Building Energy Performance Gap Issues

An International Review

IPEEC Building Energy Efficiency Taskgroup

ipeec

International Partnership for **Energy Efficiency** Cooperation

Contents

Executive Summary

Building energy efficiency has been identified as a cost-effective opportunity to reduce energy consumption and greenhouse gas emissions and a variety of policies are being implemented to harvest this efficiency potential. However, there are growing concerns about a gap between predicted or expected energy consumption levels in buildings and the actual measured energy consumption in operation, both at an individual building level as well as in the building sector as a whole. The energy performance gap has been identified as an important barrier in achieving building energy policy goals, as a variety of reports have pointed out that anticipated savings from key building efficiency policies, such as building codes, may need to be significantly discounted due to actual post-occupancy building energy consumption being markedly higher than what had been predicted by building energy performance models.

The energy performance gap has been observed in both new construction and building energy retrofit projects and is an issue that is seen in nearly all regions of the world. The performance gap is not a result of codes or regulations in any single jurisdiction, but a systemic problem globally. Bridging the gap will be critical for the building sector to achieve and deliver the ambitious energy and emissions reductions goals that many countries and sub-national governments have undertaken. Addressing this problem will require solutions in how building energy performance is estimated as well as the process for commissioning buildings. Policies will need to be adjusted to better address the gap.

Building energy modeling can be a powerful tool for understanding the likely impacts of different building system alternatives, construction practices, and occupant behavior issues. Modeling enables engineers and designers to study different scenarios of building energy and environmental performance, based on a wide variety of different model inputs.

However, building energy models are generally not intended to "predict" actual energy performance when the building is operational. The most common purpose of energy modelling, performed during a building's design phase, is to demonstrate compliance with regulated energy uses through a building code or other regulatory instrument. In operation, buildings often incur other loads which are not regulated (such as appliances, elevators, process loads, or other plug loads) and which may be significant. These are often not captured accurately in compliance-oriented energy models.

The performance gap between predicted and actual building energy consumption and performance can be significant. A large volume of technical research has documented the gap and identified the causes and some potential solutions.

In a literature review that included larger datasets of buildings, it appears that the performance gap is more significant in non-residential buildings, with smaller measured performance gaps in residences.

A major issue is the disconnect between the tools that are being used to identify the gap and their original intent. Use of energy model data based on hypothetical standardized operating conditions to predict actual energy consumption is exacerbating some of the gap findings, and more targeted modeling approaches described in this report may help to address this, and reduce the performance gap.

There is no consistent estimate of the magnitude of the gap found across all of the sources reviewed. While some work found that buildings consume between 150 to 250% of the predictions, and several other sources based on a relatively small sample size show even more significant magnitude differences, in larger datasets the magnitude of the performance gap seems to be smaller with measured energy consumption often in the range of 10 to 30% higher than predicted.

There is a need for more research and analysis to compile the various datasets available internationally to better document the size of the gap, and why in certain cases it is much bigger than others. A major source of discrepancy is that most models calculate predictions just on the "regulated energy" (excluding many plug and/or process loads, as described later in this report), while measured energy consumption includes all metered energy. Also, it appears that some of the findings which indicate a more significant performance gap may be due to smaller sample sizes, or just looking at buildings with very low predicted energy use.

There is also more that needs to be understood about the "prebound" effect, such that in "energy wasting" (often older) buildings the actual energy consumption is generally lower than predicted, whilst predicted energy use in low-energy buildings (or deep energy retrofits) seems to be subject to a bias toward overestimation of the energy reduction/savings. Specifically, more research is needed to determine whether the hypothesis that higher than predicted energy use in buildings expected to have low energy consumption, and lower than predicted energy use in less efficient buildings, holds true across larger analyses.

It is important to note that the performance gap is not only a technical problem but also has behavioral components. Closing it requires understanding building users. For example, low-income households tend to live in energy inefficient houses, so the prebound effect can hide fuel poverty where households simply cannot afford to heat up their homes to adequate levels of comfort.

There are two major opportunities to address the performance gap: (1) more accurate predictions of expected performance, using assumptions more relevant to the expected building occupancy and operation, and (2) better management of the quality control process throughout the design, construction and operation processes to make sure that the design intent for greater efficiency is not lost at some point during the building's life-cycle.

The policy areas that appear to hold promise for minimizing the performance gap are:

- greater transparency of operational/measured energy performance (and not just relying on predicted performance through modeling); and,

- outcome-based policies that essentially regulate the operational performance of the building.

These policy solutions seem to be most appropriate to reduce the gap, and are now being tested in several jurisdictions.

2 Introduction

This report, commissioned as part of the International Partnership for Energy Efficiency's (IPEEC's) Building Energy Efficiency Taskgroup (BEET), provides an overview about the building energy performance gap.

Buildings consumed over 30% of global final energy consumption in 2017, and 55% of final electricity demand (IEA 2018). Building energy consumption globally has been steadily growing, with building-related CO_2 emissions rising by nearly 1% per year since 2010. Consumption is forecast to continue to grow through 2060 without substantial new policy implementation (IEA 2017).

Despite broad policy activity on improving building energy performance in most regions of the world, building energy consumption globally continues to grow, from a final energy consumption of 119 exajoules (EJ) in 2010 to nearly 120 EJ in 2017. This is driven by the rapid increase in the number of buildings across the world: building sector energy intensity measured as energy use per square meter continues to improve at an average annual rate of 1.5%, yet global built floor area is increasing at rate of 2.3% per year, offsetting those energy efficiency and intensity improvements (UN Environment 2017). Building energy efficiency policies are thus a crucial tool in stemming emissions from buildings.

Building energy efficiency has been identified as a cost-effective opportunity to reduce energy consumption and resulting greenhouse gas (GHG) emissions. A large variety of different policies and initiatives have been developed and are being implemented to harvest this efficiency potential. However, there are growing concerns about a gap between predicted[1] or expected energy consumption levels in buildings and the actual measured energy consumption in operation, both at an individual building level as well as in the building sector as a whole in most jurisdictions.

The energy performance gap issue has been identified as an important barrier in achieving building energy policy goals, as a variety of reports have pointed out that anticipated savings from key building efficiency policies, such as building codes, may need to be significantly discounted due to actual

What is the "performance gap"?

Researchers have noted that there is no standardized definition of the performance gap, making it more difficult to compare different research results studying this issue. For the purpose of this report, the building energy performance gap is defined as "the difference between predicted and actual/measured building energy consumption, either for an individual building or for a large group of buildings."

In some research, the information is presented as a "carbon performance gap" instead of "energy performance gap"—in this report we use the more generic term "energy performance gap".

1. It should be noted that building energy models are generally not undertaken to "predict" actual energy performance, but more for energy code compliance or other purposes. As such, the "gap" is at least partially due to the utilization of this modeling output quite differently from how it was initially intended. This issue is addressed later in this report.

post-occupancy building energy consumption being markedly higher than what had been predicted by building energy performance models. The potential issues with the performance gap have been identified in earlier IPEEC BEET reports on Existing Building Energy Efficiency Renovation (IPEEC 2017) and Zero Energy Building Definitions and Policies (IPEEC 2018).

Some widely quoted studies report that measured energy use can be as much as two and a half times (or more) the predicted use—a very significant difference. A review by the United Kingdom (UK) Carbon Trust found that "…For our case study projects, the operational energy use was up to five times higher than estimates during design." (Carbon Trust 2011). Because of this, it is important to better understand issues around the building energy performance gap and identify opportunities for bridging the gap.

A substantial energy performance gap has been observed in both new construction and building energy retrofit projects, and is an issue that is seen in nearly all regions of the world. The performance gap is not a result of codes or regulations in any single jurisdiction, but a systemic problem globally. Bridging the gap will be critical for the building sector to achieve and deliver the ambitious energy and emissions reductions goals that many countries and sub-national governments have undertaken. Addressing this problem will require solutions in both how building energy performance is estimated as well as the process for commissioning buildings. Policies will need to be adjusted to better address the gap.

The purpose of this report is to provide an overview for buildings and energy policy makers on key policy and technical issues known about the performance gap between predicted and actual energy consumption in buildings, presenting a variety of information and data sources distilling the current state of knowledge about the building energy performance gap, and making recommendations about policy changes that should help address it.

3 Predicted Performance and Energy Models

Building energy modeling can be a powerful tool for comparing different building system alternatives, construction practices, and occupant behavior issues. Modeling enables engineers and designers to study different building systems and then evaluate energy consumption and other environmental performance outcomes, based on a wide variety of model inputs.

However, building energy models are generally not intended to "predict" the energy performance of a building in operation. The most common purpose of energy modelling is to demonstrate compliance with regulated energy uses in a building code or other regulatory instrument during the design phase of a building.

The methodology for energy modelling for code compliance is set out according to multiple rules in technical codes and standards. Compliance energy models generally exclude "unregulated" process loads and plug loads, because process and plug loads vary between building occupants and cannot be controlled during the design process, and they are not usually regulated by building codes. Thus, an energy model for code compliance, by definition, does not accurately capture all of the building's expected energy use during operation. That said, there are other ways energy models can be used aside from code compliance.

Two other common uses of energy models are as part of calculations for predicting actual energy use and to demonstrate eligibility for incentives. Models to predict actual energy use are developed by modelers who use the models to understand the energy implications of different design choices during the design of a building or retrofit. In order to conduct such modeling, the team would consider the building's actual energy use during operation and include assumptions about the building occupancy patterns, plug loads, process loads (like elevator use, kitchen operations, laboratory exhaust fan use), and future weather patterns. This is more data than what is required to simply demonstrate code compliance, or even eligibility for incentives.

Some practitioners who use energy modeling as a predictive tool in this way generate results that closely match actual metered energy consumption of the operating building, demonstrating it is possible for building energy models to reflect real building characteristics. However, that is currently not the most common use of energy models. In professional practice it is rare to compare building energy modeling results with actual energy performance because it is not required. As a result, it is also rare for design professionals to receive feedback that would improve accuracy. This disconnect lays at the heart of the building energy performance gap, as the models most often used to assess actual building energy performance were not calibrated to do so.

Findings from Literature Review

There has been a tremendous amount of technical research on building energy efficiency and performance in recent years, with a growing number of technical researchers digging into the performance gap. Most of the research has been on technical issues and potential solutions in either energy modeling accuracy or construction quality, with less emphasis on policy and program issues and potential policy solutions. The remainder of this section is broken down by published research quantifying the magnitude of the gap between predicted vs. actual energy performance, technical research, and policy and programmatic research findings.

Range of magnitude of gap from various sources

While some of the "headline" summaries of the performance gap highlight that there can be a factor of as much as five times the predicted to actual energy use,[1] this seems to be more the exception than the norm. There also appear to be analyses of much larger datasets of residential buildings generally showing a smaller performance gap than in the smaller samples for non-residential buildings.

A major challenge with understanding the magnitude of the performance gap is that many studies present the data on predicted performance relative to measured performance differently. In some cases, it is just a comparison of modeled vs. actual energy performance for a set of buildings, while others compare predicted/expected energy or carbon ratings relative to some measurement of actual performance. Additionally, many studies of the building energy performance gap only look at certain end uses, such as predicted vs. actual heating consumption, which may exaggerate the perceived gap for a single end use disproportionately to the impact on whole building energy performance.

As noted earlier, probably the biggest source of variation in many studies of predicted vs. measured energy (or carbon) performance is that the predicted consumption can be based on standardized conditions, using reference building operating assumptions, and exclude "unregulated" loads that can be significant in building operations.

There is no consistent estimate of the magnitude of the gap found across all of the sources reviewed. Some research has found that buildings consume between 150 to 250% of the predictions, though the studies that show large differences are generally based on a relatively small sample size. In larger datasets, the magnitude of the performance gap seems to be smaller, with measured energy consumption often in the range of 10 to 30% higher than predicted.

1. "For our case study projects, the operational energy use was up to five times higher than estimates during design." —Carbon Trust 2011

Table 1. Summary of key studies quantifying performance gap

Study	Number and type of buildings	Measured performance gap	Summary/issues
Frankel & Turner 2008: How Accurate is Energy Modeling?	90 buildings that have achieved a LEED[a] rating	Around 8% Energy Use Intensity (EUI) difference for all of the buildings	The review included both buildings that achieved LEED ratings with normal expected uses, but also some high energy intensity buildings. The overall average measured EUI was close to predicted, though varied quite widely, and the high energy use buildings (laboratories, data centers and health care) consumed nearly two-and-a-half times the predicted energy.
Carbon Trust 2011: Closing the Gap	28 buildings from the UK DECC[b] Low Carbon Buildings Programme	Average gap was about 16% higher operational energy consumption than predicted performance	The average gap among the 28 low carbon demonstration buildings (covering many sectors, including retail, education, offices and mixed-use buildings) was 16%, though 75% of designs did not perform as well as expected, and in one building, operational energy use was five times the modeled estimate.
Green Building Council of Australia (GBCA) 2013: Achieving the Green Dream: Predicted vs Actual	70 Green Star office buildings with valid NABERS[c] Energy Certificates	About 25% gap (finding that around 75% of modeled energy savings are achieved in practice)	As analyzed and reported in ABCB 2018, the relationship between predicted and actual GHG emissions is weak, and there are several outlier buildings where actual emissions are significantly higher than predicted. When the outliers are eliminated, the analysis found around 75% of modeled energy savings were achieved in practice. The original GBCA study stated that 57% of Green Star certified office buildings achieved their modeled GHG performance.
Innovate UK Building Performance Evaluation Programme (2016)	48 projects with 56 "leading edge" non-domestic buildings	Average carbon emissions 3.8 times higher than predicted	Only one building performed similar to predictions, and the remaining buildings produced emissions between 1.8 and 10 times the predicted levels. However, predicted emissions only included "regulated loads," including heating, cooling, ventilation and lighting, and did not include other energy uses that would need to be used in any building.
van Dronkelaar et. al. Review of Non-Domestic Buildings Performance Gap (2016)	62 non-domestic buildings, as detailed in a variety of technical sources	Gap between predicted and measured energy use deviates by 34%	The buildings reviewed consisted mostly of offices, schools, and multipurpose buildings. Schools were identified to have a larger gap (37% more energy per one study, and higher in others), while offices were found to be more variable, but a smaller gap (22% higher than predicted, but greater standard deviation than schools).
CarbonBuzz (ongoing, started in 2012)[d]	About 60 buildings, mostly schools, general offices, and university campuses	Found that on average, buildings consume between 1.5 and 2.5 times their predicted energy use	CarbonBuzz is a joint initiative between the Royal Institute of British Architects, the Chartered Institute of Building Services Engineers (CIBSE) and other industry partners intended to provide a platform to benchmark and track project energy use from design to operation. Detailed case studies are published on the platform.
Sidewalk Labs Toronto Multi-Unit Residential Building Study (2019)	19 recently constructed multifamily buildings in Toronto	Buildings use 13% more energy than predicted by modeling	The study compared metered energy use intensity against calibrated energy models to understand performance gap. The performance gap for certain end uses was much higher than other (space heating having the biggest absolute difference).

a. LEED is "Leadership in Energy and Environmental Design," the building environmental rating scheme developed and administered by the US Green Building Council. More information at https://new.usgbc.org/leed.
b. UK Department of Energy and Climate Change (DECC).
c. The National Australian Built Environment Rating System (NABERS) has a variety of different types of building ratings, including separate landlord services vs. tenant energy ratings for office buildings. More information available at https://www.nabers.gov.au.
d. See www.carbonbuzz.org.

It appears that the performance gap is more significant in non-residential buildings, with smaller measured performance gaps in residences. This is likely due to the fact that in residences, a larger portion of the energy consumption is in the "regulated" loads (either through a building energy code, or product efficiency standards), while a more significant part of larger, non-residential buildings may be unregulated plug or process loads, or loads that can vary more widely depending on occupant density, types of occupants, or operational decisions.

Table 1 summarizes some of the key studies that have quantified the performance gap between predicted and actual performance using datasets of at least ten buildings.

Measured gap varies by end-use

There can be a quite wide range of predicted vs. measured gap for different end-uses when there is adequate sub-metering in place to allow for analysis of energy consumption by end-use. A recent performance gap study conducted on a large set of multifamily buildings in Toronto, Canada found quite a large difference in the gap for different end-uses, as shown below (Sidewalk Labs 2019). As shown in Figure 1, by far the biggest absolute gap is in the heating system, though a larger percentage gap is seen in both common area baseload and pump energy usage (though some of this gap can be attributed to differences in how the modeling treated the various end-uses).

Technical research

Since the late 1980s, when building energy researchers became more aware of energy savings opportunities and began using energy models, there have been engineering

Figure 1. Performance gap by end use: Metered vs. modeled energy usage

Demonstration of how the measured performance gap can vary quite significantly by end use
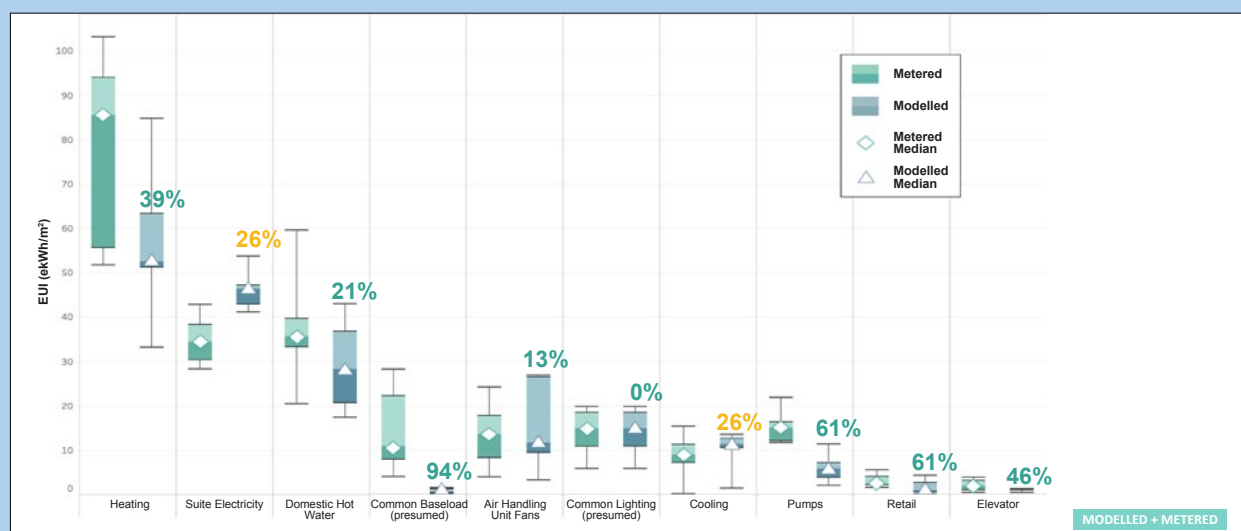
Source: Sidewalk Labs 2019

and construction life cycle case studies undertaken looking at how actual energy use compared with design predictions.

One of the earliest instances where the building energy performance gap was identified was in a technical research paper published in 1994 (though originally submitted as a Journal article in 1989), that found a "two-to-one discrepancy between measured and predicted performance of a 'low-energy' office building" (Norford et. al. 1994). The authors did an in-depth review of a low-energy demonstration office building constructed in the early 1980s, part of a pair of similar buildings built at the same time (the two buildings had different energy system design features, but both were heavily instrumented to understand relative performance). The predicted energy performance of the low-energy office building was 125 kWh/m^2, though in operation, the building was consuming 325 kWh/m^2.

Around the same time, in the UK, the PROBE (Post-Occupancy Review of Buildings and their Engineering) series of post-occupancy evaluations of recently-completed exemplar buildings was published in the Building Services Journal, and found very significant gaps between predicted and actual energy consumption (Bordass et. al. 2001 a & b).

Information about the gap between predicted and measured energy use was published by the New Buildings Institute in 2008 (Turner and Frankel 2008). That work looked at the predicted energy performance of a dataset of 121 LEED certified buildings, and found a wide range of measured energy intensity. For over half of the buildings this deviated by more than 25% from design projections, with 30% of buildings performing significantly better and 25% significantly worse. The study compared measured energy performance by level of LEED Certification.

In the past decade, there has been a tremendous increase in technical research on the performance gap, with a 2018 paper reviewing ten years of research identifying 227 papers in different scientific and technical journals as well as conference papers and reports (Zou et.al. 2018). This detailed literature review started searching on two key phrases: "building energy," and "performance gap," and found some 1,060 records that were eventually narrowed down to the 227 papers reviewed in detail.

Generally, the technical sources of discrepancies between as-built measured performance, and predicted or expected performance, can be broken into three baskets: the **design and simulation phase** (limitations, inaccuracies and assumptions in the models used to predict the energy performance); the **construction and commissioning phase** (caused by poor quality of workmanship and differences between assumed and actual materials, components and systems); and, the **operation phase** (poor-functioning of systems and/or no match between assumed and actual building usage).

The detailed review of ten years of research on this topic broke down the causes of the performance gap by the different building life cycle stages listed above[2], and then assigned different causes of the performance gap to various stakeholders. A summary of these causes is shown in Table 2.

2. Unfortunately, there is no real way to estimate the magnitude of any of these factors on the total performance gap—that will vary by individual building, as well as by jurisdiction.

Table 2. Causes of Building Energy Performance Gap

Life Cycle Stage	Stakeholders	Causes
SIMULATION STAGE	Designer	Inappropriate assumption
	Designer	Difficult to fully predict future
	Designer	Difficult to complete information collection
	Designer	Technology's actual performance is overestimated
	Designer	Energy system with poor robustness
	Designer	Lack of attention to end user
	Designer	Lack of attention to buildability and simplicity of construction
	Designer	Poor sequencing of the construction process
	Designer	Incorporation of inefficient or oversized system
	Designer	Inappropriate modelling and simulation
	Designer	Design details that are left unspecified
	Designer	Assumed operation left unspecified / no instructions provided for operation
	Designer	Poor communication
CONSTRUCTION AND COMMISSIONING STAGE	Owner	Change orders
	Owner	Unreasonable understanding of building energy saving
	Designer	Limited experience and knowledge
	Designer	Not engaged in construction and commissioning process either due to client/ contractor not engaging them or lack of interest, or both
	Contractor	Poor building quality
	Contractor	Poor workmanship
	Contractor	Cut corners
	Contractor	Improper construction technique
	Contractor	Fail to uncover hidden problems
	Contractor	Full performance testing is not allowed due to time and budget constraints
	Contractor	No training of energy manager/occupant
	Supplier	Poor quality of equipment or materials

Table 2 (continued)

Life Cycle Stage	Stakeholders	Causes
OPERATION STAGE	Occupant	Occupant behavior
	Occupant	Occupants' social and personal characteristics
	Occupant	Interaction and influence among occupants
	Occupant	Occupant's attitude
	Occupant	Occupants' experience
	Occupant	Occupants' comfort
	Occupant	Rebound effect
	Occupant	Do not know how to control energy system
	Energy manager	Limited control capability, or controls do not work as predicted
	Energy manager	Lack of fine-tuning during the first few years of operation stage
	Energy manager	No training of occupants
	Energy manager	Lack of standardization and continuity of monitoring, analysis, and control

Adapted from Zou et. al. 2018

As examples of the types of poor workmanship and improper construction techniques that can lead to much higher consumption than predicted, the photos shown below in Figure 2 document some flaws in construction when compared with what had been specified in design, as can be demonstrated through infrared thermography in lightweight wood frame construction details.

Initial work examining the measured thermal performance of building envelopes has been conducted as part of the International Energy Agency Energy in Buildings and Communities (IEA EBC) Technical Cooperation Annex 58[3] (Reliable Building Energy Performance Characterization Based on Full Scale Dynamic Measurements), and more work is being done to review other sources of the performance gap (building fabric, systems and users) in the newer Annex 71 (Building Energy Performance Assessment Based on Optimized In-Situ Measurements)[4], involving many of the same participants as Annex 58.

Policy and programmatic research

The issue of a performance gap between potential, or expected energy performance and achieved is not unique to building performance, there are a range of "gaps"

3. See https://bwk.kuleuven.be/bwf/projects/annex58/
4. See https://bwk.kuleuven.be/bwf/projects/annex71/summary.htm

where opportunities can be lost. The International Energy Agency (IEA) in 2007 published a report entitled Mind the Gap, highlighting how a significant proportion of the energy efficiency improvement potential is not realized—a result of a variety of barriers in the energy market (IEA 2007).

There has been little research on policy impacts and potential solutions to the building energy performance gap. One of the most recent and relevant policy impacts of the gap was noted in the Consultation Regulation Impact Statement reviewing proposed changes to the Commercial Building Energy Code provisions of the 2019 Australian National Construction Code. This regulatory review noted that:

Figure 2. Flaws in construction techniques leading to higher than predicted energy consumption
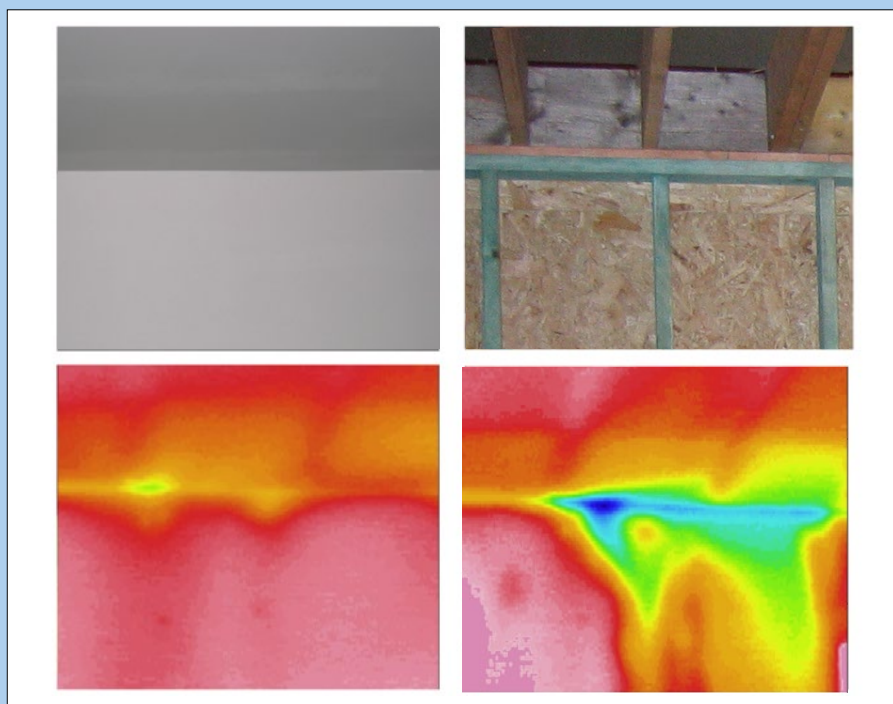

Note: The infrared photo on the right-hand side shows the lack of proper air sealing of the joint above the wood frame wall, allowing excessive infiltration of un-conditioned outdoor air into the space, and highlighted through use of a blower door infiltration rate test. The photos on the left are the same assembly after being completely insulated, yet still with more air infiltration than many new energy codes would allow.

Photos courtesy of Staf Roels, KU Leuven, Belgium

"…the available (albeit limited) evidence suggests that the relationship between simulated and actual energy consumption is relatively weak and that as low as only around half of predicted energy savings may be realized in practice. The potential for engineering estimates to overstate the energy savings from improved energy efficiency is a modelling issue raised in the international literature." (ABCB 2018).

The document goes on to report benefit estimates under three alternative scenarios, with expected savings from the code upgrades "de-rated" to reflect the expectation that only a portion of the predicted savings would be realized. The first (low) scenario assumed that 49% of modeled savings are achieved in practice, consistent with the relationship between modeled and actual GHG emissions as found through a detailed analysis of Australian building data conducted by the Green Building Council of Australia (GBCA 2013); the second (medium) scenario assumed that 75% of

Figure 3. The "prebound" effect

The "prebound" effect appears to be significant: in "energy wasting" (often older) buildings the actual energy consumption is generally lower than predicted, whilst predicted energy use in low-energy buildings (or deep energy retrofits) seems to be subject to a bias toward overestimation of the energy reduction/savings. This impact is demonstrated in the figure below.
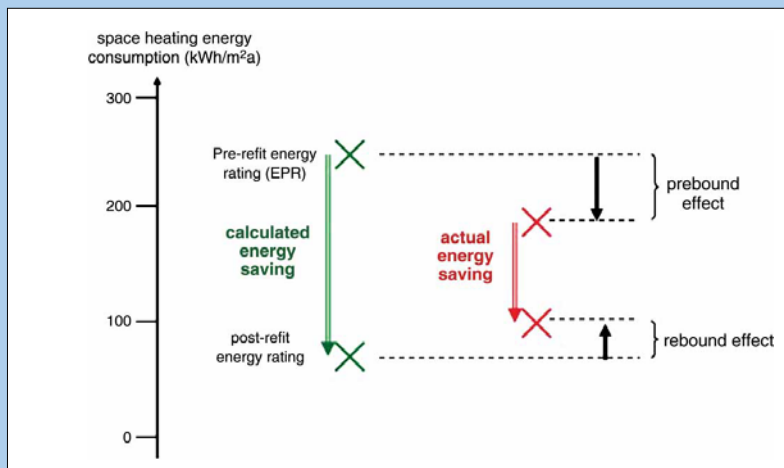
Source: Sunikka-Blank and Galvin 2012

modeled savings are achieved, consistent with the above dataset but removing the worst outliers; and, the third (high) scenario, where modeled savings are assumed to be achieved fully in practice.

The issue of the performance gap with deep energy retrofits has also been examined, with increasing evidence of expected savings from retrofit projects not being realized, and in extreme cases the deep retrofit project causing physical damage to the building it was supposed to improve (Topouzi et. al. 2019). Avoiding unintended consequences from code changes can be a key priority for some regulatory bodies, and can require time consuming research and broad industry consultation.

A detailed review of 3,400 German homes examined calculated energy performance ratings compared with their measured consumption, and found that on average occupants consume 30% less heating than the calculated rating (Sunikka-Blank and Galvin 2012). The most efficient buildings, though, tended to consume significantly more than predicted, which led the authors to suggest the presence of a "prebound effect," as opposed to the better known "rebound" effect (where it has been shown that improved comfort conditions from energy efficiency projects can lead to higher energy consumption).

In the "prebound" effect, it has been demonstrated that the measured energy consumption in lower efficiency rated buildings (those predicted to be poor performers) is often less than predicted due to occupants being used to reduced comfort quality and lack of proper conditioning. When better and more efficient systems are installed, the occupants choose higher levels of service than in the lower efficiency scenario. As a result, in an "energy wasting" building occupants consume, on average, 30% less heating energy than the calculated rating, and that percentage increases as the calculated rating predicts higher consumption. However, the opposite "rebound" effect tends to occur for predicted low-energy buildings, where occupants consume more energy than the predicted rating would suggest (Sunikka-Blank and Galvin 2012). Most prebound effect research to date has focused on residential energy performance; it is less clear whether the effect is also apparent in non-residential buildings.

The prebound research work showed that while lower efficiency, often older dwellings used less energy than predicted, newer, more efficient dwellings consumed

more than predicted. As you cannot save energy that is not being consumed, this explains why thermal retrofit programs in countries like Germany have not saved as much energy as expected.

A more comprehensive review looking at energy user/occupant aspects in the assessment of residential buildings in Germany has studied the calculated energy consumption of almost 3,000 single family and multifamily dwellings, and compared the expected performance with the measured energy consumption. The study found that there is reasonably close correlation between the calculated and measured energy performance for relatively low energy buildings (under approximately 150 kWh/m²a), though much more divergence as the calculated energy demand gets higher, with predicted higher energy consuming buildings actually consuming significantly less than expected (BBSR 2019). The results of this study are summarized in Figure 4.

This suggests that occupant behavior is potentially more significant in the predicted higher consumption, less efficient residential buildings, than occupant choices in the expected more efficient buildings.

Findings from a review of energy performance of more than 250,000 dwellings in the Netherlands found similar results. As shown in Figure 5, the actual heating consumption of the most efficient rated buildings (those with Energy Labels with an "A" or "B" rating) was higher than predicted (from predictions made in the recent generation of the building's Energy Performance Certificate (EPC)), while the actual consumption of buildings that were predicted to be worse energy performers was actually significantly lower than predicted.

Figure 4. Estimation of the uncertainties of calculated energy demand relative to measured energy consumption in German residential buildings

Figure shows how variations in the difference between calculated and measured energy performance varies, with a bigger gap, and lower than calculated energy consumption, as the calculated (predicted) demand gets higher. Abbreviations: SFH=Single Family Home; MFH=Multifamily Home
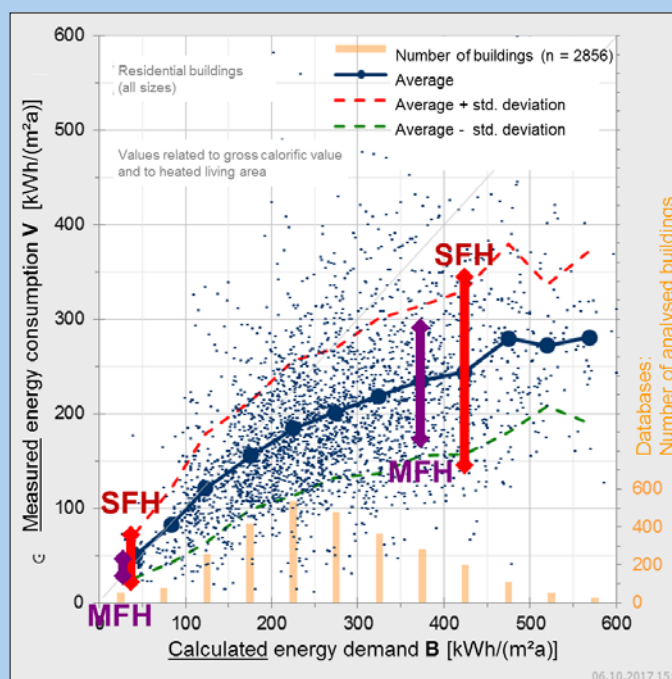
Source: BBSR 2019

Figure 5. Actual and theoretical average gas consumption for floor area in Dutch dwellings
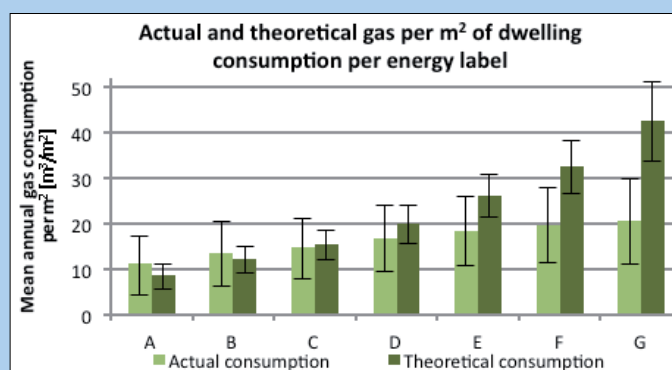
Source: Majcen et. al. 2013a

5 Issues and Discussion

In reviewing the various studies noted in the Literature Review as well as other larger datasets of residential buildings discussed later in this report, it appears that the performance gap seems to be more significant in non-residential buildings, with smaller measured performance gaps in residences. The last part of this is likely due to the fact that in residences, a larger portion of the energy consumption is in the "regulated" loads (either through a building energy code, or product efficiency standards), while a more significant part of larger, non-residential buildings consumption may be unregulated plug or process loads, or loads that can vary more widely depending on occupant density, types of occupant, or operational decisions.

In reviewing studies that examined measured vs. predicted savings in retrofits, most of the research has been on residential retrofits, concluding that the savings are generally less than predicted. Some of this may be due to a generally smaller performance gap found in larger datasets of residential buildings, but is also due to the fact that retrofits are more common in older housing, where models generally overpredict energy consumption. With the energy consumption of pre-retrofit buildings likely being lower than had been predicted by a model, reducing the actual energy consumption through a retrofit will probably have less savings impact as the predicted baseline energy use may have been higher than actual consumption.

It is well known that occupant behavior is a significant driver of building energy consumption, by some estimates as important as some of the technical design and construction choices such as building envelope and systems. The IEA EBC Annex 53 (Total Energy Use in Buildings: analysis and evaluation methods) identified six factors influencing total energy use in buildings, with occupant behavior, operation and maintenance, and indoor environmental conditions having similar impacts as building envelope and equipment choices and the climate where the building is located (IEA EBC 2013).

Modeling and regulated energy

As mentioned earlier, most building energy modeling is not intended to simulate actual occupancies and operational conditions, but is instead conducted for the purpose of code compliance and required Energy Performance Certificates (necessary for the rent/sale of the dwellings in certain jurisdictions), and uses standardized/generic conditions that are very different from the building's actual operation. This will often lead to a significant difference between the predicted consumption and reality. This issue is probably the biggest source of difference between predicted and actual performance.

In some cases, unregulated loads (as well as others that might be excluded from design regulations) can be significant, and lead to a substantial under-estimate of actual consumption, as shown in Figure 6.

Operational issues

Beyond discrepancies in the modeling of energy consumption, there are a number of technical "performance" issues that can cause significantly higher energy consumption.

A major issue in practice, particularly in larger buildings, is problems with the control of heating, ventilation, and air conditioning (HVAC) & lighting systems, particularly equipment scheduling (including stopping unnecessary off hours for space conditioning and lighting), temperature setpoints, and in some cases, even heating and cooling systems both operating at the same time in a space, fighting each other and causing substantial energy waste. Better commissioning of new buildings (or major retrofits) can sometimes identify these problems, or a process of existing building commissioning (known as retro-commissioning) can identify and solve these issues in existing building operation.
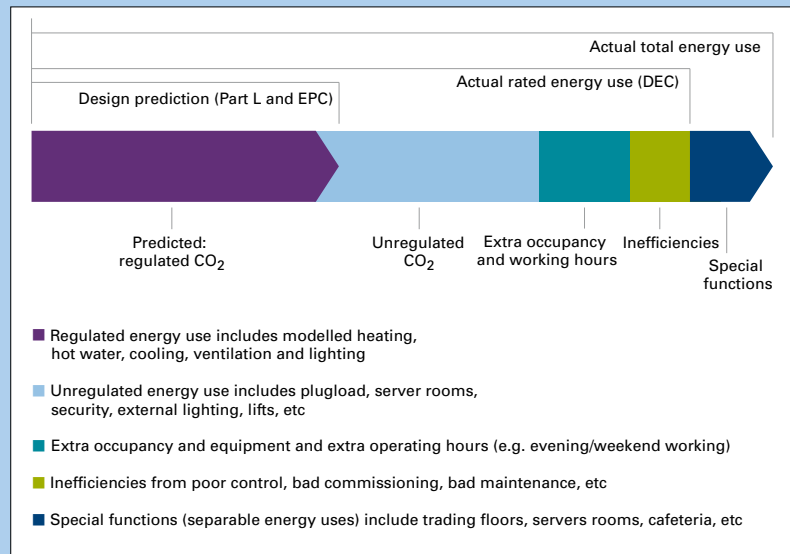
Construction quality

A major source of energy consumption causing heating and/or cooling energy use beyond what is predicted is from air infiltration (sometimes called permeation)[1] into the building. While there are well documented methods for reducing infiltration, and ways of testing infiltration levels, in a large number of cases there is substantial unintended air leakage of fresh, un-conditioned air into the conditioned space, and/or leakage of the conditioned air to the outside.

Another big technical challenge between design and construction is thermal bridging of higher conductivity/lower insulating materials in certain places in the building envelope.

Figure 6. Design predictions generally do not include all energy used in a building

Diagram shows the potential range of factors going beyond predicted carbon performance when using just regulated energy loads, with the unregulated emissions and differences from standardized prediction methods. Abbreviations: EPC= Energy Performance Certificate; DEC= Display Energy Certificate; Part L: UK Building Regulation setting standards for energy performance of buildings)

Source: Carbon Trust 2011

1. For the purpose of this report, we use the term "infiltration" to refer to the level of air permeability/air tightness of a building; the overall rate at which outside air leaks into the building (or conditioned indoor air leaks out).

Figure 7. Quality control problems with cavity wall insulation and air-sealing

Construction quality defects in cavity wall construction, leading to excessive air infiltration and thermal breaks conducting more heat than predicted

Photos courtesy of Staf Roels, KU Leuven, Belgium

Both infiltration and thermal bridging from flawed construction details can be a major source of energy consumption beyond what was predicted.[2] Some examples of in-situ monitoring of poor-quality construction details for cavity wall construction are shown in Figure 7, such as big air gaps between masonry layers and insulation, voids or bunching up of air/vapor barriers, and other poor-quality construction.

While there is often a significant gap between predicted/design air infiltration and what is found in post-construction measurement, it is not as clear how much of a direct correlation there is between the measured infiltration rate and measured building energy consumption. A detailed study was done of predicted air infiltration in a sample of UK buildings, drawn from the UK Government's National Building Performance Evaluation Program. The dataset comprised 50 Passivhaus[3] and 138 non-Passivhaus dwellings, covering a range of different built forms and construction systems (Gupta and Kotopouleas 2018). The presumption would be that dwellings meeting the Passivhaus standard should be lower air infiltration/permeability, both through design specifications as well as better construction period quality control.

In this review, the Passivhaus dwellings all had a significantly lower predicted infiltration rate, though about one third of those dwellings had higher measured infiltration, in some cases nearly three times the level predicted. The range of predicted to measured infiltration was much wider in the non-Passivhaus buildings, with some buildings showing four or more times the predicted amount. Despite the wide variability in measured infiltration in both Passivhaus and non-Passivhaus dwellings, the highest infiltration Passivhaus dwellings still showed about 60% lower infiltration rates when compared with the average infiltration of non-Passivhaus dwellings.

Despite the significant differences in infiltration rates between the Passivhaus and non-Passivhaus buildings in the dataset, the correlation between infiltration

2. While uncontrolled ventilation leads to significant energy waste, in some climate zones there is a need for adequate controlled ventilation to avoid the build-up of moisture, which can cause structural and health problems.

3. Passivhaus (or Passive House) is an international standard that sets very low consumption standards; for more information, see the IPEEC BEET report on Zero Energy Building Definitions and Policy Activity: http://bit.ly/2oxWAat

rates and measured space heating energy use did not correspond very closely to that infiltration rate variation, as shown in Figure 8.

These types of technical construction challenges can be addressed with better on-site construction quality control, including improved training of contracting trades and better, more comprehensive building commissioning. Some energy codes and technical Standards, including from the International Standards Organization (ISO), and a variety of different model code and standards bodies in various regions of the world are addressing all of the implementation phases of energy efficiency action throughout the life of a building project.

The IEA EBC Annex 71 (Building Energy Performance Assessment Based on In-situ Measurements) is addressing this by developing characterization and quality assurance methodologies that can be embedded in a framework to assess the actual building energy performance. They also plan to develop procedures to disaggregate the building energy performance issues to their three main sources: building envelope, systems, and users.[4]

Figure 8. Relationship between measured space heating consumption and measured air infiltration

Figure shows the lack of direct correlation between measure air infiltration/permeability and measured space heating consumption, demonstrating the impacts of occupant behavior and other construction quality control on space heating performance.
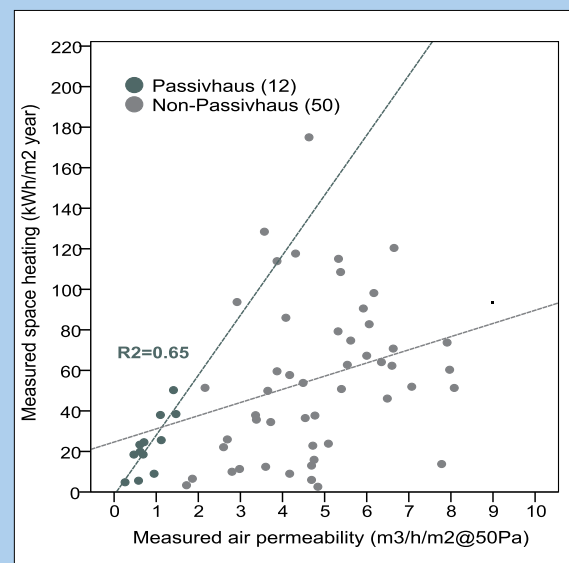
Source: Gupta and Kotopouleas 2018

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4. See Annex 71 website: https://bwk.kuleuven.be/bwf/projects/annex71/

6 Key Lessons Learned

There are two major opportunities to address the performance gap: (1) more accurate predictions of expected performance, and (2) better management of the quality control process throughout the design, construction and operation processes to make sure that the design intent for greater efficiency is not lost at some point during the building's life-cycle.

Lessons regarding modeling and performance prediction

As noted earlier, in most cases energy models are not developed to accurately predict in-use building energy performance, but more for documentation of code compliance under standardized reference conditions.

Different occupancy and operating conditions from what might be assumed as part of the standardized reference conditions can have a dramatic impact on total energy consumption.

As discussed earlier, a major source of the discrepancy is due to the use of standardized conditions (often called a "reference building") that may not be representative of how the building will actually be operated. Even if the physical characteristics of a building are carefully captured in a model, differences in occupancy patterns from the standardized conditions, or new equipment (either plug loads or different equipment from what was expected early in design when models are often developed), can result in large differences between expected and actual performance.

Predicted outcome is highly influenced by operational variables:

- For how many hours is the building really being used?

- What are the temperature setpoints?

- How much equipment is turned off at night?

as well as other factors. There are other more nuanced operational issues that are very difficult for a modeler to predict, like whether individual thermostats are fighting each other because their zones overlap, or the presence of economizers which do not operate as intended.

Most building models tend to be optimistic about building operational characteristics and perfect system operation, since compliance models generally assume the best operation and control characteristics while that is often not the case in actual, in-situ, operation. The inclusion of more realistic operational variables into the modeling process could improve initial assumptions about building operation,

making predictions more accurate. As a starting point, design professionals should model a range of typical operational parameters (like a range of operating hours) to define a potential range of performance outcomes, just like we model a range of design parameters to determine how much different insulation levels affect predicted energy use. This would go a long way towards clarifying expectations in the market about what models are actually predicting.

We would not expect a model of a building with heat recovery to accurately predict the performance of a building without this feature. So why should we expect a model of a building that assumes a ten-hour occupancy window to accurately predict the performance of a building that is occupied fourteen hours a day? We model the range of impacts for a series of design characteristics (modeling different efficiency strategies for example) but almost no one models the range of impacts of potential variation in operating characteristics, even though this is well within the capability of most modeling tools. More realistic standardized operating conditions are needed to make energy models more realistic when compared with actual operating energy performance.

Sensitivity analysis work undertaken by the New Buildings Institute showed the relative impact of certain building operations and occupancy variables (almost never regulated through typical energy codes), when compared with the impact of building envelope, space conditioning and lighting systems, which are usually the focus of building regulations (NBI 2011). Figure 9 shows the sensitivity of overall energy consumption to different system and equipment design choices, as well as the predicted impacts from operations, occupancy, and other drivers typically outside the scope of code coverage for an office building in Seattle.

Opportunities also exist for a better integration of energy models with building operations diagnostics; this will address some key aspects of incorporating operational variables into model predictions (calibrated modeling).

An important step toward better energy performance predictions is greater use of advanced modeling and simulation, not just using a "prototype" building with standardized/ generalized operational characteristics (number of occupants, operating hours, temperature setpoints), but also modeling the expected actual occupancy and operating conditions to better predict actual operational energy use. While many performance codes have been developed with standardized conditions to minimize "gaming" of targets, the reality is that what on the surface seem like very similar buildings (e.g., a range of different office buildings) are actually occupied quite differently, and will have different operating energy performance.

This can allow for an "energy performance in operation" energy target (expressed as energy use intensity, or normalized in some sort of rating) to be established, and included in contractual requirements and energy code submission materials. When this is done at the design process stage and well documented, then the expected performance can be validated against actual performance and it will be easier to understand how any gaps may have arisen.

Figure 9. Energy use sensitivity of different components regulated or unregulated by typical energy codes, sample Seattle office building

Figure shows relative impacts of typical code regulations, and varying the efficiency of different technologies, operations, ad occupant behavior, on total energy consumption.
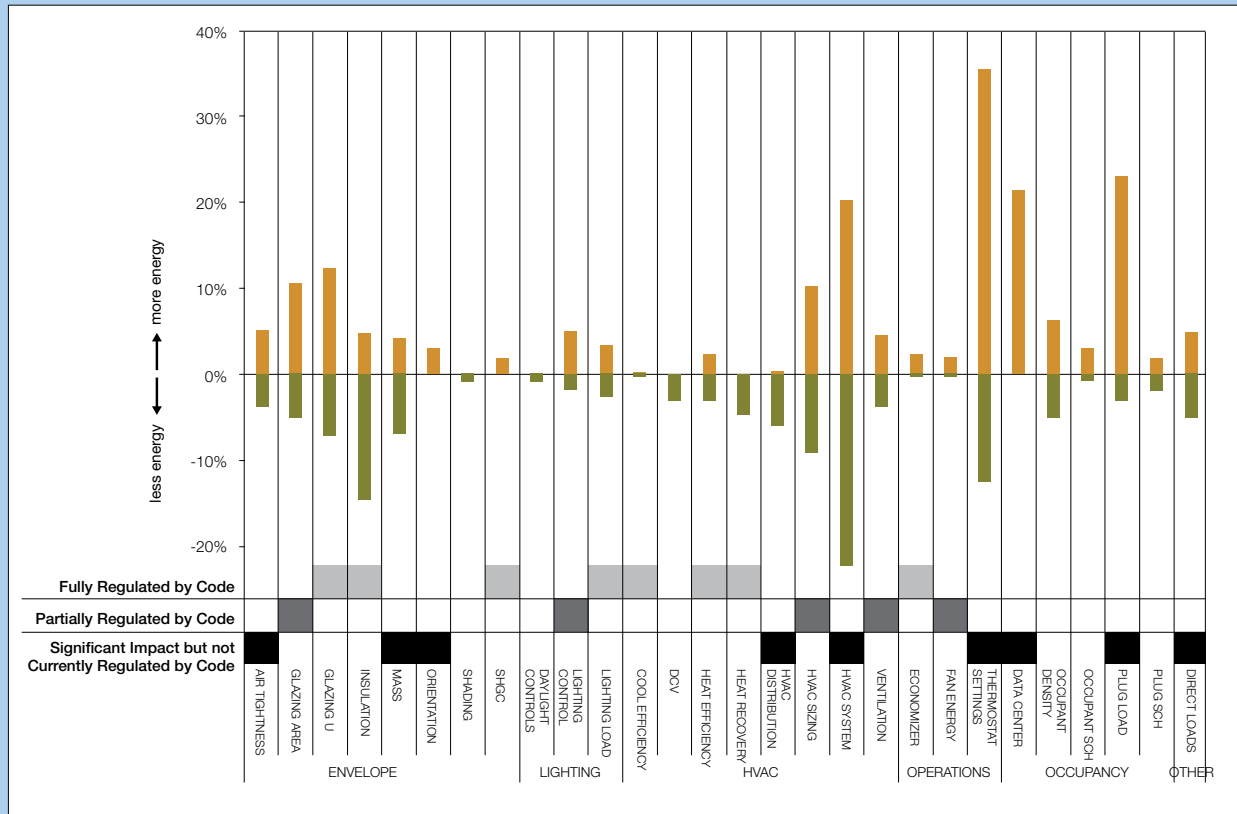
Source: NBI 2011

Quality control lessons throughout the building life-cycle

It is also necessary to ensure that a validation plan is established at the design stage and then followed through during construction, commissioning and early operation.

As part of research to identify strategies for minimizing the performance gap between design intent and reality, a research team developed some high-level summary strategies to overcome identified causes of performance gaps, as shown in Table 3 (Zou et. al. 2019a).

Table 3. Strategies to overcome identified causes of performance gaps

INACCURATE ENERGY MODELS	Inaccurate design parameters	Access to detailed information about building; Better metering, sub-metering and smart-metering to be validated against actual operation; Information based on in-practice testing.
	Failure to account for uncertainties	Accepting and accounting for risk of failures; Price forecasts.
POOR NORMS	Poor communication due to lack of guidelines for communication and badly setup project	Communication with other stakeholders; Engaging with the maintenance teams; Comprehensive design detailing; Having an engaged building manager or facilities manager; Protocols or guidelines for better communication; Providing alerts in reports.
	Lack of accountability/ irresponsible short-sighted behavior	Holding contractors accountable to an end outcome; Longer warranty periods; More strict targets in the building code for air tightness. Certified auditor accreditation; Developing better evaluation criteria to determine who gets jobs; Well-developed and ongoing relationship with the client.
HUMAN OVERSIGHT	Inefficient and over-complicated design	Educating designers in terms of passive design with simpler control systems; Integration of environmental design and sustainability within architectural coursework in universities and as part of professional registration.
	Lack of knowledge and experience	Better training to operation team; Educating procurement managers; Educating the construction industry; Hiring trained professionals; Independent commissioning agents; Having an advisor to guide end users; Automated equipment performance alarm systems; Automation to mitigate human error; Improved systems (QR codes).
	Poor performance due to lack of post-testing	Post-occupancy testing and monitoring.
	Lack of feedback and experiential learning	Ongoing feedback loop after installation; Database development for future—e.g. measuring air changes per hour and creating database of measured values; Building tuning period; Proper commissioning; Revising commissioning regularly.
	Lack of feedback and experiential learning	Ongoing feedback loop after installation; Database development for future—e.g. measuring air changes per hour and creating database of measured values; Building tuning period; Proper commissioning; Revising commissioning regularly.

Adapted from Zou et.al. 2019a

7

Potential Policy Opportunities to Bridge the Gap

With the two major opportunities for policies to address the performance gap being better predictions of expected performance, and more careful quality control throughout the design, construction and operation processes, two key potential policy options appear to have the best chance to address and rectify this gap. They are: more transparency of measured/operational energy performance, and outcome-based regulations. Both are being tested in various markets and deserve more assessment.

More transparency of measured/operational energy performance

First, and perhaps most importantly, is to develop policies that drive the transparency of the actual, measured performance of buildings, not just predicted performance based on standardized, hypothetical conditions. This is the only way to understand if a building is performing up to the expected/predicted energy performance. A large number of United States (US) cities have developed mandatory "benchmarking and transparency" policies, where the measured energy performance is submitted annually by building owners, and then publicly disclosed by the city government (IMT 2018).

In Australia, the NABERS rating system has evolved since 1999, and includes a base building rating for office buildings. With this base building rating system, designers now can embrace a "design for performance" culture. This allows for a "Commitment Agreement" for some building types, where developers and their teams sign up to an in-use performance target that can be monitored post-occupancy (Cohen et. al. 2017). In addition, the Australian Commercial Building Disclosure Program requires energy efficiency information, including the NABERS Energy Rating, to be provided in most cases when commercial office space of 1,000 square meters or more is offered for sale or lease.

In European Union countries energy performance is disclosed, however in general the mandated Energy Performance Certificates (EPCs) are based on predicted performance rather than measured performance, though the displayed EPCs required in European public buildings often include an operational energy rating.[1] As part of the studies leading to the most recent amendments to the European Energy Performance of Buildings Directive, a European Commission staff working document found that:

1. Much more information on the differences between "Operational" and "Asset" ratings was covered in Building Energy Rating Schemes: Assessing Issues and Impacts (IPEEC 2014).

"…different stakeholder groups require information that makes sense to them and can support informed decisions and the actual energy consumption appears to be information necessary to establish more strongly the business case of energy renovation, especially in a context where gaps are reported between the estimated savings at design stage and actual savings after renovation. …

"In some countries EPCs are perceived positively, and used as an information tool to inform buy/rent decision making. A common point mentioned by several stakeholders is the fact that the certificate presents estimated energy consumption (asset rating) which frequently is different from the actual energy use (operational rating). This is caused by the fact that for the estimated energy use a typical consumption profile is used, which makes the result behavior independent. However, the discrepancies are also caused by lack of quality of the national energy performance calculation methodologies in some cases." (EC 2016).

Thus, there are quite a few jurisdictions where experiences with building energy performance ratings could be analyzed to determine if such an approach results in a smaller gap and if so which performance rating program characteristics appear most effective.

Outcome codes

Another way to drive better actual performance is through use of "Outcome Codes," where a specified energy performance must be demonstrated when the building is in operation. Until recently these types of codes and regulations were more conceptual, but regulations are now beginning to be implemented that establish energy (or carbon) budgets for different building types based on measured performance, with penalties assessed when those budgets are exceeded.

From a technical perspective, one of the more advanced outcome types of codes is the Chinese National Standard for Civil Building Energy Consumption, which establishes an "energy consumption quota" for different types of buildings in different Chinese climate zones. This "outcome style" code is in relatively early implementation and is being used in conjunction with different market mechanisms in the trial jurisdictions where it has been introduced (Liu et. al. 2019).

Outcome codes are also being tested in Sweden, where regulations have been established using specific purchased energy limits, though practitioners there have experienced many challenges in the procurement process because measured performance after building occupancy often deviates significantly from the design calculations. Other potential indicators are being studied in Sweden to address these concerns (Allard et.al. 2017).

Very recently, New York City established a set of carbon intensity limits for all large buildings in the city, based on measured energy consumption and resulting emissions, such that buildings which exceed the established limits will face significant financial penalties when the "limits" take effect beginning in 2024 (Urban Green 2019). This performance/outcome code, while just recently passed and not yet into

its implementation phase, will penalize buildings based on measured performance, not on design predictions.

A number of jurisdictions have been developing or considering "Design for Performance" initiatives, somewhat based on the Australian NABERS "Commitment Agreement," where developers and their teams sign up to an in-use performance target. The process is underpinned by advanced simulation, strategic sub-metering, and post occupancy fine-tuning to help eliminate wasteful deviations from the predicted performance.

The Design for Performance process is being introduced for new UK offices, where there has been concern for many years about the gap between predicted energy performance as calculated through the EPCs and the measured energy use. A pilot is now underway with several major UK developers to test this process and understand its impacts (Cohen et. al. 2019).

Outcome style codes are often established along with other minimum design efficiency standards that prescribe performance requirements for different building systems and equipment, to minimize the low performance of buildings.

One challenge with outcome codes is that energy code enforcement currently ends at building completion, though in the case of monitoring ongoing energy performance outcomes, enforcement and administration of the regulations will extend to the operational life of the building. New mechanisms and associated funding will be required in order to facilitate full life-cycle building code enforcement.

Conclusions and Areas for Further Study

8

The performance gap between predicted and actual building energy consumption and performance can be significant. A large volume of technical research has documented the gap and identified the causes and some potential solutions. A major issue is the disconnect between the tools that are being used to assess the gap and their original intent. Use of energy model results based on hypothetical standardized operating conditions for predicting actual energy consumption is exacerbating some of the gap findings, and more targeted modeling approaches described in this report may help to lessen the performance gap.

There is no consistent estimate of the magnitude of the gap found across all of the sources reviewed. While some work found that buildings consume between 150 to 250% of their predicted energy use, and several other sources based on a relatively small sample size show even more significant magnitude differences, in larger datasets the magnitude of the performance gap seems to be smaller, with measured energy consumption often in the range of only 10 to 30% higher than predicted.

There is a need for more research and analysis to compile the various datasets available internationally to better document the size of the gap, and why in certain cases it is much bigger than others. It appears that some of the findings which demonstrate a more significant magnitude in the performance gap may be due to the bias of smaller samples, or just looking at buildings with predicted very low energy use.

While a key driver of the performance gap is unintended use of code compliance models to predict actual performance, it is not clear how significant that issue is relative to construction and commissioning stage, or operational stage, issues. This is an area that deserves further research.

There is also more that needs to be understood about the "prebound" effect. Specifically, analysis is needed to determine whether higher than predicted energy use in expected low energy consuming buildings, and lower than predicted energy use in what are considered less efficient buildings holds true across larger analyses. It is important to note that the performance gap is not only a technical problem but also has behavioral components. Closing it requires understanding building users. For example, low-income households tend to live in energy inefficient houses so the prebound effect can hide fuel poverty where households simply cannot afford to heat up their homes to an adequate level of comfort.

Two potential policy areas appear to hold strong promise for minimizing the performance gap: greater transparency of operational/measured energy performance

(and not just relying on predicted performance through modeling), and out-come-based policies that essentially regulate the operational performance of the building. These policy solutions seem to be most appropriate to reduce the gap, with some very interesting initiatives now underway and being tested in several jurisdictions. It is early in their implementation, so more review will be needed a few years from now when the results of the policies can be better understood, and it is likely that additional policies will evolve in the near future.

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