CLOSING THE GAP BETWEEN DESIGN AND REALITY OF BUILDING ENERGY PERFORMANCE

Factors and strategies at design and construction stages

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1 Introduction

The gap between the actual measured energy performance of a building and that which it is predicted or designed to perform is termed as the Energy Performance Gap. On average, a building consumes about 1.5 to 2.5 times the predicted energy consumption value [1]. The performance gap may arise due to many factors during the design, construction and operation stage of a building. This report presents a list of factors contributing to the energy performance gap at the design and construction stages, based on a literature review and interviews with experienced professionals in Section 3. Section 4 presents a detailed plan for case studies to analyse the sensitivity of these identified factors on the energy performance gap. The results would be useful to identify the most influential factors on the energy performance gap and develop mitigation strategies.

2 List of Interviewees

Twenty-four experienced professionals were interviewed, including engineers, architects, project managers and consultants. Semi-structured interviews were conducted due to the flexibility in using a guide for the process as well as follow-up questions to know more details about the factors. Suitable participants for interviews were selected based on two criteria: position and experience. The participants should have at least five years of experience as principal designers, ESD consultants, project managers and construction managers in green building projects. Table 1 shows the participant's demographic:

Table 1 Demographic of interview participants

No.	Position of participants	Years of experience
1	ESD Engineer	11
2	Senior Sustainability Engineer	6
3	Environmental management	10
4	Civil engineer/ Sustainability and energy expert	15
5	Mechanical engineer/ Energy Management/ Project engineer	5
6	Electrical Engineer/ Energy Efficiency, Management and Analytics	11
7	Energy solutions manager	5
8	Client relationship manager	5
9	Architect/ ESD Engineer	15
10	Sustainable Building Advisor	14
11	Mechanical Engineer/ Director	20
12	Architect/ Sustainability Manager	10
13	Energy Analyst/ Client Energy Manager	10
14	General Manager Growth - Energy Solutions & Products	25
15	Energy and Sustainability Manager	12
16	Project Engineer	7
17	General Manager	11
18	Principal Consultant	14
19	Director, Principal Consultant	10
20	Technical Director	7
21	Mechanical Engineer	40
22	Senior ESD Consultant	12
23	Sustainability Manager	18
24	Global Lead, Program and Project Management	10

3 Factors and strategies affecting the energy performance gap

3.1 Inaccurate design assumptions

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. In Australia, no large-scale studies have been undertaken to define the typical values of different simulation parameters such as ICT power density, ICT usage schedules, or lighting power density which significantly affect the energy usage in commercial buildings. As a result, it is very difficult for the designer to accurately estimate the values of these parameters during the design stage [2]. 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 [3]. 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 [2]. Simulation assumptions should have firm roots in statistically significant studies of building stocks with similar characteristics to the building in question. A comprehensive Australian database should be created to address the lack of data on building attributes and occupant behaviours, which influence building energy consumption [2]. The need for an Australian database for design assumptions was also highlighted by the interviewees *(Interviewee 5, 10).*

3.1.1 Assumptions regarding building operations

The designers have to make many assumptions regarding building operation. In a study conducted by [4], 19–28% of the buildings' energy went to the unoccupied part of the weekend. This is especially true of buildings that have adopted a security system, which do not allow networked equipment to be switched off. HVAC systems are run outside of working hours as well. Turning systems off at the end of working hours and turning them back on at the start next day often leads to complaints of discomfort at the start of working hours. To solve this problem, air-conditioning is often left ON all night [5]. In a case study comparison performed by [6], offices that left their equipment on overnight consumed 60% more electricity than offices that encouraged their employees to turn off their computers and screens and to switch off printer/copiers and non-essential catering equipment such as coffee machines at the end of each day. Hence it is clear that most of the energy waste in a building occurs during non-occupancy hours [7]. 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 [5], resulting in energy performance gap.

The design stage might lack a full grasp of the nature of the control system and its defaults. Designers usually assume that the control system is perfect and permits only demanded amount of supply [8]. The assumption that the supply matches the demand at all times is far from true. Another widespread problem with the control system is that it does not turn off the lights and other equipment as expected which changes the performance of the building quite considerably *(Interviewee 4, 9)*. Also, the designers assume that the equipment will run as intended and don't allow as much as required for inefficiencies that might occur in building operation (*Interviewee 6, 9*). There is a tendency to select the best case scenario which can result in overestimation of energy savings (*Interviewee 3*).

3.1.2 Assumptions regarding plug load

The reviewed literature has shown that even during working hours, there are signs of wasted energy [4]. Miscellaneous loads refer to plug loads, server rooms, small power loads, elevator loads, catering, external lighting and other loads that are not attributed to major end uses. Miscellaneous loads also include standby power. Many kinds of office equipment continue to draw electricity even

when not in use. 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 [9]. For example, unregulated energy loads amounted to 69 percent of the total load in a case study of a six-storeyed office building [10].

Revising plug loads increased the estimated energy use by 15% median (32% mean) in an experiment conducted by [11]. The study recommends revising plug loads by using sub-metered data for improved accuracy. [7] suggests 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. [4] mentions 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.

Project types with high process loads are also problematic. Lab buildings on average use more than twice as much energy as anticipated in their energy models but designers do not address this fact because designers apparently have erroneous assumptions about the workings of these building types [12].

3.1.3 Assumptions regarding building construction materials and equipment

This factor is particularly important for retrofitting projects. Access to detail information about a building is very important when creating the energy model of an existing building. In a building energy retrofit projects, quite often not enough information is available regarding building construction materials and equipment (*Interviewee 1, 2*). The energy modellers have to make many assumptions regarding the performance of building fabric and equipment. Also they have to rely on gross energy metered data in the absence of detail breakdown of consumption data *(Interviewee 4).*

3.1.4 Assumptions regarding stochastic factors

Factors such as weather, occupant density fluctuate unpredictably over the course of time. It is difficult to ascertain during the design stage their precise impact on the energy demand. Some are ever changing (weather) and others are highly dynamic (occupant density, air changes). It is important to remember that the estimations produced by simulation tools are only as accurate as the models and inputs they are based on [13]. For instance, the accuracy of energy consumption prediction depends on the accuracy of the weather predictions, which have an inherent uncertainty [14]. Such parameters are said to be stochastic. Uncertainties and errors in these input parameters get propagated to the output or the predicted energy consumption [15]

3.2 Poor design

Several problems arise from a lack of foresight during the design stage. The lack of foresight may come from the lack of feedback to designers. The designers might not think some aspects of the design and aesthetics through. For instance, the design team may specify details that are difficult or impractical to build and have to be modified on site, which also results in a lower performance [9]. To achieve energy efficiency, sometimes the engineers overcomplicate the design and includes multiple layers of control mechanisms which is difficult to understand and run (*Interviewee 2*). Since designers do not participate in the monitoring phase, but rather move on from designing one project to designing another one, 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 (*Interviewee 22*).

The above points to the need for a change in the flawed current governance that keeps designers away from post-occupancy feedback and unaware of any emergent flaws in their design. Experts suggest restructuring contracts in new ways so that occupant feedback is mandatory and

reaches the designers. Better feedback to the design community is needed to help calibrate energy modelling results. Follow-up investigation into reasons for measured-to-design deviations, and for the wide variations in modelled baseline performance, could improve future designs, modelling and benchmarking [12].

3.3 Inherent uncertainties in simulation tools

Uncertainties related to simulation also affect the accuracy of saving predictions. Simulation software tends to over-simplify building and building systems, and are based on assumptions of thermal processes, and algorithmic differences [6, 16]. Modellers may be constrained by the models due to only limited prescribed options being available within the model structure [9]. Most software packages do not efficiently model the impact of occupants and energy management on the energy performance [6]. The software packages need improvements in their integration into the concept, planning and design phases [6]. [17] discusses some software issues that lead to an over or under-prediction of energy use. Resolving these issues requires isolating the issue to a sub-system within the software and revising the solution process until it agrees with a verified numerical solution. Analysing software issues is outside the scope of a designer's responsibility. However, there is a slew of simulation packages a designer can choose from and they are not all alike. Each simulation package offers its own set of strengths as well as weaknesses. For instance, TRNSYS is unable to connect to AUTOCAD to import files, while EnergyPlus, ESP-r, IDA ICE and IES can [18]. [19] encourages users to consider adopting a suite of tools, which would support the range of simulation needs they usually see in their practice.

3.4 Value Engineering

A value engineering exercise may involve compromising the building services or replacing certain components with a cheaper alternative [8]. 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 [6]. According to [10], variations, including changes to thermal mass, insulation, orientation, controls and operational hours, may not be reassessed in terms of energy performance.

Value engineering was identified as one of the most crucial factors in performance gaps from the interviews. Interviewee 1 mentioned that there might be changes to the building fabric during the construction which means that designers' assumptions about building fabric and airtightness, particularly, are not reflective of the model. Changing a material and equipment with cheaper alternatives may compromise the functionality of that item and may result in a performance gap (*Interviewee 20).* Also, quite often, equipment is installed to save energy but the smart control system, which can run the equipment efficiently, is not installed because the client does not want to spend the extra money (Interviewees 4, 17). As a result, the installed energy efficient equipment cannot contribute to energy savings as intended. Moreover, sometimes the sub-metering systems, which can make sure that the savings are maintained, are not installed in the building (although recommended by designers) to cut the cost. Interviewees 6, 9 and 12 also mentioned the impact of value engineering on the building energy performance gap.

3.5 Incomplete commissioning

Proper commissioning and building tuning are very important for making sure that building services work properly and up to the level that is predicted by the energy model [20, 21]. However, this does not happen all the time due to contractual issues, budget issues, time pressure and poor

commissioning plans (*Interviewee 1*) which may lead to a performance gap. Often, the quality of commissioning is very poor and is not fully undertaken (*Interviewees 3, 6*). In a number of cases, a commissioning plan is not prepared properly and is too short or has unclear requirements *(Interviewees 15, 16, 22).* Also, it is common to find that installed meters are not properly commissioned and validated, and hence the data recorded by these meters are meaningless. The validation of the metering system is critical to manage a building effectively and keep it operating at its optimum [21].

Moreover, due to the lack of knowledge and skill of control contractors, sometimes the building management system (BMS) is not set up according to the design intent. Design engineers normally provide the requirements how the BMS system should run and transfer this document to control contractors. When it comes to setting up the control requirement, not many people, in reality, have a proper understanding what should be going on and have an ability to troubleshoot problems *(Interviewee 22).* As a result, buildings are run differently than the design intent which contributes to performance gap.

To overcome this problem, independent commissioning agents and people with the relevant expertise should be brought on to projects *(Interviewee 1).* Once the building is inhabited and operational, expert professional can be hired to analyse the data stored in building management system and optimise certain mechanical installations and control systems to ensure those are running as intended *(Interviewee 7)*. Design engineers need to be involved to assure thorough commissioning. To make sure this happens, responsibility needs to be clarified in the plan. This, in turn, depends on the scope of the consultant contract. If it is unclear, it is hard to involve the right people in the process *(Interviewee 23).*

Furthermore, the building commissioning only includes testing the mechanical and electrical systems of the building. There is no requirement to test the building envelope to check whether it is performing as intended or not. For example, there is no requirement to check the air infiltration of a building and it completely depends on the quality of construction work carried out by the contractors (*Interviewee 1*). Hence, there should be some auditing process in place during construction to check the construction quality.

3.6 Poor workmanship

Poor quality construction has a significant impact on the energy performance of buildings. Poor construction works could occur due to an individual issue or a combination of the issues of insufficient design details, inefficient use of quality assurance plan, or lack of knowledge or care of frontline workers. Powell, Monahan [22] stated that small defects (e.g. gaps in insulation) could reduce the energy performance of buildings. Alencastro et al. [23] highlighted the importance of preventing quality defects if construction projects aim to achieve, at the operational phase, the building energy performance intended at the design phase. They suggested that more research is required to provide a full understanding of the defects origin mechanisms and their impacts on the energy consumption of buildings, which in turn allows the development of effective quality plans and preventive measures

During a tender process for construction, clients tend to select those proposals that will provide the services at lower costs even if the proposals only provide a deem-to-satisfy solution for energy efficiency and do not address the advanced energy efficiency requirements. On the one hand, clients want to have higher energy-efficient buildings. On the other hand, they want to build them as cheap as possible. *Interviewee 15* mentioned that: “We receive what we pay for”. If energy efficiency is the main incentive, clients should pay for suitable services and technologies that help to achieve the target. Thus, clients need to understand not only energy savings strategies, but the cost that associates

with the implementation of these strategies. This knowledge may allow procurement team to propose the energy-related criteria in the tender and engage a suitable contractor for the project delivery process.

Previous studies [20, 24, e.g. 25] have also pointed out that lack of knowledge and skills of construction workers can contribute to the performance gap. Insufficient attention to insulation and airtightness may lead to poor quality of building fabrics compared to design specifications [26]. If the building fabric is constructed incorrectly, it may reduce the thermal performance of the envelope due to thermal bridging and excessive heat loss which will increase energy consumption [23].

Sometimes the contractors do not have an adequate quality assurance plan when commencing construction. *Interviewee 15* indicated that this situation does depend on “price point”. If clients aim to achieve a certain quality, draft requirements accordingly, and pay for the service, they are likely to obtain what they are expecting, and vice versa. It was also pointed out that some contractors do not implement the plan, which was submitted during the procurement, effectively *(Interviewee 16)*. This ineffective use can cause errors and omission during installation of building fabric and service systems.

Errors during installation can be rectified as long as a quality assurance plan is used effectively and an experienced inspection team is involved. However, not all errors can be recognised and solved on-site. For instance, hidden errors in insulation are not easily captured with the normal visual inspection *(Interviewee 16)*. Insulations are normally covered by finishes, e.g. brick veneer, plaster, or ceiling. A visual check may be challenging in this situation. Also, crushed duct-works cannot be identified if there is no complete commissioning of the systems.

It may also help to have more comprehensive instruction regarding construction of buildings to achieve the desired airtightness target and to install the building fabric and insulation to avoid any thermal bridge. The construction industry can be educated on how to achieve airtightness targets, and how to construct joints between windows and walls, wall-floor, and wall-roof interfaces. (*Interviewees 1, 20*).

3.7 Poor quality of materials and equipment

Poor materials quality can lead to an energy performance gap [20, 22, 27]. Poor quality materials may be installed in the building to minimise cost (value engineering). Also, new materials that are introduced in the building without comprehensive testing of their performance may not perform in-situ as expected and may lead to performance gap [26]. Particularly, imported materials and products which are not compliant with the local standards, can result in a performance gap (*Interviewees 15*, *16*, *21*). Sometimes, the quality of these materials is not up-to-the required Australian standard. As it is costly to conduct laboratory tests of these imported new products, the third party certificates are normally accepted by the project team (*Interviewee 21*).

3.8 Time pressure

Time pressure is a significant factor in construction projects because: (1) penalty can be applied for late delivery; and (2) contractors need to move to their next projects (*Interviewee 16*). Under time pressures, contractors may take shortcuts to finish works on-time. This can lower the quality of works and create defects in building components, which are connected with the risk of incorrect installation of the building’s fabric and systems. Also, to maintain progress, contractors usually reduce the commissioning duration which is not ideal *(Interviewees 17, 22, 23).*

3.9 Complex user behaviour

During the post-occupancy period, the ideal operation of the HVAC system may not be realised because of occupants’ interference *(Interviewee 1)*. In an office building, different people have

different requirements for thermal comfort, and they change the space temperature or open windows to maintain their comfort which may influence the performance of HVAC system *(Interviewee 2)*. That is why it is not recommended to allow the occupants to have control over changing the indoor temperature or operating windows. It was pointed out by *Interviewee 1* that locking out user control on space temperature resulted in successful project outcomes. To give the user a sense of control over their space temperature, a dummy controller is sometimes installed which was also found to be quite successful.

Not everyone in a commercial building is aware of energy efficient behaviour. Sometimes they forgot to turn things on and off at the right time which impacts the building energy consumption *(Interviewee 13)*. Occupant's lack of understanding about the operation of installed technologies also influence their behaviour in terms of operating those systems which may change the building energy performance (*Interviewee 11*).

3.10 Lack of ongoing monitoring

There is a need for an ongoing feedback loop to make sure that buildings are operating as intended during the design stage. Unfortunately, that feedback loop is almost always removed from a project. In both new and retrofitted energy-efficient buildings, a number of energy conservation measures fail due to inadequate ongoing monitoring. There are no follow up to confirm that savings are actually achieved and no fine-tuning of the equipment to improve energy efficiency (*Interviewee 3, 9, 10, 12*). Buildings do go out of tune and savings can drop. Due to lack of monitoring, there is no understanding of the performance of the energy usage systems within a building such as chillers, pumps, boilers, fans, lighting etc. Due to the lack of understanding, the building managers and owners do not realise the need to invest money in monitoring and tuning the building which leads to performance gap in the building (*Interviewees 1*, *4, 7, 13*). The absence of monitoring systems also leaves the designers and contractors in the dark about the performance of their completed work (*Interviewee 4*). The clients, project managers, procurement managers should be informed that spending a little bit of money on metering and control up front is going to provide the lifetime benefit over the life of the equipment (*Interviewee 4*). Lack of monitoring also creates a significant problem in case of the retrofit project. A comprehensive monitoring strategy and good monitoring data are essential to develop an energy model and identify the retrofit strategies to improve energy efficiency *(Interviewee 5)*.

3.11 Lack of knowledgeable and skilled facility managers

Once the building is handed over to the enduser, the way it is operated by the building operation staff is crucial to realising the design intent. Having a knowledgeable and skilled building facilities manager is important to operating the building as intended. This will help to reduce the performance gap significantly (*Interviewee 1*). However, it is hard to find such people for a number of reasons. The quality of education provided to facilities staff is certainly not adequate for the role that they are expected to carry out (*Interviewee 2).* They don't have the resources or the understanding of the systems that they are operating. This is particularly true if new and emerging technologies are installed in the building *(Interviewee 6)*. Also, the facility staff members are not paid very well. So there is not much incentive for people who are either degree-qualified or have years of experience. It is never going to be competitive for them to go into facilities versus consulting. So the best people do not really go into facilities (*Interviewee 2*). In some buildings, there are no dedicated facility managers, and the task of maintaining the building is transferred to a third party facility manager who does not have the technical knowledge to deal with the high tech systems of modern buildings (*Interviewee 7, Interviewee 11*).

The facilities manager should be trained to make sure that they are tracking the performance of the building and know how to get the best out of the system. Sometimes, their main objective is to make sure that it is safe and operate in such a way that they do not get any complaints regarding thermal comfort. So they tune the building to guarantee thermal comfort not to improve energy efficiency *(Interviewee 4).*

3.12 Change in space usage pattern

The buildings may not be used as envisaged during the design stage. The occupancy hour, densities and activities may be changed during the operational stage which will significantly impact the building performance and may result in a performance gap [21]**.** Fit-out may change the building in a way which clashes with original design intent.

3.13 Poor communications and collaborations

Poor interaction among various teams inhibits the development of innovative solutions that can be achieved from brainstorming. Clients and designers often do not have clear communication. According to [28], briefings are not clear, consistent or complete. Also, the designer might fail to communicate the level of management and vigilance that he expects from the users and building facilities staff. This might lead to the occupants taking the building for granted or finding the building too demanding and dissatisfactory later down the road [5].

Likewise, there seems to be a lack of communication among various inter-functional groups working on the same project. For instance, mechanical engineers tend only to focus on determining the size of HVAC according to the insulation thickness that the architect decides independently. There is no arrangement for these two groups to sit together and explore a more efficient alternative. Poor interaction among different teams often results in flaws in the building. For instance, when the concept team and the design team are different, and the aesthetics, fabric performance and building services are considered separately, this can lead to airtightness approaches being compromised and inadvertent thermal bridging [9].

Energy models of buildings that are developed during the design stage are not really representative of operational energy. Energy models are used to check compliance with a particular standard rather than to actually demonstrate how the building should operate. The level of detail needed in a model to capture how the building will actually operate is far greater than what is required by the construction code, or for NABERS or Green Star requirements (Interviewee 1). The design and construction team of a project is completely separated from the teams or companies that are going to maintain that building. Poor communications among these groups results in a building not being operated as intended. Also, lack of communication between the designer and operation people may lead to some optimistic assumptions by the designer regarding the performance of new technology which may lead to a performance gap if not working efficiently (Interviewee 9).

Previous research also indicated that poor communication during construction can also lead to an energy performance gap [29, 30]. The lack of communication between designers and contractors results in an inadequate information transfer from designer to contractors. The contractors have to work on the information they receive to complete the design before commencing construction. This is known as contractor designed element [31]. With the lack of detail design information, the chance of construction in accordance with the original design intent is low. In addition, if there are any changes in the construction, these are not fed back to the designers due to the lack of communication *(Interviewees 14, 18, 19, 23).* Therefore, it is likely that the as-built building is different from what has been designed, which lead to a performance gap.

Effective communications among various actors within the project should be ensured by scheduling regular meetings among stakeholders and design teams. 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. In turn, the designer should clearly communicate their expectations regarding the maintenance of the building to the facilities management team when it goes into operation. There should be a clear team leader or project manager who is responsible for the communications among the teams and then ultimately to the client. This will help to make sure that the project is carried out according to the specification as agreed and signed on by the client. The project manager should adhere to this agreement unless there are some changes that both the project manager and the client acknowledge and factor those changes in. This is very important to accurately determine the building energy performance *(Interviewees 1, 8).* The risks of installing new technologies can be minimised through effective communication between project managers, contractors, designers and commissioning agents. For example, by being extra cautious during installation to make sure it is done properly, going back and revising commissioning on a regular basis and having regular reviews (*Interviewee 3*).

A good communication strategy during construction may help contractors understand what and why energy conservation measures have been selected. This understanding assures that the team has the same mental space to achieve what has been proposed (*Interviewee 15*).

3.14 Lack of accountability

There are no measures to hold the designers and contractors accountable if the buildings do not perform as intended. In a project, both the designers and contractors do their respective tasks and move on to the next project [32]. Particularly, under prescriptive-based projects, one might have multiple different contractors who do their jobs to the specifications that were put forward by their client. As long as it passes the legislation, then that will be the end of their involvement. These contractors are not too worried about how efficient it is going to be after several years because they will not be responsible if the system does not perform as intended *(Interviewee 7).* Sometimes, to be successful in the competitive tendering process, some contractors promise to deliver jobs which they do not have the capacity to perform. As a result, the quality of work done is poor which can lead to a performance gap (*Interviewee 8*). Moreover, user attitudes concerning their standard of living, psychological resistance to change and apathy about energy saving result in the irresponsible consumption of electricity [33].

Too often, people try to avoid accountability by putting wiggle words in contracts. A solid and clear contract can ensure accountability in projects (*Interviewee 3*). The clients who are driving the projects need to make sure that there is some responsibility on the designers and the builders to make sure that the project outcomes are achieved and it should be clearly documented in contracts early on in the design process *(Interviewee 6).* In terms of user behaviour, [4] offers a number of resources that can be put together to develop accountability and bring out the best of occupancy behaviour, ranging from energy awareness campaigns, incentives, punitive measures, etc. Energy awareness through monitoring is useful to make users learn what a "normal" level of energy use is. Apart from alerting users about where, when and how much energy is being used, it also has the effect of prompting behavioural changes to cut out unnecessary and wasteful energy use [34, 35]. However, according to [35], monitors only help users keep their normal level of consumption stable but their ability to challenge and reduce what is considered normal is questionable. The study concludes that wider policy and other market measures are needed to reduce energy consumption further. Infosys, an Indian based IT consulting company, is developing a wireless monitoring system that measures how much energy employees use in their cubicles, and provide feedback on their pay-checks [34]. Stern

measures such as these just might help foster greater accountability in users, a much-needed change, especially in office settings.

Table 2 Factors affecting the energy performance gap

Stages	**Factors affecting the performance gap**	**Cross-cutting factors**
Design Stage	Inaccurate design assumptions - *Assumptions regarding building operations* - *Assumptions regarding plug load* - *Assumptions regarding construction materials and equipment* - *Assumptions regarding stochastic factors* Poor design Inherent uncertainties in simulation tools	
Construction and commissioning stage	Value Engineering/Design Change Incomplete commissioning Poor workmanship Poor quality materials and equipment Time pressure	Poor communication and collaboration Lack of accountability
Operational stage *(More detail on operational stage factors is presented in Report 3)*	Complex user behaviour Lack of ongoing monitoring Lack of knowledgeable and skilled facility managers Changes in space usage pattern	

4 Case studies

Two case studies will be carried out to quantitatively analyse the impact of these factors on energy performance gaps, focusing on the operational stage, and investigate ways of monitoring building performance and how to utilise this information to bridge the performance gap.

The case studies will be carried out according to the steps in Figure 1.

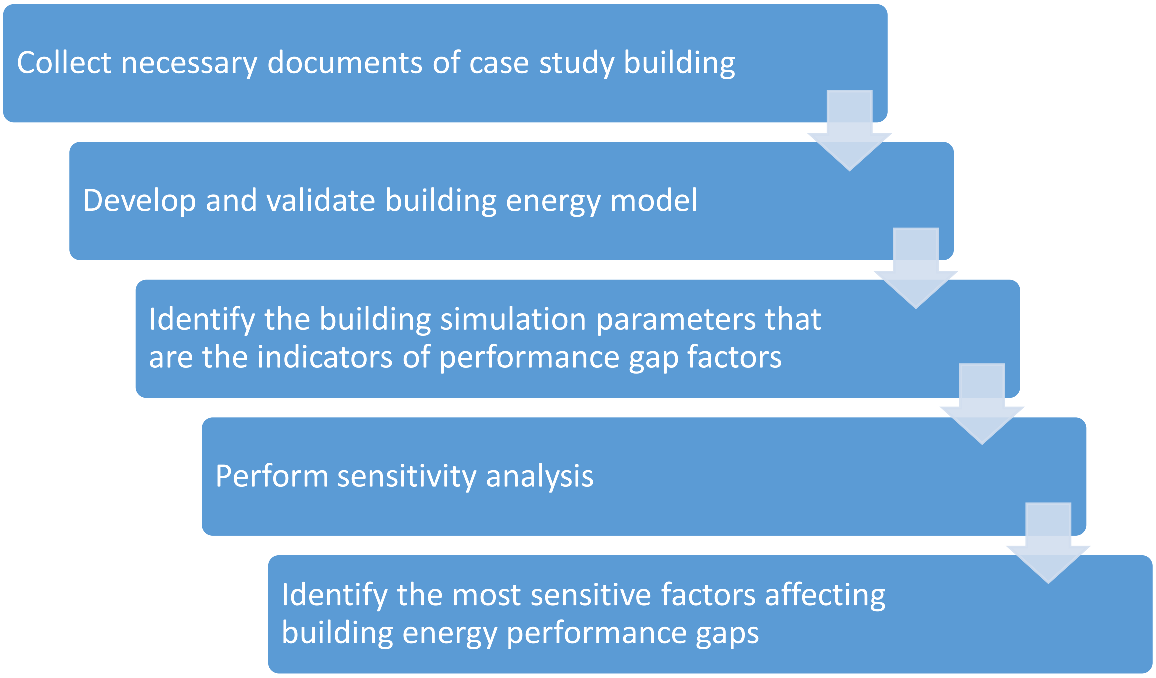

Figure 1 Steps to be followed in case studies on factors affecting energy performance gaps

The following are the documents that will be required for each case study:

1. National Construction Code (NCC) Section J compliance report
2. Documents submitted to Green Star or NABERS for compliance (if any)
3. Historical data of building energy consumptions (electricity and gas bills), zone temperature, occupant density
4. Architectural Drawing of the building that shows floor plan, windows, building envelope materials, lighting, exhaust fans, etc.
5. Thermostat settings to control indoor temperature, location of the thermostat in the zone, schedule of HVAC operation, lighting control mechanism
6. Access to the BMS system of the building to understand HVAC control mechanism
7. Documents on any changes in space usage pattern
8. Drawings of HVAC system including size and distribution of ducts
9. Design drawing of the hot water system
10. List of unregulated loads

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