LOW CARBON LIVING CRC

Addressing the discrepancy between as-built and as-designed in Australian energy efficient buildings

Rapid review

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- originality
- methodology
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- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2007), and provided constructive feedback which was considered and addressed by the author(s).

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Executive Summary

Background

Energy efficient buildings are viewed as one of the solutions to reduce carbon emissions from the built environment. However, studies worldwide indicate that there is a significant gap between the set building energy targets in the as-designed stage and the actual measured building energy consumption during occupancy. This is known as the regulatory energy performance gap (EPG). Several underlying causes for the EPG have been identified at all stages of the building life cycle. In Australia, issues relating to the construction and commissioning stages of the building have been identified. However, there is uncertainty on how to address them.

Objective

The objective of this rapid review is to locate and summarise published peer-reviewed review papers relating to the EPG in buildings. Emphasis will be placed on discussing the root causes for the gap in the pre-occupancy stages of the building life cycle focussing on the gaps relating to the construction and commissioning stages that influence the discrepancies between as-designed and as-built performance, as well as strategies to address these causes.

Data sources

Data sources included Scopus, Web of Science and ProQuest. Google Scholar and a Google search also pointed respectively to additional relevant articles and industry reports.

Study eligibility criteria

Peer-reviewed review articles (systematic literature reviews, meta-analysis and narrative literature reviews) focusing on the EPG in low carbon buildings were included in this review. Emphasis was on the building pre-occupancy stages, in particular, the construction and commissioning phases of the building life cycle. Included articles were published in English after 2010.

Study appraisal and synthesis methods

Studies that fulfilled the inclusion criteria were qualitatively summarised. The quality and risk of bias of these studies were assessed using an adapted version of the 16 questions from the AMSTAR2 tool.

Results

Nine review papers, published between 2014 and 2019 were included in this analysis. These articles collectively reviewed over 500 articles and/or case studies from several parts of the world. All articles reviewed causes for the EPG in the pre-occupancy stages of the building cycle and proposed recommendations to address the discrepancies between as-designed and as-built energy performance. Both residential and non-residential buildings were explored in the articles.

Limitations

Through the academic databases, only peer-reviewed studies that claimed to be systematic reviews or reviews of the literature were included. Due to the small number of comprehensive systematic literature reviews on the topic of interest, non-systematic reviews were also considered. An additional search using Google Scholar and Google was conducted to capture anything that may have been missed. Only studies published in English were included.

Conclusions and implications

This rapid review suggests that most causes for discrepancies between as-designed and as-built energy performance relate to a lack of knowledge and skills, lack of communication between stakeholders and a lack of accountability for building performance post-occupancy.

Recommendations to close the gap address the points above as well as improved standards. Key recommendations include:

- Training and upskilling of all new and current industry professionals
- Creating greater communication standards for stakeholders to share information
- Appointing a sustainability champion to oversee the construction, facilitate collaboration and close feedback loops
- Rating buildings' energy efficiency based on post-occupancy performance rather than predicted performance. This includes agreeing on performance guaranties
- Penalizing high operational energy use through an environmental tax
- Incentivizing savings over time through pay-for-performance programmes
- Making energy performance data accessible to promote transparency, to provide feedback to design teams and gather further evidence on the EPG
- Mandating testing and verification during the construction process.
- Developing new guidelines and standards, including residential building monitoring and verification standards, guidelines for common construction processes, equipment maintenance and commissioning to ensure as-built energy performance.

Amendments to the protocol

Two reports from the grey *(i.e.* non peer-reviewed) literature were included in this review as they were deemed critical to the subject of interest.

Introduction

Rationale

The building sector is responsible for 32% of global energy use and 19% of energy-related greenhouse gas emissions [1]. These numbers could double or triple by 2050 unless energy efficiency measures are implemented and best-practices mainstreamed [1]. Most countries and jurisdictions have regulations in place to ensure that new buildings meet minimum energy efficiency standards. For instance, the European Union requires that all new buildings are built to nearly zero-energy standards starting in 2021 as part of the wider goal to decarbonise the building sector by 2050 [2]. The jurisdiction of California (USA) requires homes built in 2020 and beyond to include renewable energy generation to cover the expected annual electricity needs of buildings [3]. Australia also has legislation in place that requires all new homes to comply with thermal energy efficiency requirements.

However, several case studies worldwide indicate that there is a significant gap between the set building energy targets and the actual measured building energy consumption post-occupancy. The operational performance of buildings can be up to 2.5 times higher than the energy modelled during the building design stage [4]. This phenomenon, known as the regulatory energy performance gap (EPG), is a concern as it hinders, and does not make the most of, global energy conservation efforts.

Several underlying causes for the regulatory EPG have been identified at all stages of the building life cycle. These include the planning stage, the design stage, the construction stage, the commissioning stage and the occupancy stage, the latter comprising of building maintenance and operation. The occupancy stage, specifically the impact of user behaviour on energy performance, has been widely researched. On the other hand, the EPG relating to the construction and commissioning stage has not been as extensively studied, being the subject of only 7.9% of articles [5].

In Australia, industry reports such as the *National Energy Efficiency Building Project* [6] point to major issues occurring during the early stages of the building life cycle, which adversely impact energy use. One of the concerns is that the energy efficiency regulations are not complied with, there are no measures in place for building verification and there is no accountability. It was also reported that some builders may not have the required energy knowledge, have poor construction practices and make product substitutions that differ from the building approved design.

Whilst some of the concerns mentioned above are well-known amongst the Australian researchers and building practitioners, there are no provisions to address them. The successful implementation of energy efficient buildings in Australia depends on a deeper understanding of the root causes for the regulatory EPG, in particular, the causes for the gap between as-designed and as-built. It is also important to understand how this problem can be addressed effectively based on international evidence-based research.

This rapid review examines international literature on the EPG of energy efficient buildings. This review focusses on the root causes for the gaps between as-designed and as-built, which relate mainly to the construction and commissioning stages of the building life cycle; and collates information on how to address this gap..The nature of this review is qualitative.

Cooking appliances (photo by Josh Byrne)

Objectives

The main question that this rapid review is trying to answer is “how can the gap between as-designed and as-built energy efficient buildings in Australia be addressed?”

The objective of this rapid review is to locate and summarise published peer-reviewed review papers relating to the EPG in buildings. Emphasis will be placed on consideration of the root causes for the gap in the pre-occupancy stages of the building life cycle, mainly occurring during construction and commissioning. Strategies to address these causes are also reported in this rapid review.

A secondary objective of this review is to assess the time and resources needed to perform a scoping / rapid meta-review on a topic related to the Built Environment. Thus, information relevant to the review team’s structure, review timeline and associated workloads are also included in this report.

Methods

Eligibility criteria

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

1. Studies published in peer-reviewed academic journals
2. Studies published in English
3. Studies published in the last 10 years, since 2010
4. Review articles
5. Full text available
6. Studies about the energy performance gap in energy efficient / low carbon buildings, discussing specifically the early stages of the building life cycle, that is, the pre-occupancy stages and in particular the construction and commissioning stages. Articles that were purely about occupant behaviour and did not mention the pre-occupancy stages were excluded.
7. Studies on how the energy performance gap can be addressed in low carbon buildings
8. Selected relevant grey literature (government and/or industry reports) where applicable, to complement the limited number of review articles found in the academic literature.

Information sources

Data sources included Scopus, Web of Science and ProQuest (Figure 1). Google Scholar and a Google search also pointed respectively to relevant articles and industry reports; these are a secondary complementary source.

Literature search and study records

Based on the research question, two search strings were devised. The first search (Search 1) was an attempt to capture review articles about the energy performance gap in low carbon buildings, focusing specifically on the early stages of the building life cycle (pre-occupancy). The second search (Search 2) focused on mechanisms to ensure building compliance. The researchers attempted to combine Search 1 and Search 2 in a single search string. However, this combined search string was too limiting and only returned a small number of articles in all databases. The attempt to find research mentioning 'Australia' was also too restrictive and did not produce any results. However, Australian cases studies were captured in the results.

Both searches were conducted on the 1st of April 2020 in the three academic databases: Scopus, Web of Science and ProQuest and the results were combined to answer the research question. Database search engines screened through articles' titles, abstracts and keywords.

Search 1

This first search combined synonyms of the following keywords: 'energy performance gap', 'buildings', 'low carbon', 'pre-occupancy' and 'review'. The specific string used for this search was the following:

(("energy performance gap" OR "energy gap" OR "performance gap") AND (building OR hous* OR home) AND ("low carbon" OR "low-carbon" OR "energy efficien*" OR green OR "sustainab*" OR "net zero energy" OR "zero energy" OR "high efficien*" OR "passive") AND ("construction" OR "commission*" OR "pre-occupancy" OR "life cycle" OR "life-cycle") AND ("systematic review" OR "systematic literature review" OR review OR "meta analysis" OR "meta-analysis"))*

Please refer to Table 1 to view the specific filters applied to each of the databases.

Search 2

The second search combined synonyms of the following keywords: 'energy performance gap', 'compliance' and 'review'. The specific string used for this search was the following:

(("energy performance gap" OR "energy gap" OR "performance gap") AND ("cause" OR "verification" OR "compliance" OR "assess*" OR "solution*" OR polic* OR "clos* the gap") AND ("systematic review" OR "systematic literature review" OR review OR "meta analysis" OR "meta-analysis"))*

Please refer to Table 1 to view the specific filters applied to each of the databases.

In addition, a search of Google Scholar and Google using the terms *'energy performance gap' buildings review* was conducted as a manner of capturing relevant industry reports and additional academic articles of interest that may not have been found through the chosen databases. Given that the results in Google Scholar / Google are sorted by relevance as well as number of citations, only the first 3 pages of results were screened. Articles and reports were selected according to their scope, study eligibility criteria and whether they consisted of reviews.

All records from Search 1, Search 2 and additional Google Scholar / Google articles were exported to the Endnote reference management software. Duplicates were excluded and titles and abstracts were screened by one reviewer, as shown in Figure 1. Articles that did not meet the eligibility criteria were excluded. The library was then exported to an Excel file for further assessment. Articles' abstracts were classified according to whether they consisted of review papers or not. Case study articles were excluded. The articles were further categorized according to their relevance, into *little relevance*, *relevant*, *very relevant*, *further assessment required* and *no relevance* by a second reviewer. The articles classified as requiring further assessment were read in full and then reclassified into *relevant*, *very relevant*, *or no relevance* by both reviewers. Only the remaining full-text review articles deemed relevant or very

relevant were read in full. Two researchers conducted the analysis of the included papers.

The search and screening process are summarized in the PRISMA diagram in Figure 1.

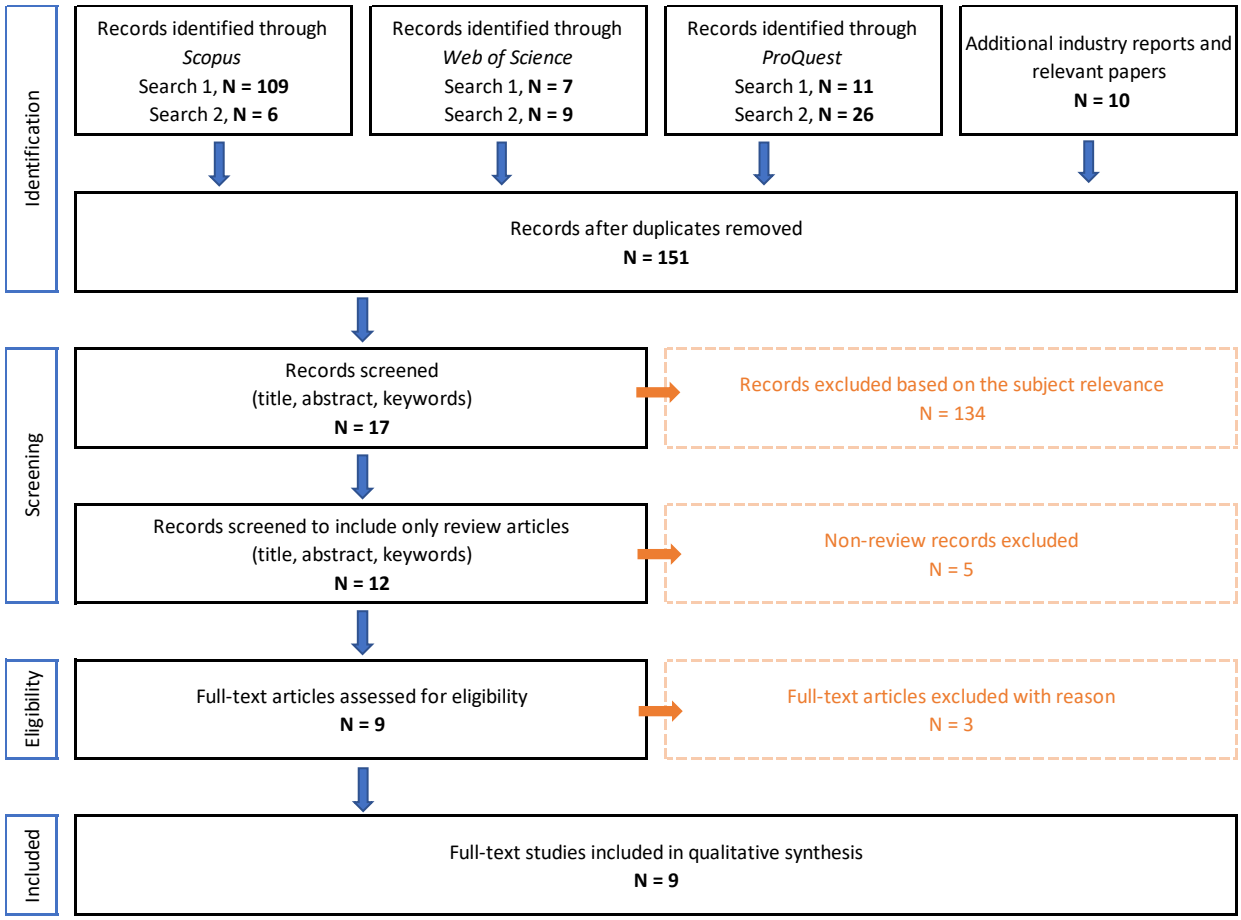


Figure 1 PRISMA diagram of the search and screening process

Table 1 Specific search strings and filters applied in different databases

Search / Database	Search string	Filters
Search 1 / Scopus [109 results]	TITLE-ABS-KEY(("energy performance gap" OR "energy gap" OR "performance gap") AND (building* OR hous* OR home) AND ("low carbon" OR "low-carbon" OR "energy efficien*" OR green OR "sustainab*" OR "net zero energy" OR "zero energy" OR "high efficien*" OR "passive") AND ("construction" OR "commission*" OR "pre-occupancy" OR "life cycle" OR "life-cycle") AND ("systematic review" OR "systematic literature review" OR review OR "meta analysis" OR "meta-analysis"))	AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010)) AND (LIMIT-TO (DOCTYPE , "re")) AND (EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "MATE") OR EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "MATH") OR EXCLUDE (SUBJAREA , "AGRI") OR EXCLUDE (SUBJAREA , "NURS")) AND (LIMIT-TO (LANGUAGE , "English")
Search 1 / Web of Science [7 results]	TS=(("energy performance gap" OR "energy gap" OR "performance gap") AND (building* OR hous* OR home) AND ("low carbon" OR "low-carbon" OR "energy efficien*" OR green OR "sustainab*" OR "net zero energy" OR "zero energy" OR "high efficien*" OR "passive") AND ("construction" OR "commission*" OR "pre-occupancy" OR "life cycle" OR "life-cycle") AND ("systematic review" OR "systematic literature review" OR review OR "meta analysis" OR "meta-analysis"))	Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC.
Search 1 / ProQuest [11 results]	noft((("energy performance gap" OR "energy gap" OR "performance gap") AND (building* OR hous* OR home) AND ("low carbon" OR "low-carbon" OR "energy efficien*" OR green OR "sustainab*" OR "net zero energy" OR "zero energy" OR "high efficien*" OR "passive") AND ("construction" OR "commission*" OR "pre-occupancy" OR "life cycle" OR "life-cycle") AND ("systematic review" OR "systematic literature review" OR review OR "meta analysis" OR "meta-analysis")))	Last 10 Years Scholarly Journals

Search / Database	Search string	Filters
Search 2 / Scopus [6 results]	TITLE-ABS-KEY(("energy performance gap" OR "energy gap" OR "performance gap") AND ("cause*" OR "verification" OR "compliance" OR "assess*" OR "solution*" OR polic* OR "clos* the gap") AND ("systematic review" OR "systematic literature review" OR review OR "meta analysis" OR "meta-analysis"))	AND (LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015) OR LIMIT-TO (PUBYEAR,2014) OR LIMIT-TO (PUBYEAR,2013) OR LIMIT-TO (PUBYEAR,2012) OR LIMIT-TO (PUBYEAR,2011) OR LIMIT-TO (PUBYEAR,2010)) AND (EXCLUDE (SUBJAREA,"MATE") OR EXCLUDE (SUBJAREA,"PHYS") OR EXCLUDE (SUBJAREA,"CHEM") OR EXCLUDE (SUBJAREA,"MEDI") OR EXCLUDE (SUBJAREA,"CENG") OR EXCLUDE (SUBJAREA,"BIOC") OR EXCLUDE (SUBJAREA,"MATH") OR EXCLUDE (SUBJAREA,"NURS") OR EXCLUDE (SUBJAREA,"PHAR") OR EXCLUDE (SUBJAREA,"AGRI") OR EXCLUDE (SUBJAREA,"PSYC") OR EXCLUDE (SUBJAREA,"IMMU")) AND (LIMIT-TO (DOCTYPE,"re")) AND (LIMIT-TO (LANGUAGE,"English")) AND (EXCLUDE (EXACTKEYWORD,"Photocatalysis") OR EXCLUDE (EXACTKEYWORD,"Solar Cells") OR EXCLUDE (EXACTKEYWORD,"Titanium Dioxide") OR EXCLUDE (EXACTKEYWORD,"Light Absorption") OR EXCLUDE (EXACTKEYWORD,"Photocatalysts") OR EXCLUDE (EXACTKEYWORD,"Wide Band Gap Semiconductors") OR EXCLUDE (EXACTKEYWORD,"Catalysis") OR EXCLUDE (EXACTKEYWORD,"Electrode") OR EXCLUDE (EXACTKEYWORD,"Fuel Cell") OR EXCLUDE (EXACTKEYWORD,"Dye-sensitized Solar Cells") OR EXCLUDE (EXACTKEYWORD,"Electric Drives") OR EXCLUDE (EXACTKEYWORD,"Gallium Nitride") OR EXCLUDE (EXACTKEYWORD,"Hydrogen Production") OR EXCLUDE (EXACTKEYWORD,"III-V Semiconductors") OR EXCLUDE (EXACTKEYWORD,"Light") OR EXCLUDE (EXACTKEYWORD,"Power Converters") OR EXCLUDE (EXACTKEYWORD,"Silicon Carbide") OR EXCLUDE (EXACTKEYWORD,"Absorption") OR EXCLUDE (EXACTKEYWORD,"Absorption Spectroscopy") OR EXCLUDE (EXACTKEYWORD,"Cadmium") OR EXCLUDE (EXACTKEYWORD,"Cadmium Sulfide") OR EXCLUDE (EXACTKEYWORD,"Catalyst") OR EXCLUDE (EXACTKEYWORD,"Copper") OR EXCLUDE (EXACTKEYWORD,"Electrodes") OR EXCLUDE (EXACTKEYWORD,"Electrolyte") OR EXCLUDE (EXACTKEYWORD,"Heterojunctions") OR EXCLUDE (EXACTKEYWORD,"Hydrogen") OR EXCLUDE (EXACTKEYWORD,"Hydrogen Production Rate") OR EXCLUDE (EXACTKEYWORD,"Indium") OR EXCLUDE (EXACTKEYWORD,"Integrated Motor Drives") OR EXCLUDE (EXACTKEYWORD,"Nanocrystals") OR EXCLUDE (EXACTKEYWORD,"Nanostructures") OR EXCLUDE (EXACTKEYWORD,"Organic Pollutants") OR EXCLUDE (EXACTKEYWORD,"Parasitic Inductances") OR EXCLUDE (EXACTKEYWORD,"Photocatalyst") OR EXCLUDE (EXACTKEYWORD,"Photochemistry") OR EXCLUDE (EXACTKEYWORD,"Semiconductor Doping") OR EXCLUDE (EXACTKEYWORD,"Semiconductor Quantum Dots") OR EXCLUDE (EXACTKEYWORD,"Solar Radiation") OR EXCLUDE (EXACTKEYWORD,"Solar Spectrum") OR EXCLUDE (EXACTKEYWORD,"Transparency") OR EXCLUDE (EXACTKEYWORD,"Water Absorption") OR EXCLUDE (EXACTKEYWORD,"Water Pollution") OR EXCLUDE (EXACTKEYWORD,"Wide Band Gap") OR EXCLUDE (EXACTKEYWORD,"Zinc Oxide") OR EXCLUDE (EXACTKEYWORD,"Absorber Layers") OR EXCLUDE (EXACTKEYWORD,"Absorption Co-efficient") OR EXCLUDE (EXACTKEYWORD,"Absorption Coefficient") OR EXCLUDE (EXACTKEYWORD,"Absorption Spectrum") OR EXCLUDE (EXACTKEYWORD,"Alloy") OR EXCLUDE (EXACTKEYWORD,"Analogous Structures") OR EXCLUDE (EXACTKEYWORD,"Automotive Applications") OR EXCLUDE (EXACTKEYWORD,"Automotive Industry") OR EXCLUDE (EXACTKEYWORD,"Azo Dyes") OR EXCLUDE (EXACTKEYWORD,"Back Surface Fields") OR EXCLUDE (EXACTKEYWORD,"Band Gap") OR EXCLUDE (EXACTKEYWORD,"Band Gap Energy") OR EXCLUDE (EXACTKEYWORD,"Band Notch") OR EXCLUDE (EXACTKEYWORD,"Band Structure Engineering") OR EXCLUDE (EXACTKEYWORD,"Band-notch Characteristics") OR EXCLUDE (EXACTKEYWORD,"Binding Energy") OR EXCLUDE (EXACTKEYWORD,"Biological Materials") OR EXCLUDE (EXACTKEYWORD,"Bipolar Semiconductor Devices") OR EXCLUDE (EXACTKEYWORD,"Black TiO 2") OR EXCLUDE (EXACTKEYWORD,"Cadmium Compounds") OR EXCLUDE (EXACTKEYWORD,"Cadmium Telluride") OR EXCLUDE (EXACTKEYWORD,"Capacitors") OR EXCLUDE (EXACTKEYWORD,"Carbon Nitride") OR EXCLUDE (EXACTKEYWORD,"Carrier Concentration") OR EXCLUDE (EXACTKEYWORD,"Carrier Diffusion Length") OR EXCLUDE (EXACTKEYWORD,"Carrier Selection") OR EXCLUDE (EXACTKEYWORD,"Catalyst Activity") OR EXCLUDE (EXACTKEYWORD,"Chalcopyrite") OR EXCLUDE (EXACTKEYWORD,"Charge Carriers") OR EXCLUDE (EXACTKEYWORD,"Charge Collection Efficiency") OR EXCLUDE (EXACTKEYWORD,"Chemical Compound") OR EXCLUDE (EXACTKEYWORD,"Chromium Compounds") OR EXCLUDE (EXACTKEYWORD,"Circuit Oscillations") OR EXCLUDE (EXACTKEYWORD,"Co-doping") OR EXCLUDE (EXACTKEYWORD,"Conductivity Modulation") OR EXCLUDE (EXACTKEYWORD,"Conjugated Polymers") OR EXCLUDE (EXACTKEYWORD,"Conjugated Structures") OR EXCLUDE (EXACTKEYWORD,"Connectors") OR EXCLUDE (EXACTKEYWORD,"Connectors (structural)") OR EXCLUDE (EXACTKEYWORD,"Contamination") OR EXCLUDE (EXACTKEYWORD,"Conventional Capacitors") OR EXCLUDE (EXACTKEYWORD,"Conversion Efficiency") OR EXCLUDE (EXACTKEYWORD,"Copper Vanadate") OR EXCLUDE (

		EXACTKEYWORD,"Crystalline Silicons") OR EXCLUDE (EXACTKEYWORD,"Dissolved Organic Matter") OR EXCLUDE (EXACTKEYWORD,"Dissolved Organic Matters") OR EXCLUDE (EXACTKEYWORD,"Dissolved Oxygen") OR EXCLUDE (EXACTKEYWORD,"EBG") OR EXCLUDE (EXACTKEYWORD,"EV")
Search 2 / Web of Science [9 results]	TS=(("energy performance gap" OR "energy gap" OR "performance gap") AND ("cause*" OR "verification" OR "compliance" OR "assess*" OR "solution*" OR polic* OR "clos* the gap") AND ("systematic review" OR "systematic literature review" OR review OR "meta analysis" OR "meta-analysis"))	Refined by: PUBLICATION YEARS: (2019 OR 2012 OR 2018 OR 2011 OR 2017 OR 2010 OR 2016 OR 2015 OR 2014 OR 2013) AND DOCUMENT TYPES: (REVIEW) AND [excluding] WEB OF SCIENCE CATEGORIES: (CHEMISTRY MULTIDISCIPLINARY OR HOSPITALITY LEISURE SPORT TOURISM OR CHEMISTRY PHYSICAL OR CHEMISTRY INORGANIC NUCLEAR OR OPTICS OR CHEMISTRY ORGANIC OR CRYSTALLOGRAPHY OR POLYMER SCIENCE OR SPECTROSCOPY OR UROLOGY NEPHROLOGY)
Search 2 / ProQuest [26 results]	noft((("energy performance gap" OR "energy gap" OR "performance gap") AND ("cause*" OR "verification" OR "compliance" OR "assess*" OR "solution*" OR polic* OR "clos* the gap") AND ("systematic review" OR "systematic literature review" OR review OR "meta analysis" OR "meta-analysis")))	Scholarly Journals Last 10 Years NOT (mathematical analysis AND condensed matter AND optical properties AND solar cells AND organic chemistry AND photovoltaic cells AND thin films AND x-ray diffraction AND electronic structure AND graphene AND insulators AND spin-orbit interactions AND density functional theory AND superconductivity AND adsorption AND spectrum analysis AND electrons AND magnetic fields AND optoelectronics AND phase transitions AND absorption AND conduction bands AND electronics AND excitons AND fermions AND magnetism AND markets AND perovskites AND phases AND photocatalysis AND photoelectric emission AND refractivity AND semiconductors AND titanium dioxide AND valence band AND band gap AND ferromagnetism AND ground state AND heterostructures AND molybdenum disulfide AND monolayers AND morphology AND photoluminescence AND photons AND quantum wells AND substrates AND superconductors AND transition metals AND zinc oxide AND aluminum AND annealing AND benzene AND brillouin zones AND carrier density AND chemical bonds AND corrosion AND corrosion effects AND corrosion inhibitors AND dielectric properties AND doping AND emitters AND ferroelectric materials AND fourier transforms AND holes (electron deficiencies) AND impurities AND inhibition AND nanocrystals AND nanoparticles AND nickel AND phosphorene AND photoelectric effect AND endoscopy AND flux density AND gender differences AND human rights AND intubation AND lean manufacturing AND medical screening AND neural networks AND obesity AND precipitation AND rechargeable batteries AND acoustic waves AND acuity AND adaptive control AND advantaged AND age groups AND age related diseases AND students AND ability tests AND academic achievement AND academic degrees AND achievement tests AND air quality AND ambition AND amplitudes AND analogies AND anelasticity AND apl (programming language) AND aviation AND backscattering AND charter of rights-canada AND compression tests AND condensates AND cooking AND curricula) Article OR Literature Review OR Review English

Data items

For each included study, the following characteristics were extracted: first author and year of publication, study title, study theme, location conditions, review type, number of articles reviewed, study funding and conflict of interests. Table 2 presents the main extracted variables (as used in Table 3 in the Results section). Data extraction was performed by two reviewers who checked the other's work. For each study, quality assessment scores, risk of bias and overall comments were provided (for details, see the "Risk of bias of individual studies" section below).

Table 2 List of the main study variables extracted

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

Outcomes and prioritisation

The main outcome of this rapid review was to identify the aspects of the EPG in buildings that related to the post-design and pre-occupancy stages of the building life cycle. Data discussing exclusively the building planning, design, occupancy or maintenance stages were not extracted. However, flow-on effects from building planning and design are observed during construction. Similarly, post-occupancy data can be used to inform construction outcomes. When such effects were mentioned in the literature, these were also included in this review..

Risk of bias in individual studies

Information on the included studies' funding sources and conflict of interest statements were recorded. Where available, information was also collected to assess the extent to which the articles addressed the study quality criteria. Methodological details and any concerns related to data collection or analysis were noted. A quality assessment of the studies included in this review was performed using the AMSTAR2 checklist [7]. Table 9 presents the 16 questions used for this assessment process, with codes and explanations. The assessment was performed by two reviewers who checked the other's work.

Data Synthesis

No quantitative assessment was performed due to the heterogeneity and small number of included studies. A qualitative summary is provided in the form of tables and a narrative description of the patterns in the literature that was reviewed.

Meta-bias(es)

Meta-bias is not applicable due to the qualitative summary nature of this review and its focus on narrative and systematic review studies only.

Results

The final study list included nine articles that fulfilled the inclusion criteria (see Table 3).

Overview of the included studies

The articles included in this rapid review were published between 2014 and 2019 and collectively reviewed over 500 articles and/or case studies. These had a global coverage, reporting results from Asia, Europe, North America, Africa and Australia.

Despite the rapid review's original intent of reviewing only systematic literature reviews or meta-analyses, only two articles met this criterion. The other seven articles are based on in-depth narrative reviews of the literature.

All articles reviewed causes of EPGs in the building sector. Five of them explored all stages of the building life cycle, from planning and design to operation and maintenance [5, 8-11], while the other four focused exclusively on the early stages of the building life cycle. Alencastro *et* al. [12] explore exclusively the EPG caused by construction quality defects and McElroy *et* al. [13] explore the impact of poor installation and commissioning of building technologies. The two reports by the Zero Carbon Hub [14, 15] explore the early stages of the building life cycle, identifying deficits relating to the planning, design, construction and commissioning stages, however only information relevant to this study has been extracted.

Four articles focus on both residential and non-residential buildings [5, 9, 11, 12], one focuses on non-residential only [10] and four others focus on residential uses [8, 13-15].

All articles review and/or propose policy steps to address the EPG based on the literature.

Qualitative summary

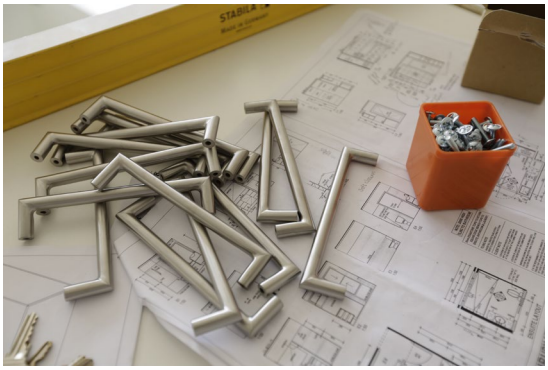
As mentioned above, some of the articles covered more than just the scope of this rapid review, including discussions about the EPG during the occupancy stage. When reviewing these articles, only the relevant information to answer the specific question set in this rapid review's objectives were selected. Table 4 provides a description of the articles' respective findings as well as recommendations to address the gap between as-built and as-designed. These are summarized in this section.

All articles provided a common level of agreement on the main factors for discrepancy between buildings' as-designed and as-built. These are described below for each of the relevant building life stages.

- Design stage

Root causes for the as-built/as-designed gap originate in the design stage, when the design team might propose a design that is too complex for the builder or does not take into consideration practical limitations of the building site. This leads to changes during construction that are not fed back to the design team.

Moreover, there is generally a lack of clarity in design documentation, in particular how different layers of the building (fabric and services) are supposed to integrate in practical terms.



Plans (photo by Kathy Johnson)

- Procurement stage

During procurement, the emphasis is often placed on cost rather than skills or quality. This results in the engagement of contractors who may not have knowledge in energy efficiency and related skills.

Change to orders often occurs at this stage, either for cost reduction or site constraints not accounted for during design. The consequences can be lower quality equipment and materials or a complete change to the design intent that affects energy efficiency. Building owners, who often have inadequate knowledge in energy and construction, endorse the changes.

- Construction stage

During the construction stage, building fabric is incorrectly constructed due to poor building techniques. Complex designs can mean that mistakes are more likely to occur. Hidden faults, such as gaps in insulation, are hard to uncover and fix once the building is finished.

Bulk insulation (photo by Brendan Hutchens)

- Commissioning stage

Building technologies and services may be incorrectly modelled, sized and installed due to a lack of relevant skills from contractors.

- Testing and verification

Building performance testing is often not completed due to time and/or budget constraints. When verification of the built form is carried out, testing protocols may not always be followed, and energy efficiency may not be prioritized.

In summary, most issues relate to lack of knowledge and skills, lack of communication between stakeholders and lack of accountability for building performance post-occupancy. There is usually no designated person responsible for overall building quality and energy efficiency. There may be no integrated delivery methods and no common platform for information recording and transfer.

Verification with a thermal imaging camera (photo by Darcy Hodgkinson)

The most common recommendations to close the gap between as-designed and as-built tend to directly address the points above. A fourth theme related to standards was also identified. Key recommendations are listed below, classified under the four main themes of training, communication, performance accountability and standards.

- Training

All new and current industry professionals should be trained and upskilled. Only adequately qualified professionals should be able to conduct building energy modelling, assessments, testing and building performance verification.

- Communication

Higher communication standards need to be in place between stakeholders to ensure comprehensive design detailing is performed early to avoid changes during the construction process.

Appointing a sustainability champion to oversee the construction would enable close monitoring of building quality as well as facilitate communication and close feedback loops between the different stakeholders.

- Performance accountability

It is recommended that buildings are rated according to their actual energy performance post-occupancy rather than their predicted performance. Project owners would have to agree on performance guaranties, including mandatory plans for how commissioning would be done, particularly in instances where the energy consumption goals are not reached.

It was also suggested that high operational energy use should be penalized, through an environmental tax. In contrast, pay-for-performance programmes were suggested as a way of incentivizing savings achieved over time.

Post-occupancy energy performance data should be made accessible not only to ensure the transparency of the rating process, but also to provide feedback to design teams and gather further evidence on the EPG.

As part of ensuring building quality and compliance, testing should be made mandatory during the construction process.

- Standards

To ensure building compliance and quality, a number of articles suggest the development of new guidelines and standards. These include developing standards for residential building monitoring and verification. Guidelines for common construction processes, equipment maintenance and commissioning should also be developed to ensure as-built performance.

Brick laying (photo by Brendan Hutchens)

Table 3 List and main characteristics of the included articles.

First Author _year	Title	Study scope	Aspect of building use	Location conditions	Review type	Number of articles or case studies included	Study funding	Conflict of interests
Alencastro_2018	The relationship between quality defects and the thermal performance of buildings	Identification of quality defects during building construction causing EPG. Review of causes and impacts on energy performance. The article also identifies gaps in research.	Construction Residential and non-residential	Researchers based in the UK. Articles reviewed were from Europe, the UK, Australia, China, Malaysia, Singapore, Canada, Iran, Nigeria and the USA.	Narrative literature review of academic articles	76 articles	Brazilian Ministry of Science, Technology and Innovation through the Science without Borders research programme	None declared
Gram-Hanssen-2018	What next for energy-related building regulations?: the occupancy phase	Review of Danish building regulations and how they affect different stages of the building life cycle (technologies, design, construction and operation). The article suggests ways of redesigning the Danish building regulations.	All stages of the building life cycle Residential	Researchers based in Denmark Article locations not specified	Narrative literature review of academic articles and grey literature	Not stated	Innovationsfonden	None declared
IPECC_2019	Building Energy Performance Gap Issues, an international review	Review of the EPG in buildings, existing modelling systems and their use in demonstrating compliance to building regulations. The article proposes areas of opportunity to address the EPG.	All stages of the building life cycle Residential and non-residential	Researchers based in France. Articles reviewed were from the UK, Australia and Canada	Narrative literature review of academic articles and grey literature	7 articles	Energy Security and Efficiency Division of the Australian Department of the Environment and Energy	None declared
McElroy_2019	Policy implications for the performance gap of low-carbon building technologies	Review of the grey literature on the EPG of specific building technologies. The article suggests policy steps to address the issue.	Installation and commissioning of building technologies Residential	Researchers based in the UK and Australia Case studies reviewed are from the UK	Review of unpublished case studies	6 case studies	Research Council, UK	None declared
Shi_2019	Magnitude, causes, and solutions of the performance gap of buildings: A review	Review of the EPG including definition, magnitude, techniques to measure/determine the	All stages of the building life cycle	Researchers based in China. Articles reviewed were from Cyprus, Portugal,	Systematic literature review	22 articles	Ministry of Science and Technology of China and the Scientific	None declared

		EPG, causes and possible solutions.	Residential and non-residential	Belgium, Canada, the UK, Italy, Spain, the USA, Germany, Denmark and Australia			Research Foundation of Graduate School of Southeast University	
Van Dronkelaar_2016	A review of the energy performance gap and its underlying causes in non-domestic buildings	Impact the EPG causes on energy performance. The article focuses on non-residential buildings.	All stages of the building life cycle Non-residential	Researchers based in the UK. Case study locations: UK, Belgium, Australia, the USA, Austria and Canada	Narrative literature review	62 case studies	Engineering and Physical Sciences Research Council (EPSRC) and BuroHappold Engineering	None declared
Zero Carbon Hub_2014a	Closing The Gap Between Design & As-Built Performance Evidence Review Report	Report discusses the causes for the gap between design and as-built building performance and reveals the mains priority areas to be addressed.	Planning, Design, construction and commissioning Residential	NGO based in the UK. Article locations not specified	Narrative literature review and survey	100 reports and academic articles (45% research) + survey of 150 assessors	No funding acknowledged	None declared
Zero Carbon Hub_2014b	Closing The Gap Between Design & As-Built Performance. End of term report	Report discusses strategic steps for industry and government to address the gaps identified in the previous report.	Planning, Design, construction and commissioning Residential	NGO based in the UK. Article locations not specified	Narrative literature review and survey	100 reports and academic articles (45% research) + survey of 150 assessors	No funding acknowledged	None declared
Zou_2018	Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives	Review of academic articles on EPG. The article analyses themes studied in previous research; reviews the causes of the gaps and actors involved in each step; reviews solutions currently proposed; and discusses further areas of research.	All stages of the building life cycle Residential and non-residential	Researchers based in Australia and China. Article locations not specified	Systematic literature review	227 articles	Australian Research Council (ARC) Research Hub and the National Nature Science Foundation of China	None declared

Table 4 Summary of article findings and authors' recommendations for the included studies

First Author_year	Summary of findings	Summary of recommendations
Alencastro_2018	Houses have on average 2.29 to 28.3 defects, most relating to thermal performance such as poor installation, gaps in the building fabric and thermal bridging through structural elements. Other general faults include incorrect installation and missing items in external walls, partitions, doors and windows, and floors and roofs. Most of these are the result of damage occurring during installation, change in or omission of materials and inefficient management during construction. These defects can result in an increase of up to 52% in total project costs.	There is a need for a clear definition in academia and industry for defect, snag, fault, failure, quality deviation and non-conformance to reduce the inaccurate identification of defects, accurately detail costs and propose mitigation strategies. Construction companies should provide appropriate training to increase awareness of the impact of the quality of work on building thermal performance and to utilise photographic tools to show how those defects commonly happen and how to avoid them. An energy champion should be appointed to monitor project progress to ensure ongoing compliance with relevant energy performance targets, during the design and construction, handover and close-out stages. Energy performance awareness amongst clients, project teams and the workforce is needed to drive these changes.
Gram-Hanssen_2018	Causes of EPG originating from the building construction stage include: - design changes due to contractors' incorrect installation or due to the design being too complex for contractors to implement; - lack of knowledge and skills in regards to energy efficient materials, leading to business-as-usual; and - changes during the tendering process favouring cost reduction. Quality control can be difficult, as the costs and benefits accrue to different actors. There is usually no single person responsible for the overall quality of the entire building to make sure it performs as specified. When there is a main contractor or system integrator amongst the contractors, then it is more likely that changes will be discovered and reported back to the designers. Commissioning could be a way to correct these problems. It involves verifying performance measurements and checking for malfunctioning technologies and solutions across all phases from design, construction to operation. However, commissioning of residential buildings is uncommon. It is unlikely that more stringent energy efficiency regulations would lead to energy reduction.	It is recommended that emphasis is placed on post-occupancy evaluations rather than pre-construction evaluations. Project owners would have to agree on performance guaranties, including mandatory plans for how commissioning would be done, particularly in instances where the energy-consumption goals are not reached. Individuals should be appointed responsible for an integrated approach to ensure a systematic assessment of the building at the time of delivery as well as at later stages of use.
IPEEC_2019	There is a disconnect between the tools used to identify buildings' EPG and their original intent which leads to inconsistencies in final build. Usually the EPG of non-residential buildings is more significant than the EPG of residential buildings.	There needs to be better management of the quality control process throughout design, construction and operation to ensure design intent is met. Greater communication standards need to be put in place between stakeholders to ensure comprehensive design detailing is performed early so changes can be made then. Ongoing feedback to the design team post-occupancy would also help inform future buildings' design. Better training and education on design for sustainability is also required. Target policy areas to close the EPG are greater transparency of operational building energy performance; and regulation of the building operational performance along with penalties for non-compliance.

McElroy_2019	All energy efficient technologies reviewed in this study presented performance gaps. Some of the causes were contextual, as some of the operation conditions were different than expected. Others were due to low quality installation, as some of the technologies were oversized and unrelated to the house size. Finally, users' operation also caused some discrepancy.	The article calls for a need for further field trials of specific technologies, new and current. Policy recommendations include: - Defining key parameters to be analysed in evaluations; - Setting up quality standards for carrying out monitoring of low-carbon technologies once installed; - Defining key aspects to be covered by post-installation audits; and - Setting appropriate methods for evaluation, monitoring and verification. It is suggested that a detailed global standard for monitoring and verification is implemented in the residential sector. Pay-for-performance programmes are also suggested as they reward real savings achieved over time rather than theoretical savings. Other recommendations include ensuring that manufacturers develop installer standards for their products; providing accreditation to installers based on training; and reviewing current installation and training guidelines.
Shi_2019	Buildings' EPG is identified and interpreted in significantly different ways leading to large variations. There is no correlation between the magnitude of the EPG and specific building parameters. Causes of the EPG between design and as-built include: inappropriate design, malpractice, construction uncertainties and physical changes to the building between design and construction.	Solutions proposed are managerial, technical and hybrid (a mix of the two). These include: - Increased communication and collaboration between all stakeholders and in particular between design and construction teams; - Managing the building process more effectively to ensure the building is constructed as modelled, with attention to detail; - Appointing a sustainability champion to monitor and provide direction as well as developing guides for efficient equipment use, maintenance and commissioning.
Van Dronkelaar_2016	The average discrepancy between predicted and measured energy use is +34%, with a standard deviation of 55%. The main underlying causes of the EPG are specification uncertainties in building modelling, occupant behaviour, and poor practice in operation. However, it is estimated that poor commissioning can cause a gap of up to 20%. It is not understood how much construction issues impact on energy use. From a construction perspective, EPG is caused by: - the complexity of the design, making mistakes in construction more likely; - low quality on-site workmanship, often affecting insulation and air-tightness; - changes after design either for cutting costs or due to site constraints; and - poor commissioning, where building services are not properly installed and compromise building operation from the start. Building audits and monitored energy consumption should become integral to the modelling process.	Key recommendations from this study are: - Robust checking and testing during construction to ensure that the quality of construction is maintained; - Making energy data accessible for further evidence gathering on the EPG; - Penalizing buildings for high operational energy use, such as through an environmental tax. Governments should relate predicted to measured performance through predictive modelling and in use regulation. Design stage calculations and assumptions should also be disclosed as well as operational energy outcomes; and - Monitoring buildings and using results to calibrate design models.

Zero Carbon Hub_2014a (presents findings) Zero Carbon Hub_2014b (proposes recommendations)	This review identified issues in the planning, design, procurement, construction and commissioning, verification and testing stages of the building life cycle. Most issues identified are related to lack of knowledge and skills, lack of communication between stakeholders and lack of accountability. For instance, the planning stakeholders lack knowledge about the implication of early decisions on building energy performance. Designers lack practical understanding about the building site and construction processes. Procurement services do not prioritize contractors with energy efficiency skills. Consequently, building fabric and services are incorrectly constructed, installed and commissioned by contractors who do not possess adequate skills. Verification processes do not prioritize energy performance and testing methodologies are not always followed. There is also lack of clarity in documentation and lack of integration between different layers of the building design (fabric and services).	Recommendations were separated into priority actions for industry and government. Industry priorities: - Develop innovative methods to demonstrate building performance; - Training and upskilling industry professionals; - Develop and maintain a Construction Details Scheme (CDS) for the major fabric junctions to ensure as-built energy performance; and - Evidence gathering and feedback for continuous improvement of the industry. Government priorities: - Funding research and development into testing, measurement and assessment techniques as well as for the development of a CDS; - Ensure only qualified professionals conduct energy modelling and assessments; and - Support industry development by leading by example, requiring energy certified operatives and professionals for developments on government land.
Zou_2018	Only 7.9% of the publications about the EPG relate to the construction stage of the building. Root causes of building EPG are situated in the design and modelling of the building, the construction and the building operation. These are the EPG causes associated to the construction stage as well as the responsible stakeholders: - Limited experience and knowledge – designer - Inadequate understanding of building construction and energy – owner - Change in orders – owner - Poor quality in equipment and materials – supplier - Change in materials to reduce costs – contractor - Poor workmanship and poor construction techniques - contractor - Failure to uncover hidden faults – contractor - Performance testing not completed due to time and budget constraints – contractor In addition, there is no accountability for building performance. Stakeholders do not communicate or collaborate due to a lack of common interest. Obstacles for collaboration include a lack of life cycle thinking and integrated delivery methods as well as the lack of a platform to facilitate information transfer.	Existing strategies for addressing the gap in the building construction stage are considered 'soft' measures and include: - Policies such as 'Display Energy Certificates' (UK), which rate buildings according to their actual energy consumption and 'Soft Landings' (UK), which keeps designers and contractors involved in the building operation stage to address the EPG; - Energy performance ratings based on actual building performance, such as NABERS (Australia) It is recommended that further research is conducted in the areas of life cycle thinking of the building EPG, stakeholders' attributions and decision criteria, stakeholders' interaction and information integrity.

Overview of the excluded studies

Table 8 in the appendix lists the three studies excluded from this review after full-text screening, alongside the reasons for exclusion. One of the studies was excluded as it did not explore the EPG, but rather methods to evaluate building performance. The other two studies were excluded as they were not reviews of the literature. Although they provided an overview of the literature on EPG as part of their theoretical framework, their results, discussion and conclusions were based on specific case studies or concepts. Despite being excluded, two of these papers (De Wilde_2014 and Tuohy_2015) provide useful and unique insights on the topic of the EPG associated with the construction stage of residential buildings.

Quality, risk of bias and confidence in cumulative evidence

Table 5 summarises the quality and risk of bias assessment of the included systematic reviews and meta-analyses, with more details provided in Table 10 in the appendix. Overall, the included reviews were of medium quality, with most failing to provide sufficient details on literature search and data extraction, and not considering the quality and risk of bias of included studies. Only three reviews (McElroy 2019, Zero Carbon Hub 2014 and Zou 2018) discussed explicitly the review methods and selection of articles, while only McElroy 2019 and Zero Carbon Hub 2014 discussed the risk of bias in the included articles. This suggests there is scope for improving how the methodologies and outcomes of systematic and narrative literature reviews are reported.

Table 5 Quality Scores (QS) and Risk of Bias (RoB) summaries for the included studies.

QS values: A – minimal flaws, B – some flaws, C – major flaws in many aspects of the review (most likely due to poor reporting or the review not being a full systematic review of evidence). Risk of Bias (RoB) values: low, medium, high – refer to the risk of bias of the conclusions of the review.

First Author _year	Title	QS	RoB	Comments
Alencastro_2018	The relationship between quality defects and the thermal performance of buildings	B	High	Study does not state search strings or how articles were selected. Funding acknowledged
Gram-Hanssen-2018	What next for energy-related building regulations?: the occupancy phase	B	High	The study does not state search strings or how articles were selected. Funding acknowledged
IPECC_2019	Building Energy Performance Gap Issues, an international review	B	High	Study does not state search strings or how articles were selected. Funding acknowledged
McElroy_2019	Policy implications for the performance gap of low-carbon building technologies	B	Medium	Study is not a systematic literature review, but explains the search and selection criteria. Funding acknowledged. Some discussion of risk of bias in articles included.
Shi_2019	Magnitude, causes, and solutions of the performance gap of buildings: A review	B	High	Study claims to be a systematic literature review but does not state specific search strings, outlines categories of focus. Funding acknowledged
Van Dronkelaar_2016	A review of the energy performance gap and its underlying causes in non-domestic buildings	B	High	The study does not state search strings or how articles were selected. Funding acknowledged
Zero Carbon Hub_2014a	Closing The Gap Between Design & As-Built Performance Evidence Review Report	B	Medium	Based on industry/government reports mainly and surveys. Study does not state search strings or how articles were selected. Some discussion of risk of bias in articles included.

Zero Carbon Hub_2014b	Closing The Gap Between Design & As-Built Performance. End of term report	B	Medium	Based on industry/government reports mainly and surveys. Study does not state search strings or how articles were selected. Some discussion of risk of bias in articles included.
Zou_2018	Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives	B	High	States keywords, databases and selection criteria. Funding acknowledged

Review Limitations

The literature search was not fully comprehensive and some relevant papers may have been missed. Through the academic databases, only peer-reviewed studies that claimed to be systematic literature reviews or reviews of the literature were included. As an attempt to capture important studies that may have been overlooked, an additional search using Google Scholar and Google was conducted. This captured two additional relevant academic articles and two industry reports. Due to the limited number of comprehensive systematic literature reviews in the topic of interest, non-systematic reviews were also considered. These yielded additional insights but pose a risk of bias. Only studies published in English were included.

Summary and conclusions

The purpose of this rapid review was to locate and summarise published peer-reviewed review papers relating to the gap between buildings as-designed and as-built. The intent was to investigate the root causes of the problem and solutions to address the gap.

Two search strings applied to three scholarly databases as well as on Google Scholar and Google were conducted and identified 151 original articles. After a screening process and evaluation of articles against a list of criteria, 9 review articles were identified for inclusion in this rapid review. These articles were published between 2014 and 2019 and collectively reviewed over 500 studies. All articles reviewed causes for EPGs in the pre-occupancy stages of the building and proposed recommendations to address the discrepancies between as-designed and as-built energy consumption. Both residential and non-residential buildings were explored in the articles.

However, only a few articles were systematic literature reviews. Many studies suffered from methodological problems and potential biases, which may limit the extent to which robust conclusions can be drawn. Examples of such limitations include not disclosing how articles were selected for review.

In spite of the small number of review articles found in the topic of interest and the risk of bias mentioned above, all articles seem to agree on the root causes for the discrepancy between as-designed and as-built. The proposed solutions to close the EPG in the early stage of the building life cycle are also aligned.

In summary, this rapid review of the international literature on the EPG suggests that most causes for discrepancies between as-designed and as-built relate to lack of knowledge and skills, lack of communication between stakeholders and lack of accountability for building performance post-occupancy.

Recommendations to close the gap address the points above as well as improved standards. Key recommendations include:

- Training and upskilling of all new and current industry professionals
- Creating greater communication standards for stakeholders to share information
- Appointing a sustainability champion to oversee the construction, facilitate collaboration and close feedback loops
- Rating buildings' energy efficiency based on post-occupancy performance rather than predicted performance. This includes agreeing on performance guarantees
- Penalizing high operational energy use through an environmental tax
- Incentivizing savings over time through pay-for-performance programmes
- Making energy performance data accessible to promote transparency, to provide feedback to design teams and gather further evidence on the EPG
- Mandating testing and verification during the construction process
- Developing new guidelines and standards, including residential building monitoring and verification standards; guidelines for common construction processes and equipment maintenance and commissioning should also be developed to ensure as-built performance.

Whilst none of the articles used in this rapid review specifically discussed the Australian situation, the solutions above were based on global research, including Australian case studies. Given the general nature of the recommendations, it is considered that they could be adopted by policy makers in the Australian context. In fact, some of the items suggested in this rapid review align with key recommendations proposed by ASBEC and ClimateWorks on how to achieve zero carbon buildings in Australia by 2050 [16]. The *Built to Perform* report specifically recommends that compliance and enforcement is addressed through compulsory training of building practitioners, audits, reporting, improved sharing of building information, post-construction verification of energy performance and increased consumer awareness [16].

As a next step, it is recommended that these solutions are discussed and validated with professionals of the construction industry in the various Australian states and territories, as well as with policy makers to determine whether these are viable for implementation in the current context.

Resources, workload and timeline

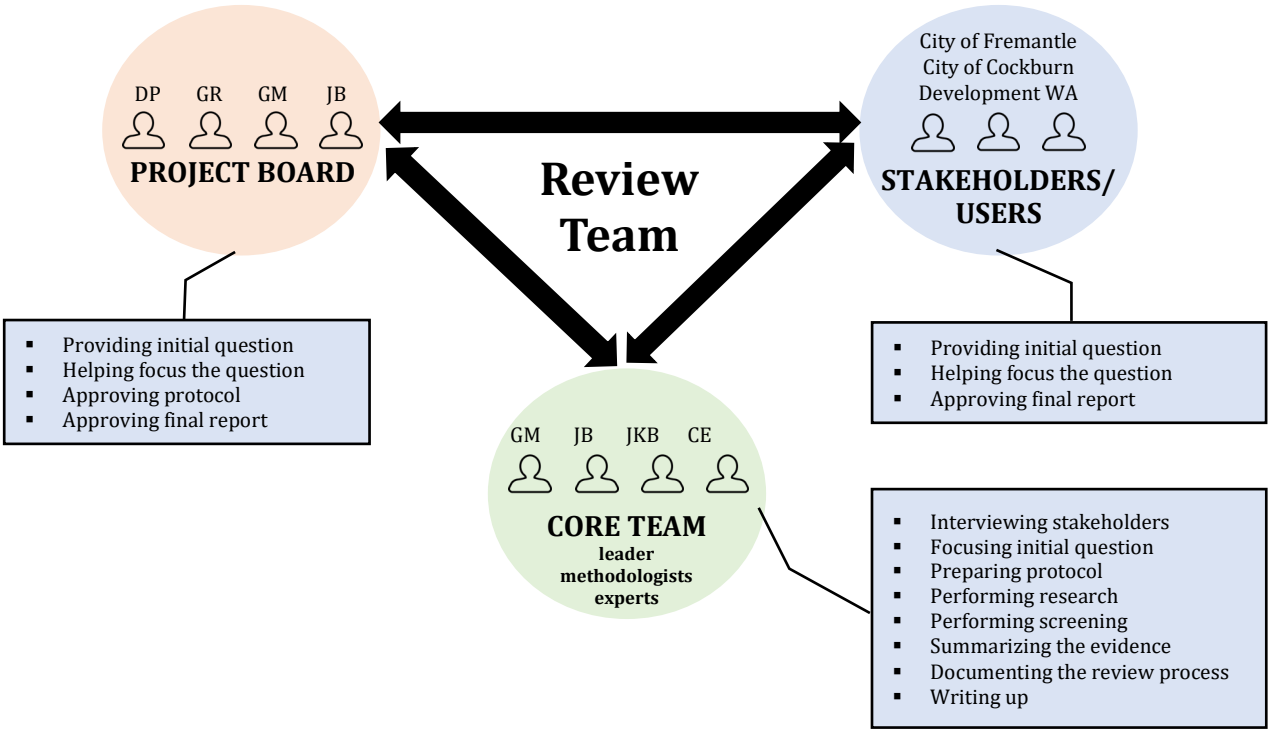


Figure 2 Review team members

Table 6 Review timeline

Activity	November 2019 (19/11/19)	December 2019	January 2020	February 2020	March 2020	April 2020	May 2020
Team formation							
Question refinement							
Protocol preparation							
Search and screening							
Data extraction							
Synthesis/report							
Approvals/Revisions							

Table 7 Workloads (in hours) of the team members for each main review stage.

Review Stage	GM	JB	JKB	CE	Total	Comments
Team formation	2	1			3	Shared with biodiversity rapid review
Question refinement	2	2	10	4	18	Shared with biodiversity rapid review
Protocol preparation	1	1	8		10	
Search and screening			15	15	30	
Data extraction			15	15	30	
Synthesis / Report	3	3	25	25	56	
Total	8	7	73	59	147	hours

Appendices

Table 8 Table of the excluded studies at the full-text eligibility stage

First Author_year	Full reference	Reason for exclusion
Borgstein_2016	E.H. Borgstein, R. Lamberts, J.L.M. Hensen, Evaluating energy performance in non-domestic buildings: A review, Energy and Buildings 128 (2016) 734-755.	The main focus of the article is on methods to evaluate the performance of buildings. The EPG is mentioned but only briefly.
De Wilde_2014	P. De Wilde, The gap between predicted and measured energy performance of buildings: A framework for investigation, Automation in Construction 41 (2014) 40-49.	The article discussion, conclusion and recommendations are based on a pilot study.
Tuohy_2015	P.G. Tuohy, G.B. Murphy, Closing the gap in building performance: learning from BIM benchmark industries, Architectural Science Review 58(1) (2015) 47-56.	The article is not a literature review.

Table 9 Quality assessment tool.

A modified AMSTAR [17, 18] and AMSTAR-2 [7] checklists, used to asses quality and risk of bias of individual systematic reviews / meta-analyses, was included in this meta-review.

Question (recommendations)	Decision rules and comments
Q1. Are the research questions and inclusion criteria for the review clearly delineated?	1 = "Yes" = Who (Population/Subject), What (Intervention, Comparator group, Outcome), Where and When described.
	0.5 = "Can't answer / not sure / partially" = Cannot decide between "yes" and "no", basing on the information provided in the paper.
	0 = "No" = research question and inclusion criteria not outlined in detail.
Q2. Did the report of the review contain an explicit statement that the review methods were established prior to the conduct of the review and did the report justify any significant deviations from the protocol?	1 = "Yes" = The authors state that they had a written protocol or guide that included ALL the following: review question(s), a search strategy, inclusion/exclusion criteria, risk of bias assessment.
	0.5 = "Can't answer / not sure / partially" = The authors state that they had a written protocol or guide that included ALL the following: review question(s), a search strategy, inclusion/exclusion criteria, a risk of bias assessment.
	0 = "No" = no mention of *a priori* design of the systematic review, as listed above.
Q3. Did the review authors explain their selection of the study designs for inclusion in the review?	1 = "Yes" = explicit justification of the study designs/types included in the review.
	0.5 = "Can't answer / not sure / partially" = more than one online source but no supplementary sources or one online source and one supplementary source. Cannot decide between "yes" and "no", basing on the information provided in the paper.
	0 = "No" = only one online source or no supplementary search used
Q4. Did the review authors use a comprehensive literature search strategy?	1 = "Yes" = searched at least 2 databases (relevant to research question), provided key word and/or search strategy, justified publication restrictions (e.g. language), AND searched the reference lists / bibliographies of included studies, searched trial/study registries, included/consulted content experts in the field, where relevant, searched for grey literature, conducted search within 24 months of completion of the review.
	0.5 = "Can't answer / not sure / partially" = searched at least 2 databases (relevant to research question), provided key word and/or general search strategy, justified publication restrictions (e.g., language).
	0 = "No" = no information on search strategy, or not fulfilling criteria for "Yes" and "Partially".
Q5. Did the review authors perform study selection in duplicate?	1 = "Yes" = either ONE of the following: at least two reviewers independently agreed on selection of eligible studies and achieved consensus on which studies to include OR two reviewers selected a sample of eligible studies and achieved good agreement (at least 80%), with the remainder selected by one reviewer.
	0.5 = "Can't answer / not sure / partially" = Cannot decide between "yes" and "no", basing on the information provided in the paper.
	0 = "No" = only one reviewer involved in the study selection or no description how many reviewers participated in study selection.
Q6. Did the review authors perform data extraction in duplicate?	1 = "Yes" = either ONE of the following: at least two reviewers achieved consensus on which data to extract from included studies OR two reviewers extracted data from a sample of eligible studies and achieved good agreement (at least 8 %), with the remainder extracted by one reviewer.
	0.5 = "Can't answer / not sure / partially" = Cannot decide between "yes" and "no", basing on the information provided in the paper.

	0 = "No" = only one reviewer involved in the study selection or no description how many reviewers participated in data extraction.
Q7. Did the review authors provide a list of excluded studies and justify the exclusions?	1 = "Yes" = provided a list of all potentially relevant studies that were read in full-text form but excluded from the review AND justified the exclusion from the review of each potentially relevant study.
	0.5 = "Can't answer / not sure / partially" = only provided a list of all potentially relevant studies that were read in full-text form but excluded from the review, but not justified the exclusion from the review of each potentially relevant study that were read in full-text.
	0 = "No" = No list of studies excluded at a full-text stage.
Q8. Did the review authors describe the included studies in adequate detail?	1 = "Yes" = ALL the following: Who (Population), What (Intervention, Comparator group, Outcome), Where and When described in detail..
	0.5 = "Can't answer / not sure / partially" = Who (Population), What (Intervention, Comparator group, Outcome), Where and When briefly described, or only some of these described in detail. Cannot decide between "yes" and "no", basing on the information provided in the paper.
	0 = "No" = no, or partial description of the included studies
Q9. Did the review authors use a satisfactory technique for assessing the risk of bias (RoB) in individual studies that were included in the review?	1 = "Yes" = specifically mentions RoB assessment of individual included studies.
	0.5 = "Can't answer / not sure / partially" = Cannot decide between "yes" and "no", basing on the information provided in the paper. RoB mentioned or not sufficiently assessed (e.g. if multiple sources of bias potentially present, but not all assessed).
	0 = "No" = no mention of RoB assessment of individual included studies.
	[RoB sources: from confounding, from selection bias, from exposure bias, from selective reporting of outcomes, selection of the reported result from among multiple measurements or analyses of a specified outcome].
Q10. Did the review authors report on the sources of funding for the studies included in the review?	1 = "Yes" = Must have reported on the sources of funding for individual studies included in the review. Note: Stating that the reviewers looked for this information but it was not reported by study authors, also qualifies.
	0.5 = "Can't answer / not sure / partially" = sources of funding mentioned for individual studies included in the review, or reported only for some of the included studies. Cannot decide between "yes" and "no", basing on the information provided in the paper.
	0 = "No" = no report of the sources of funding for individual studies included in the review.
Q11. If meta-analysis was performed, did the review authors use appropriate methods for statistical combination of results?	1 = "Yes" = The authors justified combining the data in a meta-analysis AND they used an appropriate technique to combine study results and adjusted for heterogeneity if present *AND* investigated the causes of any heterogeneity or adjusted for heterogeneity or confounding if present.
	0.5 = "Can't answer / not sure / partially" = Requirements for "Yes" only partially fulfilled. Cannot decide between "yes" and "no", basing on the information provided in the paper.
	0 = "No" = no justification of meta-analysis or inappropriate statistical methods were used for quantitatively combining and analysing the data, heterogeneity not assessed.
	N/A = "Not Applicable" = No meta-analysis conducted.
Q12. If meta-analysis was performed, did the review authors assess the potential impact of RoB in individual studies on the	1 = "Yes" = included only low risk of bias studies OR the authors performed analyses to investigate possible impact of RoB on summary estimates of effect.

results of the meta-analysis or other evidence synthesis?	0.5 = "Can't answer / not sure / partially" = Cannot decide between "yes" and "no", basing on the information provided in the paper.
	0 = "No" = no assessment of the potential impact of RoB.
	N/A = "Not Applicable" = No meta-analysis conducted.
Q13. Did the review authors account for RoB in individual studies when interpreting/ discussing the results of the review?	1 = "Yes" = included only low risk of bias studies OR the review provided a discussion of the likely impact of RoB on the results.
	0.5 = "Can't answer / not sure / partially" = Cannot decide between "yes" and "no", basing on the information provided in the paper.
	0 = "No" = no discussion of the potential impact of RoB in individual studies.
Q14. Did the review authors provide a satisfactory explanation for, and discussion of, any heterogeneity observed in the results of the review?	1 = "Yes" = There was no significant heterogeneity in the results OR if heterogeneity was present the authors performed an investigation of sources of any heterogeneity in the results and discussed the impact of this on the results of the review.
	0.5 = "Can't answer / not sure / partially" = Cannot decide between "yes" and "no", basing on the information provided in the paper.
	0 = "No" = No explanation or discussion of heterogeneity present in the results.
Q15. If they performed quantitative synthesis did the review authors carry out an adequate investigation of publication bias (small study bias) and discuss its likely impact on the results of the review?	1 = "Yes" = The authors performed graphical or statistical tests for publication bias and discussed the likelihood and magnitude of impact of publication bias.
	0.5 = "Can't answer / not sure / partially" = more than one online source but no supplementary sources or one online source and one supplementary source. Cannot decide between "yes" and "no", basing on the information provided in the paper.
	0 = "No" = The authors did not perform any tests for publication bias and did not discuss potential impact of publication bias.
	N/A = "Not Applicable" = No meta-analysis conducted.
Q16. Did the review authors report any potential sources of conflict of interest, including any funding they received for conducting the review?	1 = "Yes" = The authors reported no competing interests OR the authors described their funding sources and how they managed potential conflicts of interest.
	0.5 = "Can't answer / not sure / partially" = Cannot decide between "yes" and "no", basing on the information provided in the paper.
	0 = "No" = The authors did not provide statement on competing interests and funding sources, and how they managed potential conflicts of interest.

Table 10 Responses to quality assessment questions from Table 9 coded for each of the included studies.

The responses to each question were coded numerically and color-coded as following: green = 1 = “Yes”; yellow = 0.5 = “Can’t answer / not sure / partially”, red = 0 = “No”, grey = N/A = “Not Applicable”.

First Author _year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Alencastro_2018	1	0	0	0	0	0	0	1	0	0	NA	NA	0	1	NA	1
Gram-Hanssen-2018	0.5	0	0	0	0	0	0	1	0	0	NA	NA	0	1	NA	1
IPEEC_2019	0.5	0	0	0	0	0	0	1	0	0	NA	NA	0	1	NA	1
McElroy_2019	1	0.5	1	0	0	0	0	1	1	0	NA	NA	0	1	NA	1
Shi_2019	1	0	0	0	0	0	0	1	0	0	NA	NA	0	1	NA	1
Van Dronkelaar_2016	0.5	0	0	0	0	0	0	1	0	0	NA	NA	0	1	NA	1
Zero Carbon Hub_2014 a	0	0.5	0.5	0	0	0	0	0.5	0.5	0	NA	NA	0	1	NA	0
Zero Carbon Hub_2014 b	0	0	0	0	0	0	0	0	0	0	NA	NA	0	0	NA	0
Zou_2018	1	0	1	0.5	0	0	0	0.5	0	0	NA	NA	0	1	NA	1

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