CLOSING THE GAP BETWEEN DESIGN AND REALITY OF BUILDING ENERGY PERFORMANCE

Project overview and literature review

Research Report 1 (February 2018)

Research Team

Professor Patrick X.W. Zou and Dr Morshed Alam (Swinburne)

Collaborative Universities

Swinburne University of Technology
Curtin University

Government and Industry Partners:

Aurecon, Victoria
Building Management and Works, Department of Finance, Western Australia
Department of Housing and Public Works, Queensland

Australian Government
Australian Research Council

nanocomm
ARC Industrial Transformation Research Hub for Nanoscience Based Construction Material Manufacturing

Sustainable Built Environment National Research Centre

Executive Summary

Increasing energy efficiency of buildings is considered as one of the most effective strategies to mitigate greenhouse gas (GHG) emissions and tackle the climate change related events. However, there is significant evidence that buildings do not perform as predicted; the actual energy usage during operation is often higher than the predicted consumption during project planning stage. This disparity between the predicted energy use and the actual energy use is known as energy performance gap.

The presence of such performance gap can result in disastrous financial consequences to the investors and can reduce the impact of energy efficiency upgrades in mitigating the harmful emissions. To realise the true social, environmental and economic benefits of energy efficient building, it is very important to close the performance gap which is the primary aim of this research project.

The factors that contribute to performance gap in a building may arise from the activities during the design stage, construction and commissioning stage and operational stage. This progress report presents a state of the art review of the design stage and construction and commissioning stage factors of the performance gap. From the review, the design stage factors that contribute to energy performance gap have been categorised into the following groups:

1. Unnoticed changes during design development,
2. Miscalculation of loads,
3. Lack of database
4. Poor design,
5. Lack of accountability
6. Poor communication,
7. Design assumptions,
8. Uncertain stochastic factors and
9. Imperfection of simulation engines

The construction and commissioning stage factors that contribute to energy performance gap have been categorised into following groups:

1. Material and equipment;
2. Knowledge and working skills;
3. Construction management process;
4. Procurement process;
5. Unavailability of detail design; and
6. Client-related problems

1 Introduction

1.1 Background

Buildings are one of the largest users of energy, accounting for 32% of total global final energy use and 19% of total energy-related greenhouse gas (GHG) emissions [1]. In 2010, the building sector consumed approximately 117 Exajoules (EJ) energy and resulted in 9.18 $GtCO_2e$ GHG emissions [1]. The GHG emission in this sector grew at an annual rate of 2% since 1971, and it is projected to reach 11.1 $GtCO_2e$ in 2020 and 14.3 $GtCO_2e$ by 2030 [2] due to population growth, increase in building stock and lifestyle changes. Moreover, building energy use is also projected to grow by 60-90% of the 2005 value and reach approximately to 165EJ-200 EJ by 2050 in the business-as-usual scenario [3]. This continued growth in energy consumption and GHG emissions are contributing to global average temperature increase and may lead to catastrophic climate change-related events in future.

Improving energy efficiency in both new and existing buildings encompasses the most diverse, largest and most cost-effective energy usage and GHG mitigation opportunities. The scenario assessment has shown that by 2050, global world building heating and cooling energy use can be reduced by about 46% as compared to 2005 values through incorporating today's best practices in building design, construction, and operation, as well as accelerated state-of-the-art retrofits [4]. This is despite the over 126 % increase in building floor area during the same period, as shown in Figure 1 [4]. To achieve the energy savings, approximately US$14.2 trillion undiscounted additional cumulative investment is required until 2050. However, it is estimated that this investment will result in US$58 trillion undiscounted energy cost savings during the same period [4].

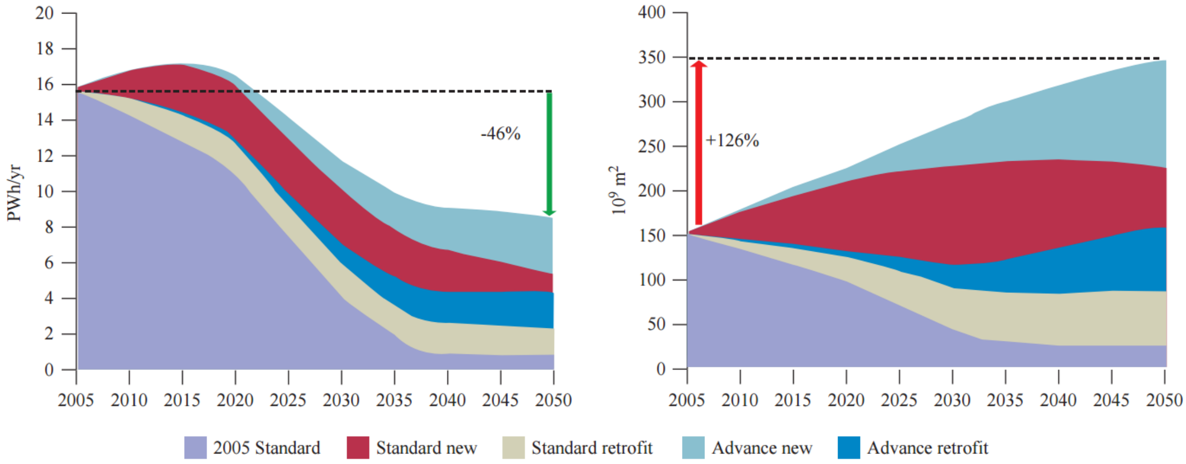

Figure 1 Global final building heating and cooling energy use projections until 2050 (left), contrasted to global floor area (on the right) projections. [4]

In 2002, the City of Melbourne, Australia set a challenging target for Melbourne to become carbon neutral city by 2020 [5]. To achieve this target, one of the objectives is to increase the energy efficiency of the commercial buildings by 40 percent [6]. Commercial buildings account for over 50% of total greenhouse gas emissions in Melbourne City and reducing emissions from this sector is vital to achieving zero net emissions. It represents the largest potential to reduce emissions which equates to around 1.6 million tonnes of emissions reduction by 2020 [6]. To improve the energy efficiency of the commercial buildings, the City of Melbourne has launched several programs. One such program is the 1200 retrofitting program which aims to energy retrofit around two-third of the municipal's commercial building stock [7]. However, it was realised that to achieve the net zero emissions City of Melbourne, state government, businesses and the people of Melbourne need to work together to successfully implement these opportunities, enhance government policy and change our energy supply, as fast as possible.

The 2015 Paris Agreement confirmed that net global emissions must be reduced to near zero well before the end of the century[8]. The climate change authority in Australia recommended that zero net emissions would likely have to be achieved by 2050 to stay within the recommended carbon budget [9]. Following this, all state governments in Australia, except Northern Territory and Western Australia, have recently committed to achieving the net-zero carbon emissions by 2050 in their respective states.

The building sector is one of the biggest sources of GHG emissions in Australia; it accounts for approximately 23% of overall GHG emission [9]. Considering energy efficiency actions in both new and existing buildings could deliver a 23% and 55% emission reduction in this sector by 2030 and 2050, respectively [9]. In monetary terms, this equates to around $20 billion in energy savings by 2030 [9]. Therefore, it can be said that incorporation of energy efficiency in the building sector can make a significant contribution towards achieving the net-zero carbon emission goals of the Australian state governments as well as can result in significant financial savings.

1.2 Energy Performance gap

There is significant evidence that buildings do not perform as predicted. Implementation of energy efficiency opportunities, both in new builds and retrofits, do not always meet the expectations; the actual energy usage is often higher than the predicted consumption. This discrepancy is known as Energy Performance Gap [10]. The magnitude of the performance gap varies significantly depending on the project characteristics. The actual energy consumption can be up to 100% or greater than predicted in some cases [10-12]. The 2011 Carbon trust report demonstrated that the actual regulated energy consumption could be up to five times higher than predicted [13]. The PROBE studies (Post-occupancy Review of Buildings and their Engineering) investigated the performance of 23 buildings previously featured as 'exemplary designs' in the Building Services Journal (BSJ) [14]. It was demonstrated that actual energy consumption in buildings would usually be twice as much as predicted. Fedoruk et al. [15] observed that actual energy consumption was around 22% higher than the prediction in a university building. Dall'O' et al. [16] investigated two high-rise residential building with 196 flats. The results showed that that actual energy consumption is higher than prediction even in identical flats. Van Dronkelaar et al. [12] reported that on average the measured energy use is 34% higher than prediction based on the observations from 62 buildings.

In 2008, the Royal Institute of British Architects (RIBA) and the Chartered Institution of Building Services Engineers (CIBSE) launched CarbonBuzz, a free online platform allowing practices to share and publish building energy consumption data anonymously. It enables designers to compare predicted and actual energy use for their projects, while also allowing for comparison against benchmarks and data supplied by other participating practices. The observations revealed that on average buildings consume between 1.5 and 2.5 times predicted values [17]. For example, Figure 2 shows that the mean energy performance gap for office and Education buildings as observed in their study are 1.71 and 1.9, respectively.

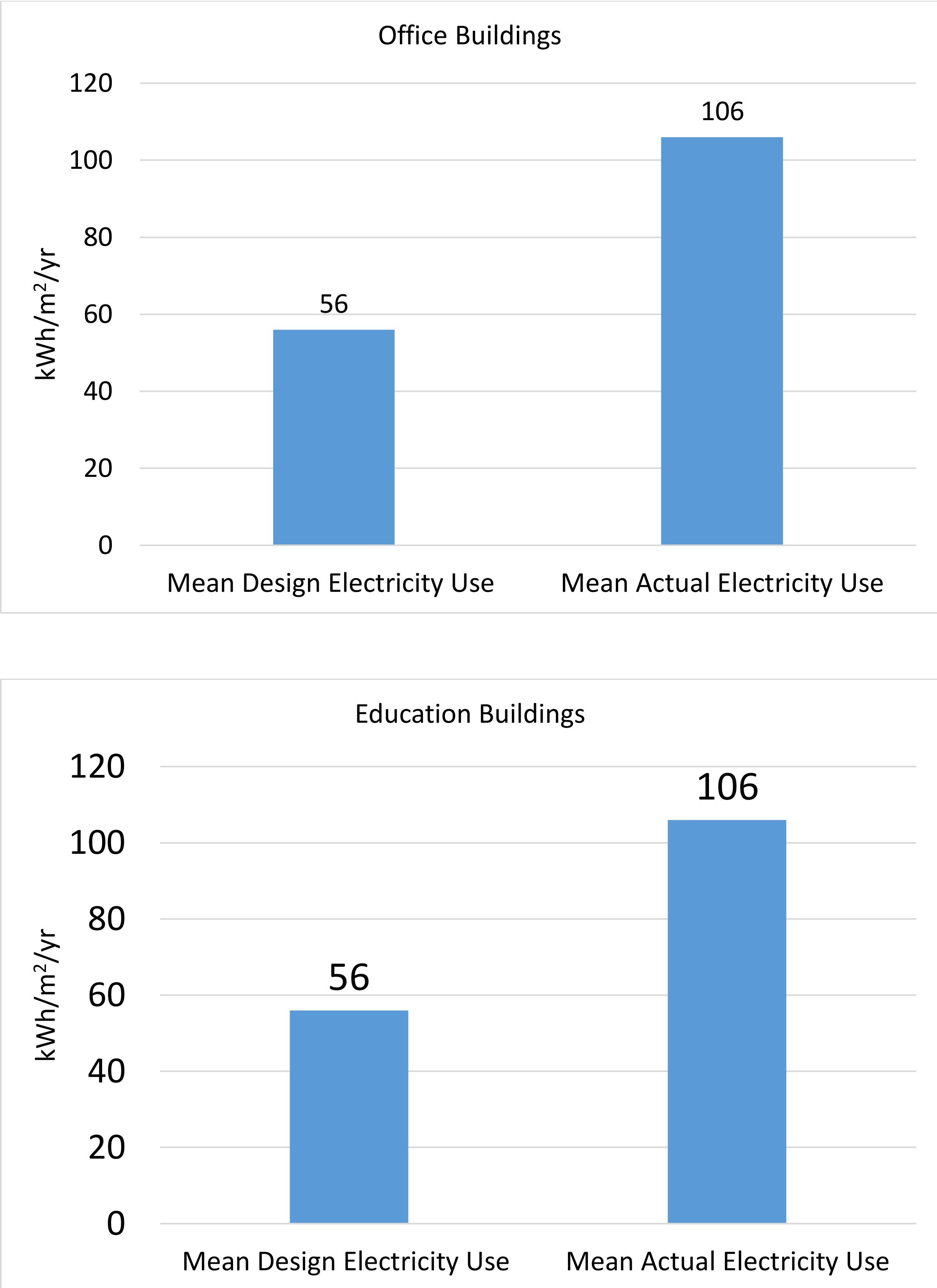

Figure 2 Measured mean energy performance gap in office and education building [17]

Investment decisions on building energy efficiency rely on predicted consumption, savings and benefits. Therefore, the presence of such a performance gap can result in disastrous financial consequences to the investors. Also, in building retrofitting projects that are carried out under energy performance contracts, the presence of an energy performance gap can cause financial damage to the Energy Service Company (ESCO).

The energy performance gap can arise from thectivities during design, construction and operation stages of a project. The total magnitude of the performance gap is the cumulative of the discrepancies arise at these three stages as shown in Figure 3.

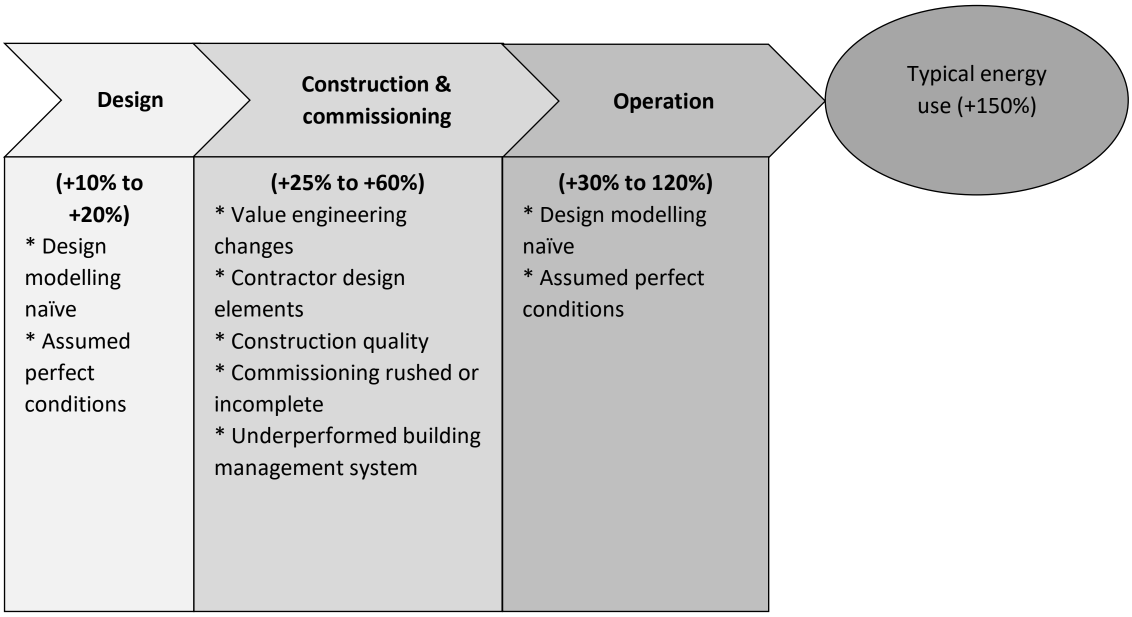

Figure 3 The energy performance gap throughout the project lifecycle [18]

In the design stage, the gap can occur due to design modelling naïve, or simplification in design modelling. Designers may merely consider energy use in typical spaces (e.g. office space in office buildings) and ignore others (such as circulation areas, support spaces, and carparks); report the energy use by normal building's services (heating, cooling, ventilation, and lighting) and left out anything else; or assume that buildings are empty at night [11]. Another factor might be that modellers assume a near-perfect control and a close match of supply to demand [11]. Rees [19] describes many factors that can lead to a difference between predicted and measured performance such as the different types of emissions data used in the production of rating values, uncertainty in building design parameters, uncertainty in operation data used in modelling, unintended errors in the calculations, and limitations in the underlying models. He argues that these are the areas that can help to improve the accuracy of energy models.

In construction and commissioning stages, the causes of the problem are various such as value engineering changes, contractor design elements, poor quality of construction works, commissioning rushed or incomplete, and underperformed building management control. During the operation stage, the gap can occur if the building is not occupied as envisaged, change in the fit-out and building's services which can slash with some of the design intentions and installed system [11]. Also, operators and users may face difficulties in understanding control systems which result in inefficient operation of the buildings [20]. In some cases, users override the building management system which also reduces the performance [20].

To realise the true social, environmental and economic benefits of energy efficient building, it is very important to close the performance gap which is the primary aim of this research project.

1.3 Research aim and objectives

This project aims to develop a methodology that will help to minimise the performance gap in both new build and retrofitted buildings. The three objectives are:

1. Identify critical factors driving BEPG in the design, construction and operational stages of buildings through literature reviews and interviews.
2. Conduct case studies to identify the root causes of BEPG and potential mitigation strategies
3. Develop a framework of strategies to close BEPG.

2 Factors at the design stage

From the study, several factors influencing the energy performance gap at the design stage were identified. The factors were categorised into seven groups. The factors and possible strategies to cope with them are summarised in Figure 4 and discussed below:

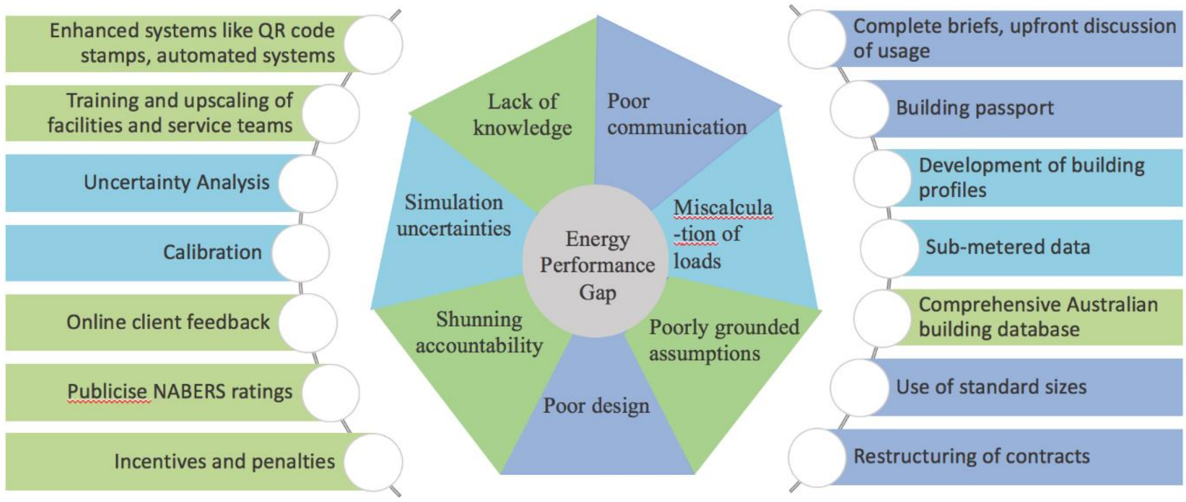

Figure 4. Summary diagram of factors and strategies affecting the energy performance gap at the design stage

2.1 Poor communication

Poor interaction among various teams inhibits the development of innovative solutions that can be achieved from brainstorming. On the other hand, clients and designers often do not use clear communication. According to [22], briefings are not clear, consistent or complete. On the other hand, the designer might fail to communicate the level of management, expenditure and vigilance that he expects from the occupant. This might lead to the occupants taking the building for granted or finding the building too demanding and dissatisfactory later down the road [23].

Similarly, the estimate might fail to take into account changes made during value engineering [24] that involve compromising the building services or replacing certain components with a cheaper alternative. If any changes are made after the estimation of energy consumption, this could cause a substantial performance gap because these alterations are rarely fed back into the energy model [21]. According to [25], variations, including changes to thermal mass, insulation, orientation, controls and operational hours, may not be reassessed in terms of energy performance.

Possible strategies:

Clients should be encouraged to provide clear and concise briefs to the designer so that the designer is fully aware of the client's expectations. According to the literature, there are two different approaches to briefing [22]. One approach is based on the idea that all briefing information should be

complete before the design process starts while the other approach is based on the idea that briefing is a continuous process, which interacts with the design process [26, 27]. In an interview study conducted by [22], architects said that on-going briefing processes can result in new requirements and many changes along the way and can frustrate the efficiency of the design process. Hence, the former approach of briefing should be encouraged. Clear communication with the client about their usage patterns would also enable designers to design for them appropriately and estimate savings accurately.

An interviewee presented the idea of making a record of the entire process as it happens, referring to it as a "Building passport".

> *One of the things we are talking about at the moment is having what we are calling a "building passport". It is an electronic record of the building process. So all the plans will be stored there, and as the construction takes place, and the insulations are installed for example, whoever is doing that can photograph that, the photos get date stamped with a location and they can send them to a digital file so it gets stored in the building's file.*

Implementing this system would make it easier to ensure that everyone involved in the project is on the same page, without letting modifications go unnoticed. It would also make it easier to identify which process was done incorrectly and whom to hold accountable.

2.2 Miscalculation of loads

The design phase usually only calculates the loads during hours when the building is in use, assuming the building is empty at night with most systems off [23], resulting in an energy performance gap. According to [28] and [29], most of the energy waste in a building occurs during non-occupancy hours. Reviewed literature has shown that even during working hours, there are signs of wasted energy [28]. This can happen as a result of plug loads, server rooms, small power loads, elevator loads, catering, external lighting and other loads that are not attributed to major end uses. Such loads may not be included at the design stage, yet can account for more than 30 percent of the electricity demand in office buildings [30].

<u>Possible strategies:</u>

Virote et al. suggest predicting the utilisation patterns of a building using data from buildings with the same activities, in the same geographic area and occupied by people that share the same cultural background [29]. Masoso et al. mention the necessity of creating profiles of energy consumption of both the occupied and non-occupied times of buildings in all kinds of climates and incorporating them to develop elaborate input profiles for simulation accuracy [28].

Revising plug loads increased the estimated energy use by 15% median (32% mean) in an experiment conducted by [31]. The study recommends revising plug loads by using sub-metered data for improved accuracy. One interviewee presented a similar suggestion:

> *Energy modelling is conducted without the utilisation of detail data or only using gross energy meter data in a building. The only way to understand how a building really operates is to do detail sub-metering or data logging of each system and equipment.*

i. Poorly grounded assumptions

Poor and outdated design assumptions are yet another reason behind energy performance gaps. Construction techniques, building stock compositions, and occupant behaviours and usage schedules can vary significantly internationally, so basing parameter values on international studies might not yield accurate results. The simulation assumptions do not always have an evidential basis for use in

Australia since the databases used in international studies to inform building simulation assumptions are not available in Australia [32]. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) made some efforts in that area with the launch of the Australian Building Energy Repository in 2013; but to date, the initiative has not received sufficient funding to achieve the goals [33].

Possible strategies:

A comprehensive Australian database should be created and funded adequately to address the lack of data on building attributes and occupant behaviours, which influence building energy consumption [33].

2.3 Poor design

Several problems arise from a lack of foresight during the design stage. For example, the designers might not think through some aspects of the design and aesthetics. For instance, not considering the aesthetics, fabric performance and building services at the same time can result in airtightness approaches being compromised and inadvertent thermal bridging [30]. Similarly, the design team may specify details that are difficult or impractical to build and which have to be modified on site, which also results in a lower performance [30]. Since designers do not participate in the monitoring phase, but rather move on from designing one project to designing another, they do not have the opportunity of studying the outcomes, receiving post occupancy feedback and verifying their prescriptions. Therefore, they might apply flawed practices to all their designs without being aware of this.

Possible strategies:

Powell et al. suggested that use of standard sizes of materials should be encouraged to avoid "cutting to fit" in order to avoid modification to the design on site [30]. Furthermore, interviewees suggested restructuring contracts in new ways so that occupant feedback is mandatory and reaches the designers.

2.4 Shunning accountability

Professionals are wary of Post Occupancy Evaluations because they think that the findings – which inevitably bring both good and bad news – may not enhance their reputations [34]. Shunning feedback from occupants about the building can lead to an inept and out-of-touch industry.

Some interviewees pointed out similar avoidance of accountability commonly exhibited by other members in the supply chain including contractors and facility managers:

> *Contractors implementing the retrofitting do not want accurate energy measurement and verification. They want things to be as cloudy as possible, and they will often suggest they will perform M&V themselves, which substantially reduces the ability to make them accountable of the outcomes at the end.*

> *The main objective of the facility manager is to make sure it is safe and operating and that he is not getting any complaints. So they often tend to tune the building so that it over-performs. They should be trained to make sure that they are tracking the system and know how to get the best out of it.*

Possible strategies:

Interviewees suggested using incentives and punitive measures to foster greater accountability in the industry:

> *There has to be some sort of penalty if the performance is not as specified, because if there is no consequence then designers are not going to be motivated to try to do their best.*

An interviewee also suggested making the NABERS (National Australian Built Environment Rating System) rating public in order to make it easier for prospective clients to evaluate and select service providers. Another original suggestion was to adopt what other trust-based services such as Uber and TripAdvisor do by accepting feedback from clients online. It gives people a chance to voice dissatisfaction about the performance gap, is a good way for businesses to be conscious of any room for improvement and can drive real change.

2.5 Simulation uncertainties

Uncertainties related to simulation also affect the accuracy of saving predictions. Simulation software tend to over-simplify building and building systems, and are based on assumptions of thermal processes, and algorithmic differences [21, 35]. Moreover, errors in the input also get propagated to the output or the predicted energy consumption [36]. The accuracy of saving estimates relies on some parameters that are inherently uncertain. For example, weather and occupant density are two uncertain stochastic factors that fluctuate unpredictably over the course of time, so it is difficult to ascertain their precise impact on the energy demand. Hence, estimations produced by simulation tools are only as accurate as the models and inputs they are based on [37].

Possible strategies:

Calibration techniques can enhance the accuracy of simulation models through iterative revisions of an initial model, correcting identified discrepancies based on evidence and expert's knowledge [38].

Furthermore, Uncertainty Analysis can be applied to estimate the probability that the energy saving target for the selected building will be achieved after the retrofitting. Uncertainty Analysis is the process of determining the probability that the outcome will be different from the "best-guess" estimate [39]. It also allows accounting for the inconsistent nature of parameters such as temperature, flow and pressure set points, which change throughout the occupancy period.

2.6 Lack of knowledge

Designers might lack the knowledge of certain limitations of various processes involved in building energy consumption, and they might base their prescriptions on a flawed perception [23]. Interviewees also pointed out a lack of expertise and a need for an upscaling exercise to enhance the expertise of facilities staff:

> *The quality of education provided to facilities staff is certainly not adequate for the role that they are expected to carry out. They often lack the resources or the understanding of the systems that they are operating. The facilities staff most of the time are not paid very well. So, there is not much incentive for highly qualified and experienced people to go into facilities.*

According to an interviewee, service people that designers rely on might also lack technical knowledge:

> *Often designers rely on service people for HVAC, ventilation and other installations. Especially in residential, people working in that field are not necessarily qualified and the technical knowledge is often lacking.*

Possible strategies:

Interviewees suggested implementing automated systems to make decisions. An interviewee suggested using QR code systems to aid installers:

> *Sometimes there are materials that are substituted in the supply line somewhere that the person installing it does not necessarily realise that they are different. An improved system where we stamp the key products with some sort of QR code would be useful so that once it is installed on site, anyone can make sure that it is actually what was specified.*

Interviewees also suggested providing better training to service and facilities people and making sure the people that are hired are qualified.

3 Factors at the construction stage

For the construction stage, risks were identified based on the literature review. From the review, the relevant risk factors are categorised into six groups: (1) materials and equipment; (2) knowledge and working skills; (3) construction management process; (4) procurement process; (5) design input; and (6) client-related problems. The categories and the risk factors under each are presented in Figure 5

The first group contains all issues relating to *materials and equipment* that will be used in a retrofitting project. For instance, materials and products used can deteriorate (e.g. with degraded insulation and airtightness), not as intended [15], [16]. New materials' performance and technologies are not tested over the years, so they do not conform to specification or do not perform in-situ as expected [17], [19]. Thus, build quality may not be up to the required specification. In addition, in some instances, value engineering process and change orders due to cost-cutting can lead to substitutions of building service equipment or materials. If they are not checked carefully against original specification, the changes may impact on performance criteria [11], [15], [16], [18], [19]. Further, suitable construction equipment is needed for completing works. Inappropriate use on-site can lead to poor working quality [20].

Variables associated with energy-efficient *knowledge and working skills* are in the second group. Lack of working skills is one of the common problems [11], [18], [19]. Poor working skills may lead to the poor quality installation of retrofit measures in buildings [17]. Often, the building fabric is constructed incorrectly, reducing the actual performance of the thermal envelope. Improper installation and poorly commissioned building services result in reduced system efficiency and compromise the airtightness and ventilation strategies. Furthermore, lack of understanding of the procurement and construction team regarding energy-performance related criteria, results in the poor installation or commissioning of services, short-term fixes and improvisations on-site without an understanding of long-term impact [19].

The next group is *procurement* variables. If tenders were high, cost savings may be necessary. Cost-cuts often affect thermal characteristics, building services and controls. If procurement teams do not prioritise energy-related skills when selecting contractors, it can lead to selection of contractors having limited knowledge on energy efficiency retrofitting. It should be noted that lack of qualified contractors/suppliers and skilled workers are current difficulties in green projects [8], [17]. In addition, tender documentation may not contain up-to-date requirements or trade specifications, resulting in the wrong products being installed on-site [18], [19], [21].

Construction management process concerns with poor communication is a common issue in both conventional projects and energy-efficient projects [18], [19]. There is also a lack of collaborative working effort, such as lack of designer input on-site if issues arise, construction teams not sufficiently

involved at the design stage, poor communication, and full design information or installation guidance produced but not available on-site [18], [19]. In addition, there is no adequate *quality assurance plan*; i.e. existing quality checks were limited and did not focus strongly enough on energy-related performance [19]. This lack of a quality assurance plan can result in incomplete commissioning of installed products [15], [16], [19]

Retrofitting projects are normally run simultaneously with normal commercial businesses. Hence project teams will face the challenge of remaining occupancy during the project process. The difficulty is to keep the project on schedule without reducing tenants' satisfaction. It is noted that failure to keep the project *on time* leads to adverse consequences, especially the quality of works [22]. Poor work quality results in a poor energy performance in retrofitted buildings.

Most studies on the energy performance gap agree that *contractor-design elements* are a big concern in building energy retrofits [11], [15], [16], [18], [19]. It is argued that incomplete design or design changes can result in construction details that may not be specified correctly [11], [15], [16], [18], [19]. Details are left unspecified and for the contractor to define, with potential risks for the creation of thermal bridges. Contractor-designed elements may not end up as originally envisaged, changing the overall performance of buildings.

The last group of factors is *client-related* variables, such as not engaging green building practices [17], lack of construction management experience in green projects [17], or unclear requirements [22]. Some owners commence a retrofitting project with an inexperienced team [17]. This can make the management process more challenging to the owner. Building retrofits may introduce new processes, modern technology and an unfamiliar environment [17]. Lack of understanding of any aspects increase the possibility of poor project performance.

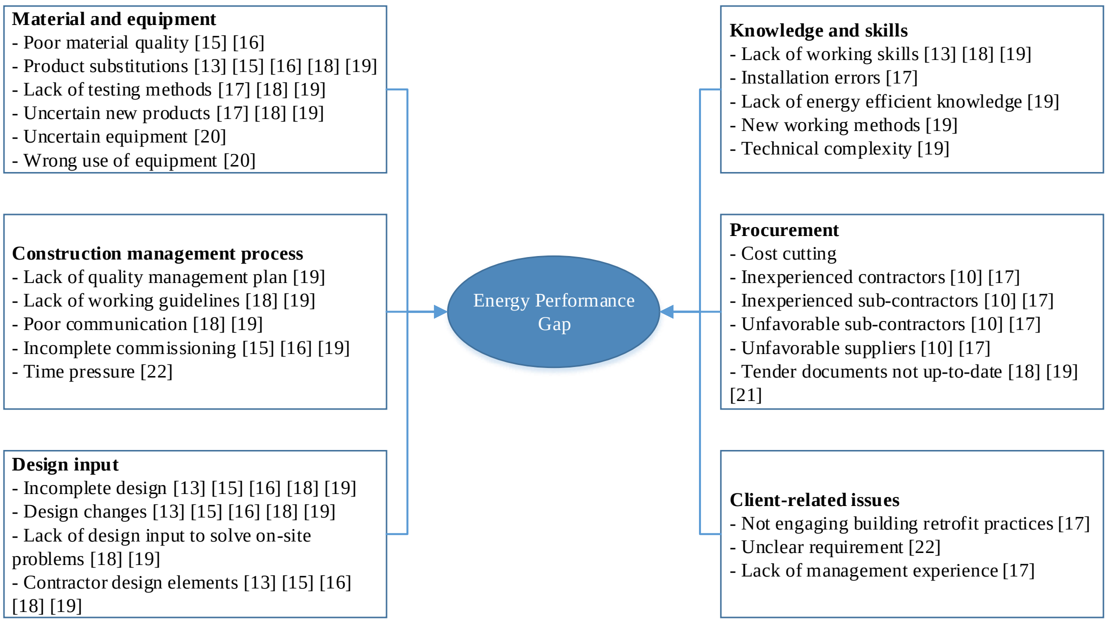

*Figure 5 Construction **and commissioning risks potentially affecting the energy performance of retrofitted buildings***

4 References

1. Lucon, O., et al., *Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*, O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. and P.E. Brunner, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx Editors. 2014: Cambridge, United Kingdom and New York, NY, USA.
2. Levine, M., et al., *Residential and commercial buildings. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* O.R.D. B. Metz, P.R. Bosch, R. Dave, L.A. Meyer, Editor. 2007: Cambridge, United Kingdom and New York, NY, USA.
3. Urge-Vorsatz, D., et al., *Best Practice Policies for Low Energy and Carbon Buildings. A Scenario Analysis.* 2012a, Report prepared by Center for Climate Change and Sustainable Policy (3CSEP) for the Global Buildings Performance Network.
4. Ürge-Vorsatz, D., et al., *Chapter 10 — Energy End-Use: Buildings. In: Global Energy Assessment-Towards a Sustainable Future*. 2012b: Cambridge University Press, Cambridge, UK and New York, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, Laxenburg, Austria,. p. 649 – 760.
5. Business outlook and evaluation, *Zero net emissions by 2020 - A roadmap to carbon neutral city*. 2002, City of Melbourne.
6. City of Melbourne, *Zero net emissions by 2020 - Update 2014*. 2014: Melbourne, Australia.
7. The City of Melbourne. *1200 Building*. 2016 [cited 16.06.2016; Available from: http://www.melbourne.vic.gov.au/business/sustainable-business/1200-buildings/Pages/1200-buildings.aspx.
8. United Nations. *The Paris Agreement*. 2015; Available from: http://unfccc.int/paris_agreement/items/9485.php.
9. ASBEC, *Low Carbon, High Performance: How buildings can make a major contribution to Australia's emissions and productivity goals*. 2016, Australian Sustainable Built Environment Council.
10. de Wilde, P., *The gap between predicted and measured energy performance of buildings: A framework for investigation.* Automation in Construction, 2014. **41**: p. 40-49.
11. Bordass, B., R. Cohen, and J. Field, *Energy performance of non-domestic buildings: Closing the credibility gap*, in *International Conference on Improving Energy Efficiency of Commercial Buildings, 21-22 April, Frankfurt*. 2004.
12. van Dronkelaar, C., et al., *A Review of the Regulatory Energy Performance Gap and Its Underlying Causes in Non-domestic Buildings.* Frontiers in Mechanical Engineering, 2016. **1**: p. 1-14.
13. Carbon trust. *Closing the gap*. 2011; Available from: https://www.carbontrust.com/media/81361/ctg047-closing-the-gap-low-carbon-building-design.pdf.
14. Bordass, B., et al., *Assessing building performance in use 3: energy performance of the Probe buildings.* Building Research & Information, 2001. **29**(2): p. 114-128.
15. Fedoruk, L.E., et al., *Learning from failure: understanding the anticipated–achieved building energy performance gap.* Building Research & Information, 2015. **43**: p. 750-763.
16. Dall'O', G., et al., *Comparison between predicted and actual energy performance for winter heating in high-performance residential buildings in the Lombardy region (Italy).* Energy and Buildings, 2012. **47**: p. 247-253.
17. CarbonBuzz. 2017 [cited 2017 27.09.2017]; Available from: http://www.carbonbuzz.org/index.jsp#performancegap.
18. Board, T.G.C. *Closing the performance gap*. 2013.

19. Rees, S.J., *Closing the performance gap through better building physics.* Building Services Engineering Research and Technology, 2017. **38**: p. 125-132.
20. Rafols, I. *Performance gap and its assessment methodology in Built2Spec project*. 2015.
21. Menezes, A.C., et al., *Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap.* Applied Energy, 2012. **97**: p. 355-364.
22. Bogers, T., J.J. van Meel, and T.J. van der Voordt, *Architects about briefing: Recommendations to improve communication between clients and architects.* Facilities, 2008. **26**(3/4): p. 109-116.
23. Bordass, B. *Energy performance of non-domestic buildings: closing the credibility gap*. in *in Proceedings of the 2004 Improving Energy Efficiency of Commercial Buildings Conference*. 2004. Citeseer.
24. Demanuele, C., T. Tweddell, and M. Davies. *Bridging the gap between predicted and actual energy performance in schools*. in *World renewable energy congress XI*. 2010. UAE Abu Dhabi.
25. Austin, B. and A. Charlson, *The performance gap: causes and solutions.* Arup, London, 2013.
26. Pena, W.M. and S.A. Parshall, *Problem seeking: An architectural programming primer*. 2012: John Wiley & Sons.
27. Barrett, P. and C.A. Stanley, *Better construction briefing*. 1999: John Wiley & Sons.
28. Masoso, O.T. and L.J. Grobler, *The dark side of occupants' behaviour on building energy use.* Energy and buildings, 2010. **42**(2): p. 173-177.
29. Virote, J. and R. Neves-Silva, *Stochastic models for building energy prediction based on occupant behavior assessment.* Energy and Buildings, 2012. **53**: p. 183-193.
30. Powell, J., J. Monahan, and C. Foulds, *Building Futures: Managing energy in the built environment*. 2015: Routledge.
31. Samuelson, H.W., A. Ghorayshi, and C.F. Reinhart, *Analysis of a simplified calibration procedure for 18 design-phase building energy models.* Journal of Building Performance Simulation, 2016. **9**(1): p. 17-29.
32. Aherne, V., *Discussion Paper: Australian Energy Modelling Protocols–Potential for Harmonisation and Alignment.* AIRAH, Melbourne, 2011.
33. Daly, D., P. Cooper, and Z. Ma, *Understanding the risks and uncertainties introduced by common assumptions in energy simulations for Australian commercial buildings.* Energy and Buildings, 2014. **75**: p. 382-393.
34. Bordass, B., A. Leaman, and P. Ruyssevelt, *Assessing building performance in use 5: conclusions and implications.* Building Research & Information, 2001. **29**(2): p. 144-157.
35. Manfren, M., N. Aste, and R. Moshksar, *Calibration and uncertainty analysis for computer models–a meta-model based approach for integrated building energy simulation.* Applied energy, 2013. **103**: p. 627-641.
36. Heo, Y., R. Choudhary, and G.A. Augenbroe, *Calibration of building energy models for retrofit analysis under uncertainty.* Energy and Buildings, 2012. **47**: p. 550-560.
37. Alspector, D.E., *Automatic calibration of baseline models for energy conservation measure analysis*. 2008: ProQuest.
38. Raftery, P., M. Keane, and A. Costa, *Calibrating whole building energy models: Detailed case study using hourly measured data.* Energy and Buildings, 2011. **43**(12): p. 3666-3679.
39. Goswami, D.Y. and F. Kreith, *Energy management and conservation handbook*. 2007: CRC Press.