survey year, origin, certification scheme, building details, survey data and research findings.

The findings of this literature survey show that there is a performance gap in certified buildings, which means these buildings are not performing according to their design intent. There is a big question here whether these green buildings initially achieved their aspirational performance when the buildings became operational first and how they performed over the years and this part needs further research effort. In this paper, we attempted to reveal the certification schemes' data tracking related strategies that influence the operational performance of buildings during the recertification phase. It is worthwhile to explore data tracking and analysis approaches prescribed by the certification schemes to reveal the underlying reasons behind this performance gap during the operational phase of green certified buildings. It is well supported by de Wilde [48] that an adequate data infrastructure not only enables building energy management personnel to track daily/monthly trends of building key performance indicators but also assist them in detecting the performance gaps and interpreting underlying reasons behind these. This, in turn, supports executing data-driven operation and maintenance strategies such as fault detection and diagnostics, occupancy-based controls, and predictive controls. A generic term that incorporates many of these different data uses is referred to as building performance tracking [49].

In the following section, selected certification schemes are reviewed to provide an insight into post-certification requirements in terms of data collection and analysis. In connection with this review, Section 5 presents information on data infrastructure and occupant feedback collection practices proposed by various certification schemes.

## 4. Post-certification requirements of existing certification schemes

The existing building certification schemes are characterized by different calculation methods, credits for features, and the weighting of those credits [50]. Also, there are variations in assessment and ranking criteria within each certification scheme. While a few of the certification programs (e.g., Energy Star) are single-attribute, most of them (e.g., LEED, BREEAM, Green Star) are multi-attribute focusing on various aspects of the built environment. To fulfill the defined objectives around post-certification requirement, this study only concentrates on the particular rating tool of an individual certification scheme that is specially designed to assess and evaluate the operational performance of existing buildings and identify opportunities for improvements in a continuous cycle. This study primarily focused on the recertification stage of those rating tools, as recertification encourages project teams to monitor their performance data on an ongoing basis and prove that their buildings are performing as intended.

As stated in Section 2, only the building certification schemes most commonly in use in North America are summarised below. Additionally, other certification programs such as Green Star are included in this description to provide a reference point. Appendix A: Table A1 presents an overview of these certification schemes.

These reviewed building rating and certification systems go through a routine amendment process often on a yearly basis to reflect new standards and goals for achieving ever higher levels of sustainability. This study extracts the relevant information from the current versions of these programs. The certification schemes discussed in the following subsections highlight various aspects of their post-certification actions in terms of data requirements. These data requirements can be classified into two categories: prerequisite and credit. Prerequisite data requirements refer to those which must be collected and submitted to the certification authority on a regular basis to maintain the validity of certificate, while credit data requirements are prescribed to gain points toward their targeted certification. It is worth noting that some prerequisite requirements may represent credit points towards certification, while others are mere requirements without a credit point For example, ASHRAE preliminary energy use analysis and an ASHRAE Level 1 audit is a prerequisite requirement of LEED v4.1O + M for which the certification scheme offers no credit point, but without fulfilling this requirement it is not possible to achieve this certification.

### *4.1. LEED v4.1 O + M*

To encourage LEED-certified project teams to monitor their performance data and to prove that their buildings are performing as intended, the LEED program was restructured in 2009 offering LEED: O&M Recertification program. Even though this recertification is available to all occupied and in-use projects that have previously achieved certification under LEED, there is a mandatory requirement for all LEED: O&M certified buildings to file for recertification every three years. The establishment and performance approach to rating system requirements acts as an important tool for orienting LEED towards existing building activities. Establishment documentation is only required during the recertification

**Table 1**
Summary of the surveyed case studies regarding post-certification performance.

| Performance category | Research Studies | Survey Year | Origin | Certification scheme | Building details | Survey data | Research findings |
|---|---|---|---|---|---|---|---|
| Occupant satisfaction | Pastore and Andersen [7] | 2017 | Switzerland | Minergie | Four office buildings | Sensor data: Indoor temperature, relative humidity, and illuminance<br>Interval: 5-min<br>Duration: Four weeks (two weeks in winter and two weeks in summer)<br>Spot measurements: indoor temperature, relative humidity, $CO_2$ concentration and illuminance<br>Occupant comfort survey: (Y)<br>On-line extensive surveys (one in winter and one in summer)<br>Point-in-time surveys | Comfort: Satisfaction rate $\geq$ 50% |
| | Menadue, et al. [42] | 2010–2011 | Adelaide, South Australia | Green Star | Four conventional office buildings and four Green Star rated office buildings | Sensor data: Indoor temperature and relative humidity<br>Interval: 30-min<br>Duration: One year<br>Spot measurements: Indoor temperature and relative humidity<br>Occupant comfort/satisfaction survey: (Y) | Comfort: Satisfaction rate of green-rated buildings $\leq$ Non-green-rated buildings |
| | Armitage, et al. [43] | 2009 | Australia (covers all Australian states except Northern Territory) | Green Star | 31 Green Star-certified office buildings (with four to six Green star ratings) | Sensor data: (N)<br>Spot measurements: (N)<br>Occupant comfort/satisfaction survey: (Y) | Indoor environment: Satisfaction rate of management > Employees |
| | Ponterosso, et al. [44] | 2016–2017 | Portsmouth, UK | BREEAM | A floor of an office building | Sensor data: (Indoor temperature and relative humidity, outdoor environmental data from local weather station)<br>Interval: 15-min<br>Duration: One year<br>Spot measurements: (N)<br>Occupant comfort/satisfaction survey: (Y) | Comfort: Satisfaction rate $\geq$ 61% |
| IEQ | Newsham, et al. [27] | 2010–2011 | Canada and the northern United States | LEED EB:O & M | Twelve green and twelve conventional office buildings | Sensor data: (N)<br>Spot measurements: Temperature, relative humidity, formaldehyde, carbon monoxide, particulate matter, illuminance, luminance, and sound pressure<br>Sample size: 974<br>Duration: Two to four days<br>Occupant comfort survey: (Y) | Indoor environment performance: Green buildings > Similar conventional buildings |
| | Ravindu, et al. [45] | 2013 | Colombo, Sri Lanka | LEED | A LEED certified factory and a similar conventional factory located in the same city | Sensor data: (N)<br>Spot measurements: Air temperature, relative humidity and sound level for acoustic quality<br>Duration: 10 min<br>Occupant comfort/satisfaction survey: (Y) | Indoor environment performance: A green factory > A conventional factory |
| Energy and/or GHG emissions | Scofield [23] | 2011 | New York, USA | LEED | 953 office buildings including 21 LEED-certified ones | Area-weighted gross site and source EUI<br>GHG emission intensity | Energy and GHG performance: LEED buildings $\leq$ other NYC office buildings |
| | Scofield and Doane [22] | 2015 | Chicago, USA | LEED | 1521 commercial buildings including 132 LEED-certified ones | Area-weighted gross site and source EUI<br>GHG emission intensity | Source energy and GHG performance: LEED buildings $\leq$ other conventional buildings in Chicago<br>Site energy: LEED buildings > other conventional buildings in Chicago |

**Table 1** (*continued*)

| Performance category | Research Studies | Survey Year | Origin | Certification scheme | Building details | Survey data | Research findings |
|---|---|---|---|---|---|---|---|
| | Zhou [47] | 2016–2017 | Canada | LEED | Ten LEED Gold certified social houses | Data: Monthly utility bills (electricity and natural gas) Duration: two-years | Energy performance: Two LEED Gold buildings > predicted modelling results Eight LEED Gold buildings < predicted modelling results |

stage if major changes have taken place. On the other hand, there is a requirement on performance data to achieve a minimum of 40 out of 100 points to be recertified every three years.

For first-time LEED O + M certification it is necessary to provide some basic information such as gross floor area, operating hours per week, number of regular building occupants, part-time employees (hours worked per employee per day), number of visitors per day and their duration of visit (in hours/day). This information is used to calculate the weighted occupancy and weighted operating hours for a project using USGBC calculator [51]. Weighted occupancy and weighted operating hours are two crucial data that are used for calculating performance scores in five categories: energy, water, transportation, waste, and human experience, during first-time and recertification phases of LEED O + M. For the same weighted occupancy and operating hours, these performance scores can differ from the initial time to subsequent times based on the annual data provided in five specified categories. Details of these prerequisite data requirements can be found in Appendix A (see Table A2).

### 4.2. BREEAM In-Use

Within this certification scheme, assessment and certification take place at several stages from design and construction to operation and refurbishment. To assess the on-going performance of existing buildings and to identify opportunities for improvements in a continuous cycle, BRE Global launched BREEAM In-Use in 2009.

This standard is divided into three parts, each looking at different aspects of a building: Part 1 – Asset Performance, Part 2 – Building Management, Part 3 – Occupier Management. Certificates for Part 1 and Part 2 can be renewed annually without any further reassessment if there are no significant changes to the asset or its management. However, where either substantial changes to the asset or its management have occurred, or two renewals have been completed previously, a full re-assessment is required against Parts 1 and 2 and a re-measurement should be done against Key Performance Indicators (KPIs) such as building GHG emissions, building energy consumption, water consumption, etc. Part 3 requires full reassessment and recertification each year. To maintain a flexible system, BREEAM In-Use adopts a 'balanced score-card' approach to the assessment and rating of asset performance. This means that to achieve a particular level of performance, the majority of BREEAM In-Use credits can be traded, i.e. non-compliance in one area can be offset through compliance in another to achieve the target BREEAM In-Use rating. For the certification as well as annual basis recertification, a building must achieve and maintain a minimum of 25% of the available score. However, to achieve a higher rating or to improve the performance rating, it is important to maintain continual data collection in all assessment categories (see Appendix A: Table A1) and share data trends related to the environmental performance of the buildings with BREEAM In-Use Assessor. Details about prerequisite and credit data requirements for BREEAM In-Use can be found in Appendix A (see Tables A3 and A4), respectively.

### 4.3. Well v2

WELL is the first certification scheme that focuses solely on the health and wellness of building occupants. WELL v2 is the latest version of WELL Building Standard and consolidates previous iterations and pilots into a single version for all project types. This certification scheme operates on a points-based system, with a total of 110 points available to each project. To earn the lowest level of WELL certification, which is WELL Silver, there is a minimum requirement of achieving 50 points including a minimum of two points per concept (or in the case of the air and thermal comfort concepts, at least four points combined). In order to uphold a current certification, WELL Certified projects must undergo performance verification and apply for recertification before the end of the three-year certification period. Data monitoring and reporting requirements for this recertification phase are presented in Appendix A (see Table A5).

### 4.4. Energy Star program

The United States (US) Environmental Protection Agency (EPA) Energy Star program is a program developed to identify and promote an energy performance-based approach for new and existing buildings [52]. In 2013, the EPA and Natural Resources Canada (NRCan) together released the first 1–100 ENERGY STAR score for Canadian buildings, which applies the same practice to assess measured performance relative to the Canadian building stock. For different US or Canadian building types, e.g., office properties, retail stores school buildings, worship facilities, warehouse properties, and supermarkets, the Energy Star program suggests different score models. To be certified as ENERGY STAR, a building must satisfy an ENERGY STAR score of 75 or higher, suggesting that it performs better than at least 75 percent of similar buildings nationwide. Portfolio manager computes the source energy use intensity using a regression equation, which is then used to calculate the energy efficiency ratio[2]. Based on this energy efficiency ratio, a building's energy performance is scored. This certification is valid for one year which indicates that an ENERGY STAR certified building owner may file for recertification every year and every time a certified building needs to comply with energy performance standard set by EPA to uphold its present certification status. Details of data collection requirements of Energy Star are also shown in Appendix A (see Table A6).

### 4.5. Boma best 3.0

This is the largest environmental assessment and certification program in North America for existing buildings, with more than

[2] Lower ratios indicate better performance

7000 buildings obtaining a certification or recertification since its inception in 2005. Energy and water benchmarking in BOMA BEST 3.0 are performed using ENERGY STAR Portfolio Manager. This certification is valid for three years and a project may file for recertification before the end of the three-year certification period. After certification, there is a requirement of continuous improvement of building energy performance (e.g., fulfilling energy reduction target) prescribed by this certification. As part of continuous improvement of building energy performance, this certification program prescribes submission of energy, water and waste data every three years. The intent of this BEST Practice is to encourage building owners and managers to review available historical consumption data while also taking into consideration planned upgrades or improvements to set realistic targets. Details of data collection requirements can be found in Appendix A (see Table A7). There is no individual minimum requirement set by BOMA BEST 3.0 for an ENERGY STAR score, weather-normalized site EUI, and water use intensity benchmarking matrix. This implies that non-compliance in one benchmarking matrix can be offset through compliance in other benchmarking matrices to achieve the target rating. During the certification and recertification phases, a building must meet the BEST Practices and achieve at least 19% on the questionnaire. However, additional points may be offered depending on the performance of benchmarking matrices.

### 4.6. Green Star – performance

Among four rating tools available within Green Star certification scheme, Green Star – Performance evaluates the operational performance of all types of existing buildings (with the exception of single-detached dwellings) across nine impact categories (see Appendix A: Table A1). Credit points are determined within this certification scheme using specific calculators developed by Green Star, each of which indicates certain features such as indoor air quality (IAQ), occupant satisfaction survey, etc. During the certification as well as three years interval recertification phases, this standard prescribes a minimum of 10–19% of available points; this point largely depends on data availability along with the performance of benchmarking matrices. Details of data collection requirements to maintain certification status are presented in Appendix A (see Table A8). Among the stated data requirements, it is necessary to provide GHG emissions and potable water use data every three years to maintain the rating after initial certification.

### 4.7. Green Globes

Green Globes for Existing Buildings (EB) is designed for operation and management of existing buildings and minor renovations. This certification's 1000-point scale allows for weighted criteria,

**Table 2**
Description of prerequisite and credit requirements of energy metering and sub-metering as per different certification schemes[l].

| Metering requirement | LEED v4.1O + M Existing Buildings | BREEAM In-Use | BOMA BEST 3 | ENERGY STAR | Green Globes – EB[4] | Green Star – Performance |
|---|---|---|---|---|---|---|
| Metering of site-level resources of the whole building (for all fuel types[5]) | Prerequisite – On a monthly basis for 12 months period | Prerequisite – Annual | Prerequisite – On a monthly basis for 12 or 24 consecutive months[6] based on building types[7]. | Prerequisite – On a monthly basis for 12 consecutive months | Credit – Annual | Prerequisite – On a monthly basis for 12 months period |
| Metering generated steam and chilled water | Prerequisite – On a monthly basis for 12 months period | Prerequisite – Annual | Prerequisite – On a monthly basis for 12 or 24 consecutive months[8] based on building types[9]. | Prerequisite – On a monthly basis for 12 consecutive months | Credit – Annual | Prerequisite – On a monthly basis for 12 months period |
| Sub-metering building's major energy end uses[10] | Credit – Monitor and record monthly energy end uses and demand at intervals of one hour or less | Credit – Annual | | | Credit – Monitor total monthly energy use and peak demand in 15–30-minute increments | Credit – Monitor total monthly energy use and peak demand in quarter-hourly, hourly or daily increments |
| Floor level or tenant level submetering of lighting and plug load | | Credit – Annual | | | Credit – Monthly | Credit – Monthly |
| Submetering Renewable energy generation | Credit – Annual | Credit – Annual | | | | |
| Tenant level sub-metering of heating and cooling | | Credit – Annual | | | | |

[4] All of the stated metering data requirement is only for initial certification.
[5] Such as electricity, natural gas, fuel oil, propane, etc.
[6] Energy data cannot be a bulk amount representing the complete 12 or 24-month timeframe.
[7] For office and universal building types (listed on eligible building types for ENERGY STAR Score) there should be at least 12 consecutive months of energy consumption data to calculate the ENERGY STAR Score whereas for Multi-Unit Residential Buildings, Health Care, Enclosed Shopping Centres, Light Industrial, Open Air Retail at least 24 consecutive months of energy consumption data is required to calculate the Weather-normalized Site Energy Use Intensity.
[8] Energy data cannot be a bulk amount representing the complete 12 or 24-month timeframe.
[9] For office and universal building types (listed on eligible building types for ENERGY STAR Score) there should be at least 12 consecutive months of energy consumption data to calculate the ENERGY STAR Score whereas for Multi-Unit Residential Buildings, Health Care, Enclosed Shopping Centres, Light Industrial, Open Air Retail at least 24 consecutive months of energy consumption data is required to calculate the Weather-normalized Site Energy Use Intensity.
[10] Such as chiller, boiler, lighting, plug load, pump and fan.
[l] Applicable for only office buildings and residential buildings. For other types of buildings there may be some other metering requirements e.g., sub-metering non-standard energy uses such as regional server room, trading floor, furnace or forming process, blast chilling or freezing etc

wherein the assigned number of points for individual criteria indicates their relative impact and/or benefit on the sustainability of the building. There is no prerequisite in terms of data collection to obtain this certification, and a building is eligible for Green Globes certification once it reaches the threshold limit, which is 35% of the overall score. There is no validity period for this certification. Hence, no post-certification evaluation is necessary to maintain this certification.

## 5. Energy metering and monitoring device requirements

The recent increase in energy-related building legislations and regulations around the world, including stringent energy efficiency requirements, act as a motivator for an increased level of metering, sub-metering, and automated control, especially in non-domestic buildings [36]. Building certification schemes play an important role in initiating operation-oriented energy efficiency measures such as lighting automation, automatic fault detection and diagnosis (AFDD), and demand control ventilation within buildings that exclusively rely on the sensor and metering infrastructure of that building. Further, periodic energy data reporting requirements to maintain the certification of green-certified buildings enhance the importance of installing advanced metering systems in buildings as a means of monitoring and control of energy consumption [54]. To encourage metering/submetering of building energy, different strategies are proposed by the certification schemes, including feature-based or point-based strategies. For instance, LEED O + M offers credit points for advanced metering of whole-building energy sources and major end uses that represent 20% or more of the total annual consumption of the building (minus plug load use). Green Globes offers credit points for submetering major end uses and recording data at 15 to 30 min intervals. Therefore, the building owners targeting a high energy performance score or seeking to improve an existing score during the recertification phase can concentrate on fulfilling these credit requirements of the corresponding certification schemes. Details of the energy metering and submetering requirements prescribed by the certification schemes are listed in Table 2.

There are some survey/audit/other monitoring requirements set by the surveyed certification schemes to monitor and maintain the performance of a green certified building. Table 3 provides an overview of these survey/audit/other monitoring requirements. This table shows that there are variations in survey and monitoring requirements among the certification schemes and these requirements can be classified into two categories: prerequisite and credit. While satisfying the prerequisite survey/audit requirements, it is important to comply with the credit monitoring requirements as this enables the building owners to obtain credit points towards targeted certifications. Additionally, depending on the frequency of monitoring requirements, they can be further classified into three categories: initial, periodic and continuous.

## 6. Discussion

### *6.1. The performance of green-certified buildings from the context of surveyed case studies*

The results acquired from surveyed case studies are mixed. While some case studies (e.g., [15,16,24–27]) demonstrated that green-certified buildings perform better than their peers in terms of energy, occupant comfort and IEQ, others (e.g., [18–22,31–33,42,45]) shown them to be no better than their peers. On the other hand, inconclusive findings have been presented by some studies [28–30,43] leading to conduct further research work for establishing a benchmark and perform a comparative study between green certified and conventional buildings. In this regard, Scofield [23] took a closer look at different levels of LEED certifications and concluded that certified buildings with a higher certification score perform better than others with a low certification score. This outcome is expected from certified buildings with high ratings. But certified buildings with low-level ratings have been found to underperform in contrast to their noncertified counterparts (e.g., [23]). However, in a later study, Scofield and Doane [22] showed that LEED Gold buildings did not outperform conventional buildings in terms of source energy and GHG emissions. Moreover, LEED-certified schools were found to use more source energy than conventional school buildings. On the contrary, LEED-certified buildings demonstrated about 10% site energy savings relative to conventional buildings. In some cases (e.g., [7,44,47]), it was found that those buildings are not performing according to their design intent. Based on the outcome of these surveyed studies, it may be logical to increase the threshold limit (the minimum passing score) of the reviewed certification schemes, along with necessary revisions to the implementation policy of different energy-efficiency and occupant-centric strategies at different post-certification stages.

To reveal the underlying reasons for the performance gap of certified buildings, this paper summarizes the certification schemes. The outcome of this review is discussed in the following subsection by performing a comparative analysis among the surveyed certification schemes. As presented in Subsection 6.3, some recommendations are developed from this comparative study, which may act as a guideline to advance the identified post-certification actions of the surveyed building certification schemes.

### *6.2. Comparison of surveyed certification schemes in terms of data tracking requirements*

While there are some common indicators set by surveyed certification schemes in the area of energy, water, transportation, waste to assess the performance of existing buildings, there are variations in data collection requirements and methods which are discussed below in the context of their strengths and weaknesses:

#### *6.2.1. Differences in post-certification requirements in terms of data tracking and their flexibility of options*

Although all surveyed certification schemes encourage maintaining or improving the performance of their certified properties, in many cases this is not reflected in their proposed strategies. For example, Green Globes EB [55], which has been specially designed for operation and management of existing buildings, does not necessitate any post-certification evaluation to maintain certification, and also there is no validity period for the achieved certification. On the other hand, LEED's v4.1 O + M [51] certification scheme offers credit points for submetering major end uses and on-site renewable energy generation. However, there is no credit compliance requirement set by the current version of LEED v4.1O + M to impose sub-metered data tracking to their clients.

Based on the survey of the literature presented in Section 4, it is revealed that some certification schemes are flexible about data tracking requirements, such as Green Globes EB, while others, e.g., LEED v4.1O + M impose minimum requirements in some specific categories (e.g., energy, transportation, water) to pass and get certified. Details about the characteristics of these certification programs in terms of data tracking requirements are presented in Table 4. This table shows that post-occupancy data collection and analysis approaches (e.g., a minimum passing score for certification, data tracking and survey requirements) prescribed by different certification programs can be classified into three categories: flexible, conditionally flexible and strict. For this catego-

**Table 3**
Description of credit and prerequisite survey/audit/other monitoring requirements as per surveyed certification schemes (here the letter I, P and C stand for initial, periodical and continuous monitoring requirements, respectively).

| Survey/Audit/other monitoring requirement | LEED v4.1O + M Existing Buildings | BREEAM In-Use | BOMA BEST 3 | Green Globes – EB[11] | Green Star – Performance | Well v2 |
|---|---|---|---|---|---|---|
| ASHRAE preliminary energy use analysis and Level I walk-through assessment | Prerequisite – I[12]<br>– | –<br>– | Prerequisite – I<br>Must have been conducted in the last 5 years of the assessment date | Credit – I<br>Within the last three years of initial certification | –<br>– | –<br>– |
| Monitor thermal comfort | Credit – C[13] & P[14]<br>As specified by ASHRAE 55–2010 or ISO and CEN Standards[18] | Credit – I & P[15]<br>Every three years | – | –<br>– | Credit – I & P[16]<br>At least twelve (12) times during the 12 months performance period, i.e., a minimum of one (1) reading per calendar month[19]. | Prerequisite – Only P[17]<br>At least twice a year (once in winter and once in summer season) |
| Transportation survey | Prerequisite – I & P<br>At least once per year | Credit – I & P[20]<br>Once a year. | – | –<br>– | Credit – I & P<br>At least once a year[21] | –<br>– |
| Waste stream audit | Credit – I & P<br>At least once every five years | Credit – I & P<br>Once or twice a year | Prerequisite – I & P<br>At least every three years | Credit – I<br>Within the last three years of initial certification | Credit – I & P<br>At least once a year | –<br>– |
| IAQ audit | Prerequisite – I & P<br>At least one per yearMeasurements of TVOC and $CO_2$ may come from installed sensors or one-time air testing during normal occupied hours, under typical minimum ventilation conditions. | Credit – I & P<br>Once a year | Credit[22] – I or P<br>At a minimum, testing should be conducted over a typical workday, taking into account fluctuations in contaminant levels that may occur. Testing should be conducted, at a minimum, in the morning and afternoon. | Credit – I<br>Must conduct in the past year of initial certification. | Credit – I & P[23]<br>Measure $CO_2$ concentration levels within the regularly occupied primary spaces during regular occupancy hours, either within the breathing zone, or at return air grilles. | Prerequisite – Only P[24]<br>At least once a year[25] |
| Lighting comfort | –<br>– | –<br>– | –<br>– | –<br>– | Credit – I & P[26]<br>Measure the general illuminance levels at least once a year | –<br>– |
| Acoustic comfort | –<br>– | –<br>– | –<br>– | –<br>– | Credit – I & P[27]<br>Measure the internal ambient noise levels of each regularly occupied primary space every three years | –<br>– |
| Outdoor air ventilation rate | Prerequisite – I[28]<br>– | Credit – I & P<br>Every three years (Must have been taken within 12 months of the assessment date and when major changes to the building or its occupancy have been made). | –<br>– | –<br>– | Credit – I & P<br>Once every three years | Prerequisite – I[29]<br>– |
| Occupant comfort survey | Prerequisite – I & P<br>At least once per year | Credit – I & P<br>At least once a year | –<br>– | Credit – I<br>Within the last three years of initial certification | Credit – I & P[30]<br>Once a year | Prerequisite – Only P[31]<br>Once a year |
| Enhanced occupant survey | –<br>– | –<br>– | –<br>– | –<br>– | –<br>– | Credit – Only P<br>Once a year |
| Green cleaning audit | Credit – I & P<br>Conduct an annual audit in accordance with APPA Leadership in Educational Facilities' Custodial Staffing Guidelines, or a local equivalent | –<br>– | Prerequisite – I & P<br>After an initial green cleaning program, reports should be annually reviewed and updated. | –<br>– | Credit – I<br>– | –<br>– |

**Table 3** (*continued*)

| Survey/Audit/other monitoring requirement | LEED v4.1O + M Existing Buildings | BREEAM In-Use | BOMA BEST 3 | Green Globes – EB[11] | Green Star – Performance | Well v2 |
|---|---|---|---|---|---|---|
| Walk-through water audit | – | – | – | Credit – I | – | – |
| | – | – | – | Within the last three years of initial certification | – | – |
| Monitor Fundamental Water Parameters[32] | – | – | – | – | – | Prerequisite – Only P |
| | – | – | – | – | – | At least once a year |
| Monitor Water Contaminant Parameters[33] | – | – | – | | – | Prerequisite – Only P |
| | – | – | – | | – | At least once a year |
| Asbestos[34] and radon[35] survey | – | – | – | Credit – I | – | – |
| | – | – | – | Record the condition of all asbestos and check if radon level is below 4p Ci/L. | – | – |

[11] All of the stated metering data requirement is only for initial certification.
[12] Projects in Europe may use the energy audit procedure defined in EN 16247-2:2014.
[13] Continuous monitoring of air temperature and humidity in occupied spaces, at sampling intervals of 15 min or less.
[14] Periodic testing of air speed and radiant temperature in occupied spaces. Using handheld meters is permitted.
[15] Only operating temperature needs to be managed. As a proof building management system reading for indoor temperature or manual recordings of summer and winter temperature can be submitted.
[16] The measured temperature and relative humidity results should be compared with the specified reference range in the Thermal Comfort Calculator of Green Star.
[17] The dry-bulb temperature, relative humidity, air speed (only for projects that use elevated air speed method) and mean radiant temperature are monitored in regularly occupied spaces within the building for 10 min, with measurements recorded at least once every minute.
[18] Projects in India may use THE NATIONAL BUILDING CODE OF INDIA 2005 (NBC 2005) to meet the desired comfort criteria.
[19] Measurements should be taken at different times throughout occupied hours.
[20] In case of BREEAM In-Use transportation survey is limited to staff commute survey only. This does not include additional business-related trips, such as external meetings.
[21] Determine conventional single-occupant vehicle use.
[22] There should have an IAQ monitoring plan even though IAQ audit is not a prerequisite.
[23] Measurement of CO2 levels (ppm) or outdoor air flow rates.
[24] Minimum of one continuous hour (10 min of acclimation time followed by 50 min of measurement time), with measurements recorded at least once every minute.
[25] Measurement method: measurement of individual VOCs or total VOCs using real-time direct reading instrument.
[26] The measurement of lighting levels.
[27] Internal noise levels – Measured sound level dB (A).
[28] Use minimum IAQ calculator to calculate minimum outdoor air rate.
[29] For mechanically ventilated spaces maintain outdoor air ventilation rate as per ASHRAE 62.1 – 2019 or CEN Standards EN 15251:2007 and EN 16798-3:2017 or AS 1668.2 – 2012 or CIBSE Guide A. For naturally ventilated spaces maintain outdoor air ventilation rate as per ASHRAE 62.1 – 2019 or CIBSE AM10.
[30] Determine occupant satisfaction market position in IAQ, thermal comfort, acoustic comfort etc Occupant survey covers general building and occupancy information including job type or time spent in the building, indoor environmental quality of air, water, light, sound and thermal comfort, ergonomics.
[31] Occupant survey covers general building and occupancy information including job type or time spent in the building, indoor environmental quality of air, water, light, sound and thermal comfort, ergonomics, layout and aesthetics, maintenance and cleanliness, amenities, self-rated health and well-being etc.
[32] Such as turbidity, coliforms.
[33] Such as dissolved metal, organic pollutant, disinfectant by-products etc.
[34] This survey is only applicable if asbestos was used in construction.
[35] Radon is a colorless, odorless, naturally occurring, radioactive gas produced by radium decay that can cause lung cancer.

**Table 4**
Characteristics of surveyed certification programs in terms of data tracking flexibility.

| Certification Schemes | Assessment Criteria | Data Tracking Flexibility |
|---|---|---|
| LEED v4.1 O + M | Need to obtain minimum passing score (40–49%) to get certified.<br>Need to obtain minimum passing score (40%) in each performance category.<br>Need to fulfill prerequisites which largely depends on data collection in five categories: Energy, Water, Transportation, Waste and Human Experience<br>Need to fulfill prerequisite survey requirements e.g., occupant comfort survey, IAQ survey, transportation survey etc. | Strict |
| BREEAM In-Use | Need to obtain minimum passing score (≥25 to <40%) to get certified.<br>Adopt a 'balanced score-card' approach which means majority of credits can be traded, i.e. non-compliance in one area can be off-set through compliance in another to achieve the target rating.<br>Need to obtain minimum standards of performance in key areas e.g. energy, water, waste – a part of which involves data collection in water and energy category. | Conditionally flexible |
| BOMA BEST 3 | Need to achieve up to 19% on the questionnaire to get certified.<br>There is no minimum passing score in each performance category.<br>Need to satisfy prerequisite data tracking e.g., water, energy and survey requirements. | Conditionally flexible |
| ENERGY STAR | Need to obtain ENERGY STAR score ≥ 75% to get certified.<br>Need to satisfy prerequisite data tracking requirement in Energy category. | Strict |
| WELL v2 | Need to obtain minimum passing score (50 points – 45.45%) to get certified.<br>For Air and Thermal Comfort concepts it is necessary to fulfill a minimum of two points per concept or at least four points combined.<br>Need to satisfy prerequisite data tracking requirements for certain categories e.g., indoor air quality, thermal comfort, water, community. | Strict |
| Green Globes – EB | Need to obtain minimum passing score (≥35%) to get certified.<br>There is no prerequisite in terms of data collection to obtain this certification. | Flexible |
| Green Star – Performance | Need to achieve minimum practice score (10 – 19%) to get certified.<br>Need to maintain prerequisite data tracking requirement for greenhouse gas emissions and potable water. | Conditionally flexible |

rization, the post-occupancy data collection and analysis approaches listed in Table 4 acted as the assessment criteria.

### 6.2.2. Differences in energy metering and submetering requirements

As discussed in Section 5, energy conservation strategies proposed by surveyed certification schemes include various energy metering and sub-metering requirements which differ from one certification scheme to another. Before we delve into presenting the data infrastructure prescribed by the certification programs, the flow of energy is considered first in a building structure. As shown in Fig. 1, energy flowing into a building can be divided into four segments: resource at site, end-use level, system-level and zone level. Electricity and natural gas are recognized as two site level resources that are common for all buildings. In many cases, electricity generated from different forms of renewable energy is added to the main electricity grid and distributed afterwards into the buildings. To identify the portion of a building's total energy use being meet by renewable energy systems, there is a necessity of using submeter for this. Subject to credit compliance set by different certification schemes a certain proportion of credit points can be earned and this point varies depending on the percentage of renewable energy generated or the percentage of green power purchased or carbon offsets. As illustrated in Fig. 1, submetering major end uses refer to submetering major energy consuming equipment such as chillers, boilers, lighting, plug loads, fans and pumps. To understand the flow of energy into a building in system and zone level, a more detailed data infrastructure is required which is only possible if floor or tenant-level submeters are available for lighting and plug loads. Submetering system-level chilled water and steam/hot water enable tracking of heating and cooling load for individual air handling units (AHUs) while zone level submetering allows tracking of heating and cooling loads for individual variable air volume (VAV) boxes.

A comprehensive data infrastructure covering all energy segments enables continuous monitoring of building performance, which in turn supports executing data-driven operation strategies. Fig. 1 portrays these energy metering and sub-metering requirements prescribed by certification schemes in the context of a building's energy flow. It is prescribed by all certification programs to meter site-level resources for all fuel types. It is also proposed by all certification schemes to meter generated steam and chilled water. However, there are variations in submetering requirements at the end-use level, system-level and zone-level. Please note the symbols n, m and k used in Fig. 1 stand for respectively the number of floors, AHUs and VAV boxes existing in a building and these numbers may vary depending on the building and HVAC system configurations. The black, blue and red lines with arrows indicate the flow of electricity, chilled water and steam respectively within a building.

### 6.2.3. Imbalance between site-level and user-level resource savings

As shown in Fig. 1, all reviewed certification schemes emphasized the environmental context of site-level resource savings by establishing a prerequisite for data collection of source energy consumption (e.g., electricity, natural gas, fuel oil, steam, chilled water) even though this data collection is not mandatory for Green Globes EB. On the other hand, user-level resource savings have a lower priority in the surveyed certification schemes. There is no clear framework set by Energy Star and BOMA Best 3 for end-use submetering or tenant submetering or floor-level submetering that encourages user-level resource savings, while for other surveyed certification schemes these requirements act as credit requirements. It is worthwhile to note that credit data requirements are separated in this paper from prerequisite data requirements as there are some flexibilities in credit compliance for these data. However, fulfilment of these credit data requirements enables gaining points towards targeted certification and impacts the total credit points which is especially important when a high score is targeted or where there is a necessity to improve the level of certification during the recertification phase. On the other hand, in case of the certification schemes (such as BREEAM In Use) which are based on feature specific approaches, none of the data collection requirements acts as a prerequisite except the energy consumption data for 12 consecutive months. However, a minimum credit point is set by these certification programs and it is not possible to achieve this score only fulfilling the prerequisite requirement. Therefore, to achieve the minimum point score, some of the credit requirements must be fulfilled.

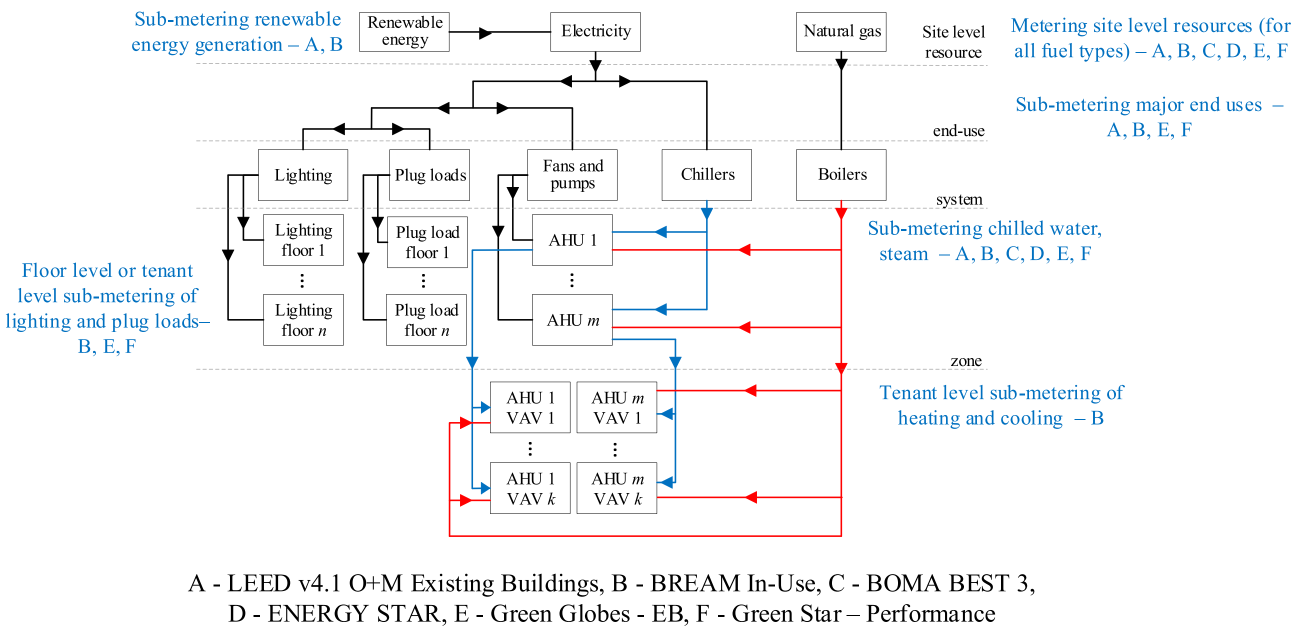



**Fig. 1.** Energy metering and sub-metering requirements as per surveyed certification schemes.

*6.2.4. Differences in energy meter-data tracking intervals*

Although it is a general requirement from all surveyed certification schemes to monitor and record whole building energy meter data for all fuel types such as electricity, natural gas, chilled water, steam, fuel oil, propane, etc., there is an important difference between these certification schemes in terms of prescribed data logging interval and data-logging period. While LEED O + M, BOMA BEST 3, Energy Star, Green Star-Performance prescribes monthly interval data for 12 consecutive months, some certification schemes such as BREEAM In-Use, Green Globes EB are flexible about the monthly data tracking requirement and allow recording only annual energy consumption. It is important to note that once a building is Green Globes – EB certified, there are no further data tracking requirements to maintain its certification.

*6.2.5. Inconsistency between data submission interval and data recording period*

While LEED O + M, Green Star-Performance, and BOMA BEST 3 certification schemes have made it compulsory for their certified projects to submit data e.g., energy, water, etc. every three years to maintain their certifications, there is no requirement to maintain the data log for the whole period. As detailed in Section 4, only one-year of data is needed during recertification to reassess the performance of their certified buildings. On the contrary, Energy Star and BREEAM In-Use necessitate annual data submission for the renewal of certification.

*6.2.6. Differences in building-specific requirements and categorization*

While some surveyed certification schemes (e.g., BOMA BEST 3, Energy Star) recognize that because of structural differences and specific applications, different building types necessitate different or additional sustainability strategies associated with data collection, others, e.g., Green Globes EB, Green Star Performance suggest the same method for all building types. A brief description of the building categories included within these certification schemes can be found in Appendix B Table B1. This table also points out relevant limitations of individual certifications.

*6.2.7. Differences in energy performance assessment approaches*

There are differences in energy performance assessment approaches proposed by different certification schemes. For instance, LEED v4.1 O + M, BOMA BEST 3, Energy Star, and Green Star – Performance compare performance indicators (e.g. EUI or GHG emissions) against established benchmarks. On the other hand, feature-specific approaches are used by BREEAM In-Use where credits are awarded when the criteria for specified features (such as availability of energy meter and sub-meter data for the specified period, conduct IAQ and occupant comfort survey once a year, etc.) are met. Green Globes – EB follows a hybrid energy performance assessment approach.

*6.2.8. Differences in survey or audit requirements*

Table 3 shows that Well v2 puts special emphasis on thermal comfort, IAQ, water quality and occupant comfort surveys. However, energy use analysis, transport, and waste stream surveys are beyond the scope of this certification scheme. LEED v4.1O + M and BREEAM In-Use prescribe quite similar survey requirements, although LEED v4.1O + M specifies more comprehensive surveys, such as an energy use analysis survey, and a green cleaning survey. Also, the surveys prescribed by LEED v4.1O + M are mostly the prerequisite requirements which must be fulfilled during certification. On the other hand, BREEAM In-Use offers credit points for measuring ventilation rates every three years. Thus, this certification scheme ensures monitoring and adjusting the fresh air percentage intermittently to maintain IAQ whereas LEED v4.1O + M prescribes this measuring requirement as a prerequisite for initial certification only. The surveys proposed by BOMA BEST 3 can be considered inadequate compared to that of LEED v4.1O + M as they lack some general survey requirements, such as thermal comfort, transportation, occupant comfort surveys, etc. The only non-North American certification scheme considered in this study is Green Star – Performance. This certification scheme covers almost all identified surveys except the ASHRAE preliminary energy use analysis and Level I walk-through assessment survey. Additionally, this certification scheme suggests some additional survey requirements such as visual and acoustic comfort. However, this certification lacks any prerequisite survey requirements for the initial and post-certification stages. Fig. 2 presents a synopsized picture of the proposed survey/audit/other monitoring strategies of different certification schemes. This figure shows that IAQ audits, occupant comfort surveys, and waste stream audits are the most common audit requirements suggested by almost all surveyed certification schemes. On the contrary, enhanced occupant survey, lighting and acoustic comfort, and monitoring water parameters are some of the least common audit/monitoring requirements suggested by the certification schemes.

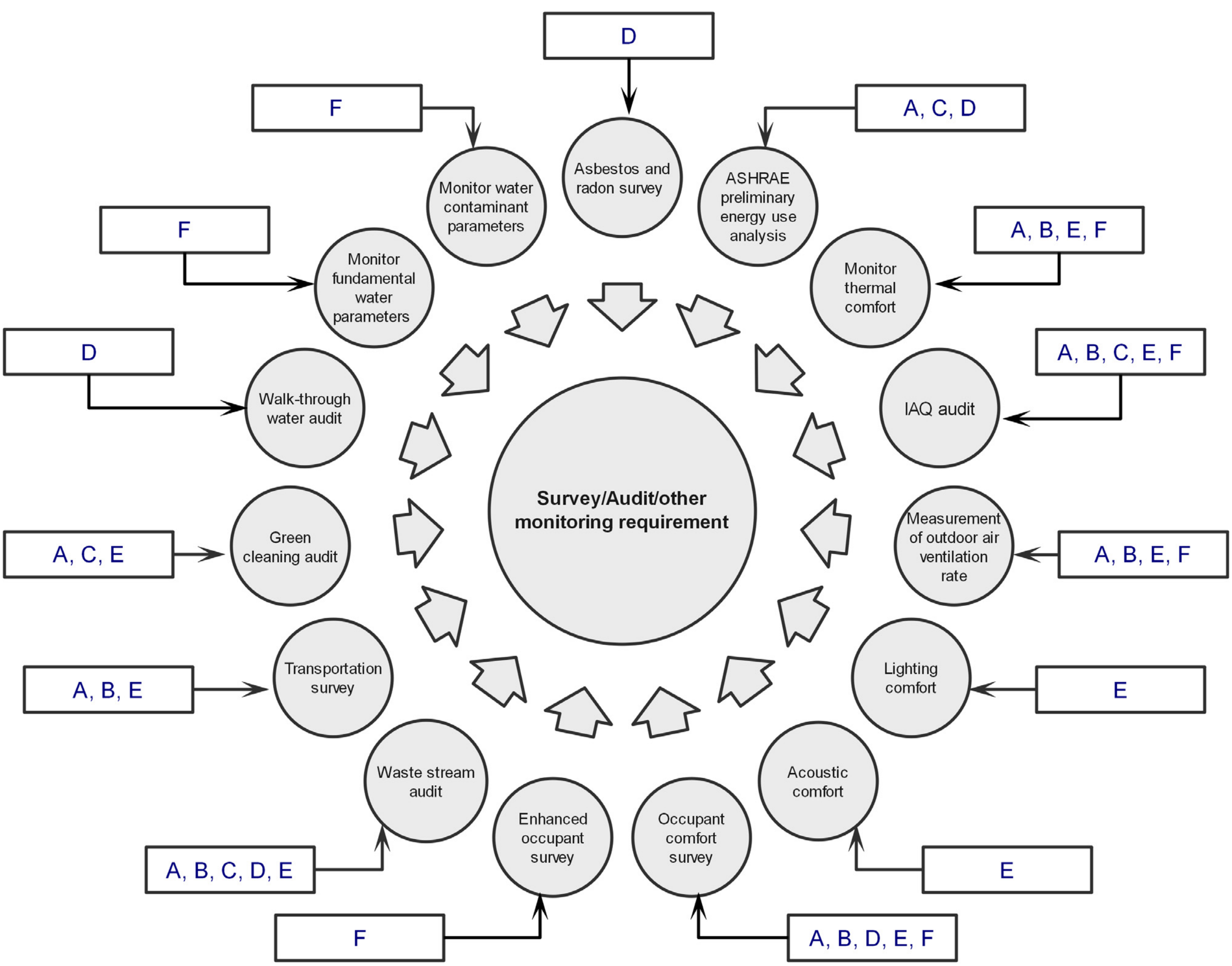
### 6.3. Recommendations

The review of existing case studies indicates that there are major discrepancies between design and measured performance in certified buildings. The need for more effective data management in both design and operation has been recognized by Gerrish, et al. [56] to support building performance management. Data-driven building operation strategies can help us realize the benefits envisioned by the certification programs. To implement data-driven building operation strategies, the certification programs should prescribe standard data infrastructure such as detailed meter and submeter infrastructure and occupant feedback collection practices. This standard data infrastructure may act as an enabling technology to ensure that building performance can be continuously monitored, and anomalies can be detected and addressed.

The absence of data infrastructure and operational data collection standards currently undermine the potential of green building certification schemes. However, more research is required to decide exactly what data should be collected and how. The decision to invest in data infrastructure (sensors, meters, submeters, data archiving systems) should not be arbitrary. They should be linked to data-driven building operation applications: performance benchmarking, fault detection and diagnosis, predictive controls, and occupant-centric controls.

The limitations of surveyed certification schemes identified through their comparative studies yield some recommendations as discussed below.

- The energy performance improvement strategies of certification schemes should be quantitative since the outcomes of qualitative strategies such as developing a phantom power reduction program (using technology and human behaviour to shut down equipment) are not measurable. On the other hand, quantitative strategies such as submetering end uses allow setting a quantitative energy saving goal within a definite period. In this regard,




A - LEED v4.1 O+M Existing Buildings, B - BREEAM In-Use, C - BOMA BEST 3, D - Green Globes – Existing Building, E - Green Star – Performance, F - Well

**Fig. 2.** A synopsized picture of the proposed survey/audit/other monitoring strategies of different certification schemes.

Ahmad, et al. [36] stated that the increased installation of energy meters and environmental monitoring sensors can enable analytics solutions to diagnose operational issues and reduce energy use and GHG emissions. Regardless of setting an energy saving goal, detailed submetering facilitates data archiving which in turn supports data analytics to improve building operational performance [57]. Therefore, we recommend that the certification schemes would impose prerequisite requirements to submeter total energy usage at floor-level, by tenant and for major energy end uses. Besides, it is necessary to ensure that data collected from submetering devices is utilized efficiently to pinpoint building operational faults which can ultimately provide insights into any performance gaps if exists and guide in improving the performance of a building.

- A performance-based approach should be used by the certification schemes to assess the energy performance of a building, based on quantifiable performance indicators. However, it involves the establishment of an appropriate method for quantification of the energy performance and some specific criteria to judge the performance of the assessed buildings. To establish the performance-based approach and to encourage the buildings to perform better, there should be some specific guidelines (e.g., prerequisite data tracking requirements for key performance indices accompanied by relevant surveying requirements) proposed by these certification schemes.
- There should be consistency between the data tracking period and data submission interval set by the certification schemes to minimize the tendency of disregarding data logging for the whole period. Also, the data tracking interval of an energy meter should support the instantaneous response of demand-side management and troubleshooting on an hour or sub-hour basis.
- Building types should be clearly distinguished in certification schemes since baseline energy and water use is different for different building categories. Based on the application of building types there should be some strategic differences within the applied certification strategies.
- There should be continuous/periodic data tracking and monitoring requirements established by the certification schemes for energy, water, transportation, GHG emissions, occupant comfort, IAQ, etc. to improve the performance of existing certified buildings in order for them to their design intent.
- There should be credit point-based submetering requirements included within the certification schemes to promote on-site renewable energy systems; this requirement already exists in BREEAM In Use certification scheme.
- Overall, the levels of certification schemes including, minimum passing score, should be refined to achieve noticeable differences between certified and conventional buildings in terms of energy and occupant comfort performances.

## 7. Conclusions

Building post-certification activities are largely responsible for upholding the performance of green-certified buildings as well as incremental improvement of their environmental performance. Building certification schemes can play an important role by setting up a framework with action-oriented post-certification activities as well as re-certification at regular intervals. The review of case studies highlighted the performance gap in certified buildings. A survey of major operation and maintenance-related building certification schemes supported by case studies demonstrated that there are major discrepancies in data infrastructure and archiving practices that hinder the certified buildings from performing according to their design intent. This survey revealed the shortcomings of post-certification activities such as absence of data infrastructure and operational data collection standards, inconsistencies between data tracking periods and data submission intervals etc. Lastly, recommendations are developed for the standardization of data infrastructure and archiving practices to enable data-driven building operation strategies such as benchmarking, fault detection and diagnosis, predictive controls, occupant-centric controls, etc. As an outcome, it is expected that the findings of this study will shed light on the re-certification pathways providing new possibilities to explore in terms of their effectiveness.

Therefore, the contribution of this paper is to bring together a vast amount of information regarding post-occupancy data collection and analysis approaches prescribed by the surveyed certification schemes. The shortcomings of post-certification actions identified through surveying major operation and maintenance-related building certification schemes show new directions to strengthen the prescribed data tracking strategies.

Although this study attempts to provide a deep insight into different aspects of building post-certification actions directed by surveyed certification schemes, our focus was largely on the data requirements. Therefore, as future work, this study can be extended exploring policy and awareness related strategies suggested by the certification schemes that have an influence on building post-certification activities. Further, there is a necessity to put further research effort in utilizing the data for advanced level analysis to enable data-driven building operation and maintenance strategies which in turn can ensure building performance improvement.

In addition, taking into account the ongoing situation of COVID 19 pandemic, the certification schemes can prescribe additional IAQ sensing technologies and ventilation system audit requirements to minimize the risk of exposure to infectious aerosols.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This research is supported by research funding provided by Natural Resources Canada, CopperTree Analytics, Sensible Building Science, Delta Controls, Bentall GreenOak, and National Research Council Canada. The authors acknowledge Dr. Guy Newsham of the National Research Council Canada for his critical review.

## Appendix A

**Table A1**
An overview of existing building certification schemes.

| Certification scheme | Country of origin | International recognition | Assessment criteria | On-site verification authority for approval |
|---|---|---|---|---|
| LEED v4.1 O + M [51] | USA | 167 countries and territories | Location and Transportation (LT)<br>Sustainable Sites (SS)<br>Water Efficiency (WE)<br>Energy and Atmosphere<br>Materials and Resources (MR)<br>Indoor Environmental Quality (EQ)<br>Innovation (IN) | Green Business Certification Inc. reviewers |
| BREEAM In-Use [58] | UK | 84 countries | Management<br>Health & Wellbeing<br>Energy<br>Transport<br>Water<br>Materials<br>Waste<br>Land Use & Ecology<br>Pollution | Independent BREEAM assessors, trained, qualified and licensed by BRE Global Limited |
| WELL v2 [59] | USA | 58 countries | Air<br>Water<br>Nourishment<br>Light<br>Movement<br>Thermal Comfort<br>Sound<br>Materials<br>Mind<br>Community<br>Innovations | On-site performance verification is conducted by a WELL Performance Testing Agent followed by a performance review by a Green Business Certification Inc. (GBCI) WELL reviewer |
| Green Star – Performance [60] | Australia | Australia, New Zealand, and South Africa | Green Star – Performance assesses the operational performance of buildings across nine impact categories.<br>Management<br>Indoor environment quality (IEQ)<br>Energy<br>Transport<br>Water<br>Materials<br>Land use and ecology<br>Emissions<br>Innovation | An independent, third-party assessment panel of sustainable development experts |
| Energy Star [61] | USA | USA and Canada | Energy | A licensed Professional Engineer (PE) or Registered Architect (RA) |
| Green Globes EB [55] | USA | USA and Canada | Green Globes for existing buildings program covers six different environmental assessment areas:<br>Energy<br>Water<br>Resources<br>Emissions<br>Indoor Environment<br>Environmental Management | A third-party Green Globes Assessor |
| BOMA BEST Sustainable Buildings 3.0 [62] | Canada | USA and Canada | Energy<br>Water<br>Air<br>Comfort<br>Health and Wellness<br>Custodial<br>Purchasing<br>Waste<br>Site<br>Stakeholder Engagement | A third-party assessor, retained by BOMA Canada or Local BOMA Associations |

**Table A2**
Prerequisite data requirement during recertification phases of LEED O + M.

| Category | Prerequisite data requirement | Frequency of data collection and duration |
|---|---|---|
| Energy | Whole building energy use meter or submeter data[36] e.g., electricity, natural gas, chilled water, steam, fuel oil, propane, etc.<br>Note 1: Meters owned by third parties (e.g., utilities or governments) are exempt. | On a monthly basis for twelve consecutive months |
| Water | Water consumption meter data for total potable water[37] use for the entire building and associated grounds including water subsystems e.g., irrigation, indoor plumbing fixtures and fittings, domestic hot water, process water, reclaimed water, boiler water, cooling towers etc<br>Note: Points are awarded based on water performance score[38]. It is a prerequisite to obtain a minimum water | On a monthly basis for twelve consecutive months |

**Table A2** (*continued*)

| Category | Prerequisite data requirement | Frequency of data collection and duration |
|---|---|---|
| | performance score of 40 which is equivalent to 6 points | |
| Transportation | Conduct a transportation survey[39] of building occupants on their commute patterns | Annually |
| Waste | The total weight of consumable waste (in lbs., kg, or tons) that is generated, and the total weight that is diverted from landfills and incineration facilities. | For one full year |
| Human Experience | Conduct an occupant satisfaction survey and/or an indoor air quality e.g., $CO_2$, Total Volatile Organic Compound (TVOC) evaluation[40]. | At least annually |

[36] Utility-owned meters capable of aggregating total project energy use are acceptable.
[37] Potable water is defined as water that is suitable for drinking and is supplied from wells or municipal water systems.
[38] The water performance score rates the building's total water consumption against the total water consumption of comparable high-performing buildings.
[39] Building occupants shall provide information e.g., Commuting transportation mode(s) and Distance travelled (in miles or kilometres) on their two-way commutes over one work week and consider seasonal variations and variations in work schedules.
[40] Measurements may come from installed sensors or from one-time air testing. For TVOC, measurements must be provided in μg/m3. CO2 data must be reported in ppm.

**Table A3**
Prerequisite data requirement during recertification phases of BREEAM In-Use.

| Prerequisite data requirement | Frequency of data submission |
|---|---|
| Meter readings or utility bills specifying the total quantity of water consumed (in cubic metres) in the reporting year | Annually |
| Copy of annual utility bill for all energy uses. | Annually |
| Where the building has been occupied for more than 3 years: copy of last two years of energy use records | |
| Where the building has been occupied for less than 3 years: copy of last 12 months of energy use records | |

**Table A4**
Credit data requirement during recertification phases of BREEAM In-Use.

| Credit data requirement | Frequency of data submission |
|---|---|
| Copies of verified sub-meter data of other energy uses: exterior lighting, all means of vertical transportation (e.g. lifts and escalators), display and aesthetical effects of lighting, ventilation, heating and cooling in transitional spaces (e.g. air curtains and revolving doors), small power for the first and last date of the 12-month reporting period. | Every three years[41] |
| Copies of bills or verified heating and cooling sub-meter data[42] for tenanted areas for the 12-month period specified | Every three years[43] |
| Relevant spreadsheets or energy benchmarking data[44] identifying energy performance trends | Annual |
| Energy saving data such as electricity savings from the main supply source, natural gas savings, LPG savings, oil savings, solid fuel savings, district heating and cooling energy savings, increase of renewable energy generated onsite based on a benchmark of energy used 3 years ago in kWh/annum/$m^2$ | Annual |
| Meter readings or utility bills specifying the amount of water consumed from potable and non-potable water sources (including groundwater, rainwater and municipal water supply) by the asset in the reporting year ($m^3$/annum) | Every three years |
| Calculations based on metered data for both mains and alternative supplies to demonstrate the percentage of water consumption obtained from alternative supplies. Or | Every three years |
| Meter readings for both mains and alternative supplies to allow assessor to calculate percentage of water from alternative supplies. | |
| Copy of non-mains water extraction metered data to avoid over-extraction | Every three years |
| Water consumption meter readings for two successive years including current year demonstrating continual improvement of water performance | Annual |
| Meter readings or utility bills specifying the total quantity of water consumed (in cubic metres) during the last calendar year | Annual |
| Measurement of fresh air rates[45] | Every three years |
| Conduct staff commuting[46] survey illustrating a relevant transport data for car, train, bus etc. in km/annum | Annual |
| Collect business travel e.g., long haul flights, short haul flights, domestic flights, car, train etc. transport data | Annual |
| Data on transport of goods e.g., heavy goods vehicle, large goods vehicle, van etc. to and from the asset (km/annum) | Annual |
| Conduct occupant satisfaction surveys | At least annually |
| Monitoring of internal air quality and making changes to address issues raised | Annual |
| Recording/monitoring[47] waste arisings within the asset by providing up to date figures for waste types such as paper, cardboard, packaging, plastics etc. produced within the asset on (at least) a monthly basis and presented annually. | Annual |
| Conduct waste management audit | Annual |
| Quantity of waste sent to landfill in metric tonnes during last calendar year | Annual |
| Quantity of waste diverted from landfill in metric tonnes during last calendar year | Annual |
| Quantity of waste sent for incineration in metric tonnes during last calendar year | Annual |
| Conduct office surveys and occupant surveys associated with minimising, recycling and managing waste | Annual |

[41] On condition there are no significant changes.
[42] For naturally ventilated assets: only heating sub-meters must be provided.
[43] On condition there are no significant changes.
[44] All energy consumption on site such as electricity, natural gas, LPG, District heating and cooling, etc. should be measured and compared with historical data and performance targets.
[45] Must have been taken within 12 months of the assessment date and when major changes to the building or its occupancy have been made.
[46] Staff commute relates to the total distance that people that work in the asset travel to and from work. This does not include additional business-related trips, such as external meetings.
[47] Bills from waste carriers, does not count as active monitoring/recording.

**Table A5**
On-going prerequisite and credit data monitoring and reporting requirements for WELL v2 certification.

| Category | On-going data report | Measurement details | Measurement time and sampling interval | Monitoring Interval |
| --- | --- | --- | --- | --- |
| Air[48] | Prerequisite – Monitor fundamental air parameters e.g., individual VOCs or total VOCs | Measurement method: real-time direct reading instrument of | Minimum of one continuous hour (10 min of acclimation time followed by 50 min of measurement time), with measurements recorded at least once every minute. | At least once a year |
| | Credit – Implement indoor air monitors | Indoor air monitoring data are analysed for regularly occupied hours (e.g., median, mean, 75th, 95th percentile)<br>Indoor air monitors should be recalibrated or replaced annually, with documentation attesting to their calibration or replacement | – | – |
| Water[49] | Prerequisite – Monitor Fundamental Water Parameters e.g., turbidity, coliforms | Test turbidity and coliforms at 5% of the total number of fixtures (as applicable) for drinking water, handwashing, showers/baths and for cooking purposes within each configuration of in-building water treatment[50]. | – | At least once a year |
| | Prerequisite – Monitor Water Contaminant Parameters e.g., dissolved metal, organic pollutant, disinfectant by-products etc. | – | – | At least once a year |
| | Credit – Test and Display Water Quality | All water delivered to the project for human consumption is tested for Lead, Copper, Turbidity and Coliforms. | – | Four times a year |
| Movement[51] | Credit – Promote Participation Awareness | Report anonymized monthly averages of awareness of engagement in physical activity promotion programs | – | – |
| Thermal Comfort[52] | Prerequisite – Monitor Thermal Parameters | The dry-bulb temperature, relative humidity, air speed (only for projects that use elevated air speed method) and mean radiant temperature are monitored in regularly occupied spaces within the building | Total of 10 min, with measurements recorded at least once every minute. | At least twice a year (once in winter and once in summer) |
| | Credit – Monitor Thermal Environment | Thermal comfort monitoring data are analysed for regularly occupied hours (e.g., median, mean, 75th and 95th percentile)<br>Dry-bulb temperature and relative humidity sensors should be recalibrated or replaced annually. Air speed and mean radiant temperature sensors should be calibrated as per manufacturer's specification. | – | – |
| Community[53] | Prerequisite – Administer Survey and Report Results | Aggregate results from the occupant survey[54] are reported | – | Once a year |
| | Credit – Select Enhanced Survey | Aggregate results from the enhanced occupant survey are reported | – | Once a year |
| | Credit – Administer Pre-Occupancy Survey and Report Results | Aggregate results from the pre-occupancy Survey are reported<br>Pre-occupancy survey results are compared against results of the post-occupancy survey, and the results of comparison are included in an annual report | – | Once a year |
| | Credit – Facilitate Interviews and Focus Groups | Aggregate results from the stakeholder interviews, focus groups and/or observation are reported | – | Once a year |

[48] A01 Fundamental Air quality and A08 Air Quality Monitoring and Awareness.
[49] W01 Fundamental Water Quality, W02 Water Contaminants and W05 Water Quality Consistency.
[50] Details about test method can be found in [59]. *WELL Performance Verification Guidebook*, I. W. B. I. (IWBI), 2019. [Online]. Available: https://a.storyblok.com/f/52232/x/c175c47f05/well-performance-verification-guidebook-with-q3-2019-addenda_final.pdf
[51] V11 Physical Activity Promotion.
[52] T01 Thermal Performance and T06 Thermal Comfort Monitoring.
[53] C03 Occupant Survey, C04 Enhanced Occupant Survey.
[54] Occupant survey covers general building and occupancy information including job type or time spent in the building, indoor environmental quality of air, water, light, sound and thermal comfort, ergonomics, layout and aesthetics, maintenance and cleanliness, amenities, self-rated health and well-being etc.

**Table A6**
Prerequisite data requirements during recertification phases of Energy Star certification.

| Category | Prerequisite data requirement | Frequency of data collection and duration |
| --- | --- | --- |
| Energy – An ASHRAE Level 1 Energy Assessment | Whole building energy consumption meter data (in kWh) for all fuel types e.g. electricity, gas, oil, steam, onsite renewable energy, etc. | On a monthly basis for 12 most recent consecutive months[55]. |

[55] Energy data cannot be a bulk amount representing the complete 12-time frame.

**Table A7**
Prerequisite data requirements during recertification phases of BOMA BEST certification.

| Category | Prerequisite data requirement | Frequency of data collection and duration |
| --- | --- | --- |
| Energy – An ASHRAE Level 1 Energy Assessment | Whole building energy consumption meter data[56] for all fuel types e.g. electricity, gas, oil, steam, onsite renewable energy, etc[57]. | On a monthly basis for 12 or 24 consecutive months[58] based on building types[59]. |
| Water assessment | Water consumption data for all meters (indoor and outdoor)[60]. | For 12 consecutive months[61]. |
| Waste | Conduct a waste audit (The analysis must, establish an overall picture of the building's performance by providing a summary of waste generated for each of the different measured sub-categories such as paper and cardboards, recyclable plastic, metals and aluminium etc., the resulting diversion rate[62] and the capture rate[63]. | At least every three years[64] |

[56] This data is used to calculate the weather-normalized site EUI and an ENERGY STAR Score. There should be at least 12 consecutive months of energy consumption data to obtain an Energy STAR Score.
[57] The entered data must not be any older than the past 36 months.
[58] Energy data cannot be a bulk amount representing the complete 12 or 24-month timeframe.
[59] For office and universal building types (listed on eligible building types for ENERGY STAR Score) there should be at least 12 consecutive months of energy consumption data to calculate the ENERGY STAR Score whereas for Multi-Unit Residential Buildings, Health Care, Enclosed Shopping Centres, Light Industrial, Open Air Retail at least 24 consecutive months of energy consumption data is required to calculate the Weather-normalized Site Energy Use Intensity.
[60] The entered data must not be any older than the past 18 months nor should it represent consumption during periods of major renovations.
[61] Water consumption data can be a single bulk value representing the complete 12-month timeframe.
[62] The Diversion Rate is the proportion by mass of all waste diverted from disposal (i.e. landfill or incineration) to the total weight of all waste material generated, expressed as a percentage.
[63] The Capture Rate is the proportion by mass of all waste currently diverted from disposal (i.e. landfill or incineration) to the total mass of all waste material that could have been diverted, expressed as a percentage.
[64] Annual audits are recommended.

**Table A8**
Prerequisite and credit data requirements during recertification phases of Green Star – Performance certification.

| Category | Sub-category | Prerequisite and credit data requirements | Frequency of measurements |
| --- | --- | --- | --- |
| Indoor Environmental Quality | Indoor air quality | Indoor Pollutant Control: Carbon Dioxide Concentration –measurement[65] of CO2 levels (ppm) or outdoor air flow rates | Measured data can be logged for all regularly occupied primary spaces throughout the building or a representative sample of (at least 10) regularly occupied primary spaces can be selected to log measured data.<br>Alternatively, the ventilation effectiveness section of the valid NABERS[66] Indoor Environment Report can be submitted |
| | Lighting comfort | General Illuminance | The measurement of lighting levels should be performed at least once during the performance period, within the normal hours of operation of the lighting systems.<br>Alternatively, the horizontal illuminance section of the valid NABERS Indoor Environment Report can be submitted confirming that greater than 80% of 'locations sampled' are in accordance with AS 1680. |
| | Thermal comfort | Indoor temperature<br>Note: The measured temperature results should be compared with the specified reference range[67] in the Thermal Comfort Calculator of Green Star. | At least twelve (12) times during the 12 months performance period, i.e. a minimum of one (1) reading per calendar month[68]. |
| | | Indoor relative humidity<br>Note: The measured relative humidity results should be compared with the specified reference range[69] in the Thermal Comfort Calculator of Green Star. | At least twelve (12) times during the 12 months performance period, i.e. a minimum of one (1) reading per calendar month[70]. |
| | Acoustic comfort | Internal noise levels – Measured sound level dB (A) | A verification of sound levels should be performed at least once during the performance period during the normal operation of the building's systems.<br>Alternatively, the ambient sound section of the NABERS Indoor Environment Report can be submitted |
| | Occupant satisfaction | Occupant satisfaction levels – Determine occupant satisfaction market position in indoor air quality, thermal comfort, acoustic comfort etc. | Conduct occupancy comfort survey once a year.<br>Alternatively, a valid NABERS Indoor Environment Report can be submitted |
| Energy | Greenhouse gas emissions[71] | Building Energy Baselines – Building annual energy consumption data (GJ) from individual energy sources e.g., electricity, green power, natural gas, LPG etc. | – |
| | Peak electricity demand | Preliminary benchmark for commercial buildings | Month wise data for peak electricity demand (kVA) for 12 consecutive months |
| Transport | Transport modes | Improved transport modes performance | Conduct a transport mode survey annually to determine conventional single-occupant vehicle use |
| Water | Potable water | NABERS Water[72] – Amount of recycled/non-potable water[73] (kL) e.g., rainwater or stormwater, or recycled/recovered from a previous use such as blackwater or greywater recovery and non-recycled/potable water (kL) | – |

(continued on next page)

**Table A8** (*continued*)

| Category | Sub-category | Prerequisite and credit data requirements | Frequency of measurements |
|---|---|---|---|
| Material | Procurement and purchasing | Consumable materials[74] – Total amount of materials and amount of materials purchased according to procurement framework (L, kg, reams) | – |
| | | Refurbishment materials – Total cost of refurbishment materials and cost of refurbishment materials purchased according to procurement framework (by cost) | – |
| | Waste from operations | Waste to landfill reduction – The amount of operational waste e.g. general waste, paper & cardboard reduced through waste-to-landfill diversion practices (by weight or by volume) | – |
| | Waste from refurbishments | Waste diverted from landfill – The amount of waste diverted from landfill | Month wise waste from refurbishments data (total amount of materials leaving the building, waste sent to landfill, recyclables/reusables in tonnes) for 12 consecutive months. |

[65] Measurements can be taken, e.g. using an automated Building Management System (BMS), handheld equipment, or other specialised measurement equipment either within the breathing zone, or at return air grilles.
[66] NABERS stands for National Australian Built Environment Rating System.
[67] Reference range used for indoor air temperature is based on an 80% occupant acceptability level, in accordance with Section 5.2/5.3 of ASHRAE 55 – 2013.
[68] Measurements should be taken at different times throughout occupied hours.
[69] The reference range used for indoor relative humidity is based on an 80% occupant acceptability level, in accordance with Section 5.2/5.3 of ASHRAE 55 – 2013.
[70] Measurements should be taken at different times throughout occupied hours.
[71] Building greenhouse gas emissions (kg.CO2-e p.a.) is calculated from energy consumption by multiplying individual source energy consumption data by corresponding emissions factor.
[72] This is a minimum requirement for buildings targeting a Green Star – Performance certification of 4 Stars or higher.
[73] It does not include water from rivers, lakes or groundwater (bore water) unless the water has previously been used.
[74] Excluding utilities such as electricity, gas, and services.

## Appendix B

**Table B1**
Building specific requirements, relevant characteristics and categorization as per surveyed certification schemes.

| Surveyed certification schemes | Building specific requirements, relevant characteristics and categorization | Limitations |
|---|---|---|
| LEED v4.1O + M | Existing whole buildings<br>Existing interiors[75]-<br>permanently install sub-meters for total potable water use for any fixtures or fittings in the project scope or pro-rate water use, using occupancy and base building water use.<br>permanently install sub-meters for all electricity and fossil fuels for equipment within the project scope or pro-rate energy use, using occupancy and base building energy use. | Building types are not clearly distinguished in this certification scheme. |
| BREEAM In Use | This certification suggests separate sub-meter for non-standard energy uses such as furnace or forming process, blast chilling or freezing for industrial buildings<br>Part 1 and part 2 of this certification is specially designed for all non-domestic existing building types.<br>Part 3 (Occupier Management) of this certification scheme is categorized for three types of existing non-domestic buildings: offices, retail – pilot version and healthcare – pilot version and specific data requirements have been set to serve only these three types of buildings. | This certification scheme is not suitable for domestic buildings in-use.<br>To receive a complete certification including all parts the asset must be an office, a retail or a healthcare building. |
| BOMA BEST 3 | This certification scheme classifies commercial buildings into two sections –<br>BEST Practices for Office, Enclosed Shopping Centre, Light Industrial, Open Air Retail, and Universal buildings<br>BEST Practices for Multi-Unit Residential Buildings and Health Care buildings.<br>Different minimum threshold requirements for certification are proposed for two specified categories | – |
| ENERGY STAR | This certification scheme recognizes detailed property types and any of the property types on their list is eligible to receive a 1 – 100 ENERGY STAR score[76] | – |
| Well v2 | – | This certification provides a common platform for all project types including new and existing buildings and interiors, educational facilities, commercial kitchen, retail, restaurants and multifamily residential without further categorization in terms of data or monitoring |

Table B1 (continued)

| Surveyed certification schemes | Building specific requirements, relevant characteristics and categorization | Limitations |
|---|---|---|
| | | requirements even though different sampling rates are suggested for multifamily residential. |
| Green Globes EB | – | The strategies proposed by this certification associated with data requirements are generalized for large commercial buildings without further categorizing them for different commercial building types. |
| Green Star – Performance | – | This certification is not suitable for single detached dwellings (single houses). There is no data categorization for individual building types. |

[75] Existing interior spaces refer to a portion of an existing building. Interior spaces may serve commercial, retail, or hospitality purposes.
[76] ENERGY STAR score is calculated by comparing a property with their similar properties nationwide that acts as a baseline.

## Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2020.110367.

## References


[1] E. Delzendeh, S. Wu, A. Lee, Y. Zhou, The impact of occupants' behaviours on building energy analysis: a research review, Renew. Sustain. Energy Rev. 80 (2017) 1061–1071, https://doi.org/10.1016/j.rser.2017.05.264.
[2] F. Fuerst, Building momentum: an analysis of investment trends in LEED and Energy Star-certified properties, J. Retail Leisure Property 8 (4) (2009) 285–297.
[3] United Nations Environment Program for Sustainable Buildings and Construction, UNEP, 2018., 2018. [Online]. Available: https://www.unenvironment.org/explore-topics/resource-efficiency/what-we-do/one-planet-network.
[4] J. Yudelson, The green building revolution (no. Book, Whole). Washington: Island Press, 2008.
[5] J. Wangel, M. Wallhagen, T. Malmqvist, G. Finnveden, Certification systems for sustainable neighbourhoods: what do they really certify?, Environ. Impact Assess. Rev. 56 (2016) 200–213, https://doi.org/10.1016/j.eiar.2015.10.003.
[6] A. Devine, N. Kok, Green certification and building performance: implications for tangibles and intangibles, J. Portfolio Manage. 41 (6) (2015) 151–163.
[7] L. Pastore, M. Andersen, Building energy certification versus user satisfaction with the indoor environment: Findings from a multi-site post-occupancy evaluation (POE) in Switzerland, Build. Environ. 150 (2019) 60–74, https://doi.org/10.1016/j.buildenv.2019.01.001.
[8] D. Licina, S. Bhangar, and C. Pyke, "Occupant Health & Well-Being in Green Buildings," (in English), Ashrae J., Article vol. 61, no. 4, pp. 74-77, Apr 2019. [Online]. Available: <Go to ISI>://WOS:000469118600008.
[9] "Project for Lean Urbanism Refining Research to Inform Field," in States News Service, ed, 2014.
[10] Pieter de Wilde, The gap between predicted and measured energy performance of buildings: a framework for investigation, Automation Constr. 41 (2014) 40–49, https://doi.org/10.1016/j.autcon.2014.02.009.
[11] Anna Carolina Menezes, Andrew Cripps, Dino Bouchlaghem, Richard Buswell, Predicted vs. actual energy performance of non-domestic buildings: using post-occupancy evaluation data to reduce the performance gap, Appl. energy 97 (2012) 355–364, https://doi.org/10.1016/j.apenergy.2011.11.075.
[12] P. de Wilde (Ed.), Building Performance Analysis, John Wiley & Sons, 2018.
[13] R. Galvin, Making the 'rebound effect' more useful for performance evaluation of thermal retrofits of existing homes: defining the 'energy savings deficit' and the 'energy performance gap', Energy Build. 69 (2014) 515–524, https://doi.org/10.1016/j.enbuild.2013.11.004.
[14] Daniel Godoy-Shimizu, Peter Armitage, Koen Steemers, Torwong Chenvidyakarn, Using Display Energy Certificates to quantify schools' energy consumption, Build. Res. Information 39 (6) (2011) 535–552.
[15] P. MacNaughton et al., Energy savings, emission reductions, and health co-benefits of the green building movement, J. Exposure Sci. Environ. Epidemiol., vol. 28, no. 4, p. 307, 2018.
[16] G.R. Newsham, J.A. Veitch, Yitian (Vera) Hu, Effect of green building certification on organizational productivity metrics, Build. Res. Information 46 (7) (2018) 755–766.
[17] J.H. Scofield, J. Cornell, A Critical Look at "Energy Savings, Emissions Reductions, and Health Co-benefits of the Green Building Movement, Nature Publishing Group, 2019.
[18] C. Menassa, S. Mangasarian, M. El Asmar, C. Kirar, Energy Consumption Evaluation of U.S. Navy LEED-Certified Buildings, J. Perform. Constr. Facil. 26 (1) (2012) 46–53.
[19] G.R. Newsham, S. Mancini, B.J. Birt, Do LEED-certified buildings save energy? Yes, but..., Energy Build. 41 (8) (2009) 897–905.
[20] A. Chokor, M. El Asmar, A novel modeling approach to assess the electricity consumption of LEED-certified research buildings using big data predictive methods, Constr. Res. Congress 2016 (2016) 1040–1049.
[21] C.M. Saldanha, S.M. O'Brien, A study of energy use in New York City and LEED-certified buildings, Proceedings of SimBuild, vol. 6, no. 1, 2016.
[22] J.H. Scofield, J. Doane, Energy performance of LEED-certified buildings from 2015 Chicago benchmarking data, Energy Build. 174 (2018) 402–413.
[23] John H. Scofield, Efficacy of LEED-certification in reducing energy consumption and greenhouse gas emission for large New York City office buildings, Energy Build. 67 (2013) 517–524, https://doi.org/10.1016/j.enbuild.2013.08.032.
[24] H.-H. Liang, C.-P. Chen, R.-L. Hwang, W.-M. Shih, S.-C. Lo, H.-Y. Liao, Satisfaction of occupants toward indoor environment quality of certified green office buildings in Taiwan, Build. Environ. 72 (2014) 232–242, https://doi.org/10.1016/j.buildenv.2013.11.007.
[25] S. Leder, G.R. Newsham, J.A. Veitch, S. Mancini, K.E. Charles, Effects of office environment on employee satisfaction: a new analysis, Build. Res. Information 44 (1) (2016) 34–50.
[26] P. MacNaughton, J. Spengler, J. Vallarino, S. Santanam, U. Satish, J. Allen, Environmental perceptions and health before and after relocation to a green building, Build. Environ. 104 (2016) 138–144, https://doi.org/10.1016/j.buildenv.2016.05.011.
[27] G.R. Newsham et al., "Do 'green' buildings have better indoor environments? New evidence," Building Research & Information, vol. 41, no. 4, pp. 415-434, 2013/08/01 2013, doi: 10.1080/09613218.2013.789951.
[28] G. Baird, A. Leaman, J. Thompson, A comparison of the performance of sustainable buildings with conventional buildings from the point of view of the users, Architectural Sci. Rev. 55 (2) (2012) 135–144.
[29] A. Hedge, L. Miller, J.A. Dorsey, Occupant comfort and health in green and conventional university buildings, Work 49 (3) (2014) 363–372, https://doi.org/10.3233/WOR-141870.
[30] Y.S. Lee, D.A. Guerin, Indoor environmental quality differences between office types in LEED-certified buildings in the US, Build. Environ. 45 (5) (2010) 1104–1112, https://doi.org/10.1016/j.buildenv.2009.10.019.
[31] S. Altomonte, S. Schiavon, Occupant satisfaction in LEED and non-LEED certified buildings, Build. Environ. 68 (2013) 66–76, https://doi.org/10.1016/j.buildenv.2013.06.008.
[32] S. Altomonte, S. Schiavon, M.G. Kent, G. Brager, Indoor environmental quality and occupant satisfaction in green-certified buildings, Build. Res. Information 47 (3) (2019) 255–274.
[33] Z. Gou, S. S.-Y. Lau, and Z. Zhang, A comparison of indoor environmental satisfaction between two green buildings and a conventional building in China, J. Green Build., vol. 7, no. 2, pp. 89-104, 2012.
[34] Maryam Khoshbakht, Zhonghua Gou, Yi Lu, Xiaohuan Xie, Jian Zhang, Are green buildings more satisfactory? A review of global evidence, Habitat International 74 (2018) 57–65.
[35] Y. Geng, W. Ji, Z. Wang, B. Lin, Y. Zhu, A review of operating performance in green buildings: Energy use, indoor environmental quality and occupant satisfaction, Energy and Buildings, vol. 183, pp. 500-514, 2019/01/15/ 2019, doi: 10.1016/j.enbuild.2018.11.017.
[36] M.W. Ahmad, M. Mourshed, D. Mundow, M. Sisinni, Y. Rezgui, Building energy metering and environmental monitoring – a state-of-the-art review and directions for future research, Energy Build. 120 (2016) 85–102, https://doi.org/10.1016/j.enbuild.2016.03.059.
[37] Y. Li, S. Kubicki, A. Guerriero, Y. Rezgui, Review of building energy performance certification schemes towards future improvement, (in English), Renew. Sust. Energ. Rev., Review vol. 113, p. 13, Oct 2019, Art no. Unsp 109244, doi: 10.1016/j.rser.2019.109244.
[38] U. Pont et al., Acquisition and processing of input data for building certification: An approach to increase the reproducibility of energy certificates, in eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2016: Proceedings of the 11th European Conference on

Product and Process Modelling (ECPPM 2016), Limassol, Cyprus, 7-9 September 2016, 2017: CRC Press, p. 243.
[39] W. Wei, O. Ramalho, C. Mandin, Indoor air quality requirements in green building certifications, Build. Environ. 92 (2015) 10–19, https://doi.org/10.1016/j.buildenv.2015.03.035.
[40] P. Wu, C. Mao, J. Wang, Y. Song, X. Wang, A decade review of the credits obtained by LEED v2.2 certified green building projects, Build. Environ. 102 (2016) 167–178, https://doi.org/10.1016/j.buildenv.2016.03.026.
[41] D.T. Doan, A. Ghaffarianhoseini, N. Naismith, T. Zhang, A. Ghaffarianhoseini, J. Tookey, A critical comparison of green building rating systems, Build. Environ. 123 (2017) 243–260, https://doi.org/10.1016/j.buildenv.2017.07.007.
[42] V. Menadue, V. Soebarto, T. Williamson, Perceived and actual thermal conditions: case studies of green-rated and conventional office buildings in the City of Adelaide, Architectural Sci. Rev. 57 (4) (2014) 303–319.
[43] L. Armitage, A. Murugan, H. Kato, Green offices in Australia: a user perception survey, J. Corp Real Estate 13 (3) (2011) 169–180.
[44] P. Ponterosso, M. Gaterell, and J. Williams, Post occupancy evaluation and internal environmental monitoring of the new BREEAM "Excellent" Land Rover/Ben Ainslie Racing team headquarters offices, Build. Environ., vol. 146, pp. 133-142, 2018/12/01/ 2018, doi: 10.1016/j.buildenv.2018.09.037.
[45] S. Ravindu, R. Rameezdeen, J. Zuo, Z. Zhou, R. Chandratilake, Indoor environment quality of green buildings: Case study of an LEED platinum certified factory in a warm humid tropical climate, Build. Environ., vol. 84, pp. 105-113, 2015/01/01/ 2015, doi: 10.1016/j.buildenv.2014.11.001.
[46] Q. Zhou, Design versus actual energy performance in green buildings, 2018
[47] Q. Zhou, Design versus actual energy performance in green buildings, Master of Applied Science, Department of Mechanical Engineering, University of Victoria, 2018. [Online]. Available: http://dspace.library.uvic.ca/bitstream/handle/1828/10416/Zhou_Qi_MASc_2018.pdf?sequence=1&isAllowed=y.
[48] P. de Wilde, Ten questions concerning building performance analysis, Build. Environ. 153 (2019) 110–117, https://doi.org/10.1016/j.buildenv.2019.02.019.
[49] H. Friedman, E. Crowe, E. Sibley, M. Effinger, The Building Performance Tracking Handbook, California Commissioning Collaborative, 2011.
[50] B. Mattoni, C. Guattari, L. Evangelisti, F. Bisegna, P. Gori, F. Asdrubali, Critical review and methodological approach to evaluate the differences among international green building rating tools, Renew. Sustain. Energy Rev. 82 (2018) 950–960, https://doi.org/10.1016/j.rser.2017.09.105.
[51] LEED v4.1 Operations and Maintenance, U. S. G. B. C. (USGBC), July 2019. [Online]. Available: https://www.usgbc.org/resources/leed-v41-om-beta-guide.
[52] US Environmental Protection Agency (EPA). https://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager (accessed).
[54] B. Nordman et al., Energy Reporting: Device Demonstration, Communication Protocols, and Codes and Standards, 2019.
[55] Green Globes for Existing Buildings, G. B. Initiative, February 9, 2018. [Online]. Available: https://thegbi.org/files/training_resources/Green_Globes_EB_Technical_Reference_Manual.pdf.
[56] T. Gerrish, K. Ruikar, M. Cook, M. Johnson, M. Phillip, C. Lowry, BIM application to building energy performance visualisation and management: challenges and potential, Energy Build. 144 (2017) 218–228, https://doi.org/10.1016/j.enbuild.2017.03.032.
[57] H. Burak Gunay, Weiming Shen, Guy Newsham, Data analytics to improve building performance: a critical review, Autom. Constr. 97 (2019) 96–109, https://doi.org/10.1016/j.autcon.2018.10.020.
[58] "BREEAM In -Use International 2015 " in "SD221 - 3.2," September 2019. [Online]. Available: https://tools.breeam.com/filelibrary/BREEAM%20In%20Use/SD096_-_Rev_24.1_BREEAM_In-Use_Scheme_Document.pdf.
[59] WELL Performance Verification Guidebook, I. W. B. I. (IWBI), 2019. [Online]. Available: https://a.storyblok.com/f/52232/x/c175c47f05/well-performance-verification-guidebook-with-q3-2019-addenda_final.pdf.
[60] Green Star – Performance, G. B. C. o. A. GBCA, 2017. [Online]. Available: https://new.gbca.org.au/green-star/rating-system/performance/.
[61] ENERGY STAR certification U. S. E. P. A. (EPA). [Online]. Available: https://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/earn-recognition/energy-star-certification.
[62] "Application Guide "BOMA BEST Sustainable Buildings 3.0"," BOMA Canada, April 2018. [Online]. Available: http://bomacanada.ca/bomabest/resourcesupdates/v3guide/.