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Published in:
Journal of Building Performance Simulation

DOI (link to publication from Publisher):
10.1080/19401493.2024.2332245

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

Taylor & Francis
Taylor & Francis Group

Journal of Building Performance Simulation

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tbps20

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To cite this article: Ardeshir Mahdavi & Christiane Berger (15 Apr 2024): Ten questions regarding buildings, occupants and the energy performance gap, Journal of Building Performance Simulation, DOI: 10.1080/19401493.2024.2332245

To link to this article: https://doi.org/10.1080/19401493.2024.2332245

Published online: 15 Apr 2024.

JOURNAL OF BUILDING PERFORMANCE SIMULATION
https://doi.org/10.1080/19401493.2024.2332245

Ten questions regarding buildings, occupants and the energy performance gap

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ABSTRACT
Buildings' energy use in the operation phase can significantly deviate from prior estimations obtained from calculation or simulation. This divergence is commonly labelled as the energy performance gap and multiple factors have been suggested to be responsible for it, including, prominently, occupants' behaviour. However, the literature on the contributors to and magnitude of the energy performance gap is rather inconclusive. The purported role of occupants as the main culprit of the energy performance gap is likewise insufficiently substantiated. This paper poses and treats 10 questions to address these issues and contribute to a more rigorous discussion of the building-related energy performance gap.

ARTICLE HISTORY
Received 28 November 2023
Accepted 1 March 2024

KEYWORDS
Buildings; energy; performance; gap; occupants

1. Introduction

Prior to new constructions or thermal retrofit measures, buildings' expected energy use is commonly estimated using various calculation and simulation methods. However, the subsequent energy use of buildings in the operation phase can considerably deviate from such predictions. This divergence is labelled as energy performance gap and multiple factors have been suggested to be responsible for it, including, prominently, occupants' behaviour (Gram-Hanssen and Georg 2018; Shove 1998). The study of the technical literature in this area, however, does not provide clear and conclusive evidence with regard to the contributors to and magnitude of the energy performance gap. Specifically, the purported significant role of occupants in causing the energy performance gap cannot be suggested to have been sufficiently substantiated (Mahdavi et al. 2021; Mahdavi and Berger 2019). In this paper, we pose and treat 10 questions to address these issues at multiple levels and thus contribute to the building-related energy performance gap discourse.

An overview of these questions, organized in terms of five clusters, is provided in Figure 1. The first three questions pertain to the energy performance gap (EPG) terminology. The fourth and fifth questions address the implications of calculation purpose for the EPG, and the reasons for the significance of the EPG discourse. Questions 6 to 8 cover the factors responsible for the EPG, the empirical evidence regarding the scope of the EPG, and the quality of the related studies. The ninth question focuses on the necessary condition for a proper causal study of the role of occupants in the EPG. The tenth and final question is concerned with the implications of the EPG discourse for the design of buildings and the modelling of their performance.

2. What is the EPG?

The term energy performance gap (EPG) may not have a unique, exact and universally agreed-upon definition (Gram-Hanssen and Georg 2018; Shove 1998). It is therefore important that we state here at the outset what we mean by this term. Many manufactured artefacts require energy for their operation, including machines, vehicles and buildings. Various methods can be applied to estimate the future energy use of such artefacts. However, the actual energy use of these artefacts may deviate from prior estimations. Energy performance gap refers to this deviation.

3. What is the building-related EPG?

The operation of buildings requires energy use. Specifically, energy is needed for heating, cooling, ventilation, lighting and equipment. Buildings' expected energy use can be estimated prior to construction via different calculation and simulation methods and tools. Subsequent to commissioning and occupancy, buildings' actual energy

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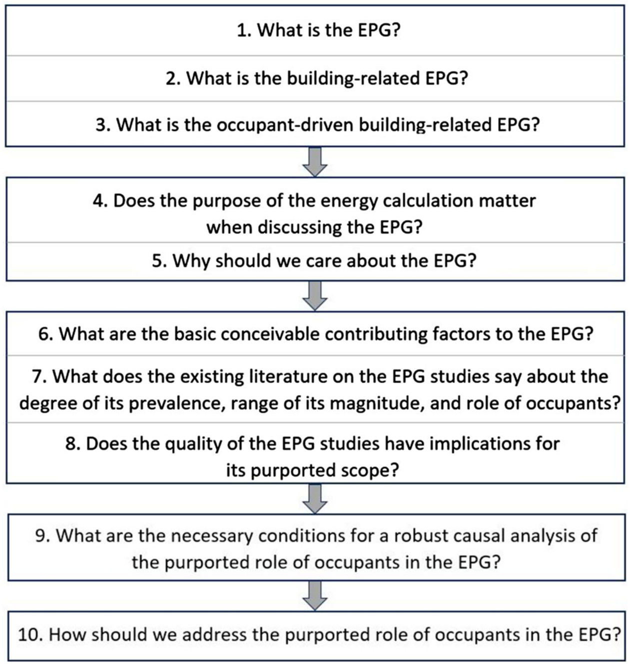

Figure 1. Overview of the 10 questions regarding buildings, occupants and the energy performance gap.

use can be metered over specified periods of time. Building-related energy performance gap refers to the difference between prior estimations (e.g. simulation results in the design phase) and actual energy use during the operation phase of the building (Geraldi and Ghisi 2020; Sunikka-Blank and Galvin 2012). Note that in the rest of this paper, the term EPG refers specifically to the building-related energy performance gap.

4. What is the occupant-driven building-related EPG?

Multiple factors may contribute to the magnitude of EPG (see Question 6 for a detailed treatment). It has been suggested that occupants' patterns of presence and particularly their behaviour are amongst such factors. Occupants' behaviour in this context denotes their operation of building components and systems such as windows, lights, as well as heating and cooling equipment. We refer to this purported role of occupants in EPG as the occupant-driven building-related EPG. It has been suggested at times, that occupants' behaviour must be viewed as the main culpable factor behind EPG, arguing that improved quality of building envelope and the more efficient environmental control systems must have diminished the scope of their influence on the EPG (Hong et al. 2016; Jia, Srinivasan, and Raheem 2017; Yan et al. 2015; Yoshino, Hong, and Nord 2017). This of course cannot be confirmed without examination of available empirical evidence (see Questions 7 and 8).

5. Does the purpose of the energy calculation matter when discussing the EPG?

Strictly speaking, the EPG discourse would be genuinely meaningful only if simulation of buildings' energy performance is explicitly assumed to constitute prediction of future energy use. But the calculation of a building's energy use must not be necessarily intended as prediction. Calculations may be performed for very different purposes (Gaetani et al. 2023). For instances, they may be meant to provide the basis for certification, benchmarking and compliance check with applicable standard. However, even if not warranted in principle, such calculations are sometimes treated as if they would yield predictions of actual future energy use. To be conceptually consistent, it would be preferable to speak of the EPG only when energy use calculations have the explicit intention of providing prediction of a building's future energy use. For instance, simulation-based estimations of a building's future energy demand may be applied toward sizing of HVAC (Heating, Ventilating and Air-Conditioning) and renewable energy systems and estimation of needed monetary resources for energy purchasing. Professionals using such calculations typically treat those with considerable caution and account for uncertainties involved, as they are aware that, due to multiple reasons, it is doubtful that energy calculations could provide exact predictions of future energy use. One obvious reason for this scepticism lies in the stochastic characteristics of both weather conditions and occupants' behavioural patterns. Consequently, the validity of computational process and its results can be only judged with respect to the model input assumptions. In other words, the initial model input assumptions would have to be revised (aka, normalized) after the fact so as to reflect the reality of the constructed (or retrofitted) building and its actual internal and external boundary conditions (Berggren and Wall 2017).

To make this point clearer, consider a comparison with the automobile industry. Fuel efficiency of a specific model of an automobile, as declared by manufacturer (e.g. in terms of kilometres per litre fuel), is derived under very specific test conditions pertaining to, for instance, road properties and the driving speed. Actual fuel consumption depends of course on how often, how long, on which surface, and by whom a car the automobile is driven. Similarly, calculations of buildings' energy demand of the type undertaken for energy certificates involve specific (i.e. standardized) boundary conditions and should not be viewed as formal predictions of a building's future energy use. This is true in principle also of detailed performance simulations of buildings: even if it can be assumed that the as-designed physical elements of a building's fabric and system will be implemented as specified, reliable predictions of the boundary conditions can be made only for a relatively short time horizon.

Notwithstanding these reservations, it may be possible to avoid the confusion of benchmarking with prediction and still find it legitimate and useful to compare estimated and actual energy use magnitudes, independent of the original purpose of the underlying calculations. To this end, however, it would be of paramount importance to carefully address the aforementioned challenges: We can expect the calculated and actual energy use to match only if we have: (i) confidence in the reliability of the applied calculation method and tools, (ii) accounted for the differences between as-designed and as-implemented building construction and systems and (iii) considered the differences between assumed boundary conditions (weather conditions, occupancy-related events) at the initial modelling stage and the actually prevailing conditions in the building's operation phase. These issues can be presumably addressed, at least to a certain degree, via a proper normalization procedure (see Question 8 for more details).

6. Why should we care about the EPG?

Given the preceding discussion, it appears evident that the exact prediction of the performance of a complex system such as a building may be beyond reach. Consequently, some degree of the EPG is to be expected as a matter of course. Nonetheless, very large deviations of the actual performance from the expected one (even if not explicitly intended as prediction) provide a reasonable justification for a closer scrutiny of the matter. As with other domains, there is also in the building sector an interest in developing reliable representations of entities and processes involved. As such, the search for and the identification of the main causes of the EPG, particularly if accompanied with systematic normalization steps, may provide insights that can improve, among other things, the fidelity of the computational tools and the integrity of the modelling processes. Multiple benefits could be expected if such an improvement could be achieved. For one thing, smaller EPG magnitudes would avoid generating false or misleading expectations on the side of the relevant stakeholders involved. Moreover, systematic errors involved in large EPG values may also contribute to inadequate configuration and sizing of buildings' service systems, as these rely on prior load calculations. Moreover, the lessons learned in the process of identification of common EPG causes can not only improve the quality of the energy calculation methods and procedures but also inform approaches to the design of relevant building features (specially control elements and systems) and their user interfaces (Berger et al. 2023). Last but not least, investigating the EPG can provide incentives to enrich the knowledge base and data repositories regarding occupants' behaviour (Dong et al. 2022; Huebner and Mahdavi 2019) and also encourage the inclusion of high-resolution metering infrastructures in the course of both new building designs and building retrofit projects.

7. What are the basic conceivable contributing factors to the EPG?

We shall later examine the empirical evidence for the existence and extent of the EPG (see Questions 7 and 8) as well as the kind of causal analysis that could provide evidence for the relative share of various factors (including occupants' behaviour) in the EPG magnitude (see Question 9). However, it may be beneficial to the clarity of our discussion, if we briefly reflect on the logical option space of potential contributors to the EPG. Such a reflection reveals a number of relevant contributors, as summarized in the following list:

- The differences between as-designed versus as-realized construction features, including building envelope, fabric and components (Gupta, Kapsali, and Howard 2018; Lehmann, Khoury, and Patel 2017).
- The deviations of the actually installed and operated building systems (for heating, cooling, ventilation, lighting, etc.) from their respective specifications in the design phase (Calì et al. 2016).
- The differences between actual weather conditions during the operation phase of the building and the corresponding assumptions in the design phase (e.g. standard weather files for the pertinent location) (Cuerda et al. 2019).
- The differences between the building's actual contextual settings (e.g. configuration of adjacent buildings and green spaces, the prevailing air flow patterns) and the assumptions in the design phase (Yousefi, Gholipour, and Yan 2017).
- The differences between occupants' actual pattern of presence and behaviour in buildings and the modelling assumptions in the design phase (e.g. occupancy schedules, preferred indoor-environmental settings, disposition to and frequency of actions on control devices) (Gupta, Kapsali, and Howard 2018; Lehmann, Khoury, and Patel 2017; Gill et al. 2010).
- Limitations of the deployed calculation methods and tools in view of resolution, fidelity and adequacy for the purpose, validity, as well as inadequate use of such

tools (mistaken input data, improper simulation settings, etc.) (Cozza et al. 2019).
- Limitations of the coverage and resolution of the methods and devices used to monitor occupants' presence and behaviour in buildings, as well as potential errors in documenting and interpreting the collected behavioural data.
- Limitations of the coverage and resolution of the deployed energy metering infrastructure as well as potential errors in monitoring and documenting the magnitude of consumed energy (Cozza et al. 2019).

8. What does the existing literature on the EPG studies say about the degree of its prevalence, the range of its magnitude and the implied role of occupants?

Past research efforts have frequently reported on EPG in their studies. Especially, the role of building users as contributors to the EPG has attracted much attention recently. In this context, a recent literature review effort examined a number of scientific publications in view of the empirical evidence for the existence and extent of the EPG (Mahdavi et al. 2021). Specifically, 144 relevant publications were identified and reviewed in a multi-step selection and screening process. A subset of these studies reported actually quantified values of energy performance gap. These articles varied in terms of the range of the reported EPG magnitude. On average, the EPG magnitude was 55% (±90%) across all reviewed research studies. Figure 2 gives an overview of the EPG separately for residential and non-residential buildings. Thereby, it can be seen that the range of the EPG magnitude indicates both underestimation (positive numbers) and overestimation (negative numbers). However, cases of positive EPG are relatively speaking more frequent than negative EPG cases, suggesting a tendency to higher actual energy use as compared to predicted values. Studies concerning residential buildings show a median of +30% whereas those concerning non-residential buildings show a median of +14%.

The majority of the reviewed studies (70%) include occupant-driven causes for the EPG related to mechanical equipment, building envelope (e.g. operation of windows and blinds), internal heat gains, plug-loads and lighting (Al Amoodi and Azar 2018; Ali et al. 2020; Cuerda et al. 2019; Gill et al. 2010; Gupta, Kapsali, and Howard 2018; Lehmann, Khoury, and Patel 2017). With regard to mechanical systems, about one-third of the studies report that the actual indoor temperatures are higher compared to the assumptions. Other studies report that heating periods are shorter or longer compared to the assumptions made. About 35% of the reviewed studies state the

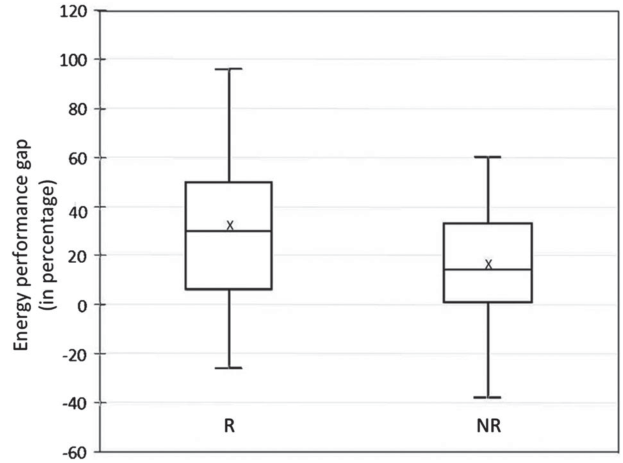

Figure 2. The EPG magnitudes (in %) in the reviewed publications for both residential ('R') and non-residential ('NR') buildings. Thereby, the data in this graph is based on 43 and 17 studies for residential ('R') and non-residential ('NR') categories respectively (adapted from Mahdavi et al. 2021).

frequency of window operation (and the related actual heating demand increase) as an occupant-driven cause of the EPG. Furthermore, the actual and assumed magnitude of plug-loads, lighting usage and internal heat load is reported in a number of studies (40%) as a contributor to the EPG (Azar and Menassa 2016; Carpino et al. 2020; Herrando et al. 2016; Menezes et al. 2012).

Although a number of reviewed studies indicate some form of occupant-related EPG, strong and conclusive evidence for the conclusiveness of the role of occupants in the EPG is not provided. In this context, it has to be noted that only 14% of the reviewed studies covered quantitative data on both occupant behaviour and building energy use.

9. Does the quality of the EPG studies have implications for its purported scope?

The discussion on the empirical evidence for the existence and extent of the EPG as outlined in Question 7 led to a further review effort that specifically focused on the data quality and strength of evidence reported in the EPG studies (Amin, Berger, and Mahdavi 2022). Thereby, 51 studies were reviewed and assessed to evaluate the quality of the EPG studies along three criteria, namely (i) data quality, (ii) normalization extent and (iii) used method to conclude the gap cause. The criterion 'data quality' referred to the resolution of data regarding both occupants and energy, monitoring period, data source, data collection method, number of measured parameters related to occupants. The results were subsumed in terms of three data quality categories, namely 'low', 'medium' and 'high'. For instance, annual energy use data at the building scale's level was categorized as 'low' in terms of data quality due to the low degree of resolution regarding the temporal and spatial dimensions. In contrast, detailed monitored data on occupants' presence as well as event-based data on occupants' interactions with windows and thermostats were categorized as 'high' in terms of data quality. Respective numerical values were assigned to the three categories concerning both energy and occupants' data quality, namely 0, 0.5 and 1. The normalization criterion concerned the variables that are adjusted for energy use. The third criterion referred to the method that was used to describe the EPG (i.e. direct versus indirect methods). To assess the three criteria in a systematic approach, a weighting scheme involving a ratio of 2:2:1 for the three criteria (data quality, normalization and method) was included.

The assessment results indicated that 98% of the reviewed studies reported the influence of occupants' behaviour as the main contributor to the EPG. However, the respective claims were not sufficiently substantiated, as only 6% of the reviewed studies included underlying empirical evidence that can be classified as 'high' quality. Furthermore, the available data quality, relating to both energy and occupants, varied among the reviewed studies. The majority of the reviewed efforts were classified as medium or low quality due to, for instance, low temporal data resolution or data collection issues. For instance, in most cases energy-related data is captured and processed in terms of large (monthly or annual) time intervals. Occupant-related data is commonly captured using sensors (38%) or questionnaires (37%). Moreover, it has to be noted that most studies did not describe the source for their assumptions regarding occupancy-related processes.

Figure 3 shows the EPG distributions obtained in the course of this review for the aforementioned three assessment quality categories of the reviewed studies. As it can be seen from this figure, the magnitude and variance of the EPG were smaller in case of high-quality studies, as compared to the studies with lower quality.

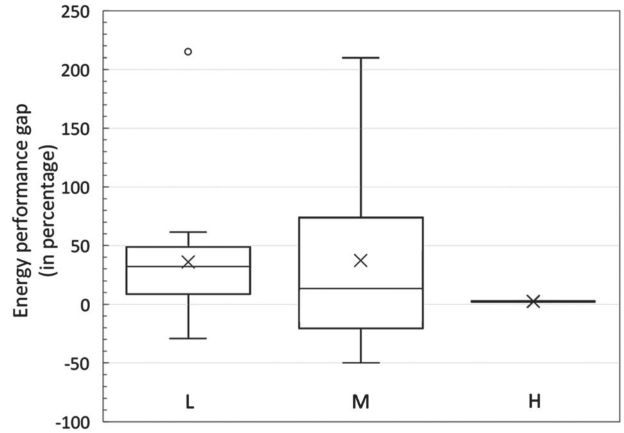

Figure 3. Evaluation result concerning data quality, separated in three levels: 'L' indicates low, 'M' indicates medium and 'H' indicates high in the reviewed studies. Thereby, the data in this graph is based on 22, 26 and 3 studies for the levels L, M and H respectively (adapted from Amin, Berger, and Mahdavi 2022).

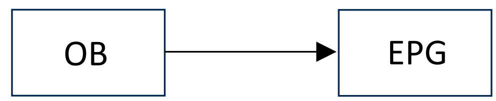

Figure 4. Depiction of occupant behaviour (OB) as the cause of the energy performance gap (EPG).

10. What are the necessary conditions for a robust causal analysis of the purported role of occupants in the EPG?

We have argued that the data and analysis in existing studies of the EPG have not provided a conclusive validation of the frequently purported significance of the role of occupants in the emergence of the EPG. But what strategy could actually lead to a conclusive verification (or falsification) of this matter? To approach this question open-mindedly, consider the hypothesis in Figure 4, which simply suggests that occupant behaviour (OB) is responsible for the energy performance gap (EPG).

Let us assume, for the time, that both OB and EPG could be properly and reliably operationalized. But the question still persists: How would we go about testing such a hypothesis? It has been frequently suggested that randomized controlled trials represent the gold standard when exploring suspected causal relationships. However, one needs only to briefly reflect on the matter of the purported causal role of OB in EPG to recognize the enormous challenges involved in any attempt to investigate this role in a generalizable manner via a randomized trial approach. Presumably, one would need two samples of buildings, representing different typologies, sizes and topologies, that would be located in different settings, surroundings and climatic regions. The experimental sample would have to accommodate occupants representing a variety of individuals and groups (e.g. families of different sizes) from all walks of life and different social and cultural backgrounds. The control sample of buildings would have to ideally be identical with those in the experimental group. But what could be the sample of occupants in the control group? There does not seem to be a way to answer this question in a coherent manner. Perhaps all buildings in the control group would have to be operated following a control regime that would supposedly represent a proper behavioural pattern. But does

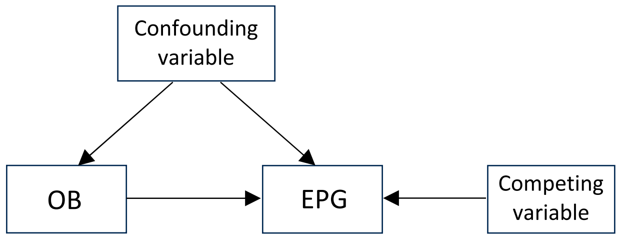

Figure 5. Illustrative depiction of the influences of competing and confounding variables relevant to the examination of the purported causal role of occupant behaviour (OB) with respect to the energy performance gap (EPG).

this imply that buildings in the control group would be operated in an automated mode? Be that as it may, the experimental and the control samples of buildings and the occupants of the former would have to be monitored over an appropriate period of time (perhaps a year) to generate and process the necessary data for hypothesis testing. It is probably not necessary to belabour this scenario any further, such an experimental plan is obviously neither realistic nor feasible. More troublingly, it is perhaps not even coherent.

Of course randomized tests are not the only option for the investigation of causal hypotheses. Assuming availability of past data, or the possibility of future data collection, there are also the options of retrospective and prospective studies. In fact, in many instances where, due to various reasons, it is not possible or feasible to conduct experimental studies, relevant observational (e.g. field) data may still be available. In such cases, it may be possible to explore causal relationship via retrospective studies and causal inference approaches (Nogueira et al. 2022; Pearl 2009). However, conducting a proper causal inference study of the occupant-driven EPG hypothesis (Figure 5) is arguably a non-trivial matter and must be carefully deliberated. To this end, a first step would be to discuss two levels of complexities that present themselves immediately. These pertain to the presence of (a) competing causal variables and (b) confounding variables. The competing variables denote factors, other than the purported cause (in this case, OB), that can be shown to also influence the effect (in this case, EPG). In our discussion of the Question 6 above, we listed some of those factors, such as the weather conditions. Confounding variables refer to factors that are assumed to be not only responsible for the effect (in this case, EPG), but can also influence the suspected cause (in this case, OB). To continue with the example of weather, we can understand that it influences the building-related thermal processes and hence the energy use, but it can also influence occupant behaviour. Figure 5 illustrates this circumstance graphically.

A proper causal inference study must thus, among other matters, take as many competing and confounding variables into account as possible and formally analyse them, for instance using a DAG formalism (Ahrens and Pigeot 2014; Arif and MacNeil 2022). Short of such an analysis, a causal claim cannot be convincingly established. It is not possible here to exhaustively demonstrate the structure and details of a detailed causal inference as applied to our causal hypothesis (Figure 4). Nonetheless, to illustrate the complexity involved, it may be useful to cover a number of key variables and their standing as competing and confounding (see Table 1).

- The prevailing weather conditions during a building's operation phase will almost certainly deviate, to a greater or lesser degree, from those assumed while estimating its energy demand. The resulting implications for the thermal processes occurring in and around buildings obviously contribute to the EPG, thus rendering weather as a competing variable. But weather conditions can also act as a confounding variable, given their potential impact on occupants' behaviour. For instance, people's operation of windows, blinds and lights upon arrival in a building depends on prior experience in the outside environment (Berger and Mahdavi 2023). Weather patterns (for instance, spells of warm and cold weather) can also influence people's expectations and their adaptive behaviour.
- Due to various circumstances and processes (including the so-called value engineering), the as-built realization of a building may differ from the design-stage documentation. This can contribute to the EPG, given the fact that the latter is the default source of information for the computation of thermal processes in building energy modelling. Even though less obvious, the as-designed versus as-built discrepancy can also play a role as a confounding variable. For instance, assumptions in the modelling stage regarding occupant behaviour may correspond to default building component properties (e.g. windows' visual transmission coefficient and their user interfaces). Occupants' disposition toward operating windows for daylight modulation and solar control may be influenced by properties of as-built components.
- As with the building fabric, deviations of the as-installed version of building systems (including their components and their operation logic) from the modelling-phase assumptions may be responsible for potentially considerable differences between the predicted and actual energy use. Moreover, different types of systems (e.g. radiant vs convective heating)

as well as the different aspects of the realized control logic (e.g. thermostat deadband or degree of provided override functionality in automated control scenarios) can bring about different behavioural responses, confirming their status as a confounding variable.

- Representations of a building's surrounding and micro-climate may be subject to different levels of simplifications, including exclusion of microclimatic circumstances (e.g. Urban Heat Islands). Such contextual representations may also turn out to be invalid, for instance due to interventions not anticipated or considered in the design and modelling stage. These include new buildings and other interventions adjacent to or in the vicinity of the building. This clearly establishes the status of such interventions as a competing variable for the EPG, given their obvious implications for physical (i.e. heat transfer) processes. For instance, the size, height and form of adjacent buildings influence the level of solar occlusion and the air flow patterns. The latter attributes of a building's surroundings may influence occupants' behaviour, for instance in terms of the frequency and pattern of shading and ventilation behaviour. Hence, they could be suggested to constitute a confounding variable.
- It should be obvious that limitations of the energy modelling tools in view of resolution, fidelity, adequacy for the purpose and validity, as well as their inadequate use (mistaken input data, improper simulation settings, etc.) can falsify computational results and be thus directly responsible for some fraction of the observed EPG. This clearly establishes the role of modelling tools and processes as a competing variable. But the same cannot be suggested to be the case with regard to a role as a confounding variable, as it might suggest that the occupants should remain unaffected by whatever errors were committed by the modellers in the design phase. Nonetheless, it is true that modelled energy performance results may be communicated to occupants at some point and in some way, such as energy efficiency classes in energy certificates, or some 'green' label according to some building rating systems. It has been argued that occupants' consciousness of the sustainability reputation of the buildings they live and work in may influence their behaviour in terms of energy-conscious behaviour. This link and its role in the context of confounding variables may be viewed as rather tenuous, but it cannot be categorically dismissed.
- Theoretically, limitations of the coverage and resolution of the methods and devices used to monitor occupants' presence and behaviour in buildings, as well as potential errors in documenting and interpreting the collected behavioural data, can misrepresent occupants' actual behaviour, acting thus as a competing variable with respect to the EPG. An argument regarding the standing of monitoring as a confounding variable can be made in those cases, where occupants are aware of being observed and of their actions being monitored. As the so-called Hawthorne effect implies, occupants who are aware that their control actions are being observed might display behaviour that would have been different otherwise.
- Limitations of the coverage and resolution of the deployed energy metering infrastructure as well as potential errors in monitoring and documenting may misrepresent the magnitude of actually used energy and thus contribute, in terms of a competing variable, to the derived EPG. A potential role as a confounding variable is perhaps less plausible, even though it could exist in specific cases where occupants receive frequent energy use feedback, for instance in their workstations in an office building. Presumably, the provision of such feedback to the occupants reminds them of the presence of an individual-specific monitoring system, which could trigger the Hawthorne effect and influence the occupants' behaviour.

These observations and the – by no means exhaustive – listing of competing and confounding variables (see Table 1) underline the aforementioned challenges in isolating the role of occupant behaviour as a clear, direct and strong causal factor behind energy performance gap. Nonetheless, pursuit of a rigorous and transparent causal inference study could at least demark the line between pure speculation and reasonable indication regarding the role of OB in the EPG. Some of the implications of competing variables could be addressed via normalization. For instance, one could go back to the original model and ensure that the process of selection and application of calculation tools and methods have been errorfree. The original model could be then re-instantiated with modified input assumptions with respect to actually realized building fabric and systems, actual weather data and actual state of the surroundings. The result of this normalized model is suggested to have excluded the influence of relevant competing variables, thus isolating the role of OB in the EPG. At this point, it should not be difficult to recognize the severity of challenges involved in such an endeavour. For one thing, existing observation data pertaining to EPG and OB (Dong et al. 2022; Mahdavi et al. 2021) fall short of the coverage and quality that would enable the kind of rigorous analysis and normalization. A further problem is that normalization may allow, to certain extent, to address the potential influence of competing variables, but it is not sufficient to address the effects

Table 1. Compact description of the instances of competing and confounding variables in the causal study of occupant-driven energy performance gap.

	Status as competing variable	Status as confounding variable
Actual weather conditions	Can result in thermal processes different than those assumed in the modelling phase	Can influence occupants' expectations and their adaptive behaviour
Actual building construction	Causes thermal processes different than those assumed in the modelling phase	Can influence occupants' disposition toward engaging in control actions
Actual building systems and control routines	Causes thermal processes different than those assumed in the modelling phase	Can influence occupants' control-oriented behaviour, for instance due to system's inertia and responsiveness
Actual contextual settings	Influence physical processes via factors such as solar access, air flow patterns and further microclimatic circumstances	Can influence occupants' daylight control, shading and ventilation behaviour
Applied modeling tools and methods	Can falsify computational results due to limitations in view of resolution and validity, as well as improper or erroneous use	May generate misleading results that if purposefully communicated to occupants in terms of a quality attribute could influence their state of mind in terms of energy consciousness and hence their behaviour
Applied occupant monitoring setup, tools and methods	Can falsify data regarding occupants' actual patterns of presence and behaviour in buildings	Could influence, due to the occupants' awareness of their existence, their behaviour (via the Hawthorne effect)
Applied energy metering infrastructure	Can falsify collected data on buildings' actual energy use	Could influence occupants' behaviour, if they receive frequent energy use feedback (via the Hawthorne effect)

of confounding variables in the context of a causal inference study. This, however, does not diminish the value of a systematic causal study: Whereas certain effects of both competing and confounding variables may have to be excluded or truncated due to insufficient availability of data or insufficient knowledge of the involved causal mechanisms, a rigorous causal study could perhaps provide qualified estimates of the effect level of OB with respect to the EPG.

11. How should we address the purported role of occupants in the EPG?

Reports of – at times significant levels of – the EPG should not come as a surprise, given the multitude of factors influencing the energy performance of buildings and difficulties in accurate prediction of the future states of these factors. Specifically, isolating the role of occupants is a non-trivial matter, as it was illustrated in the course of the treatment of the previous question. Indeed, past research's aim at providing conclusive evidence for occupants' responsibility for the EPG does not pass muster in terms of a rigorous causal inference study. However, this does not mean that occupants' potentially considerable influence on buildings' energy performance should be trivialized or even dismissed out of hand. In fact, both plausibility considerations and some measure of observational data do seem to support the supposition that, occupants' behaviour can in fact influence buildings' energy performance and that this influence can be, in certain circumstances and to some degree, detrimental. It is thus prudent to contemplate common-sense strategies and derivative measures that could help mitigating potentially negative occupant-driven influences regarding the EPG. To this end, we can distinguish two broad categories. One category entails measures related to methods and technologies for building design and operation. The other category pertains to measures related to provision and dissemination of information.

Let us first focus on a number of measures that would fall within the building design and technology category.

- The zonal granularity of a building's environmental control systems (e.g. heating, cooling, lighting, ventilation) can be shown to be relevant to the implications of occupants' control actions. A classic example of a disadvantageously low zonal granularity would be the case where a single thermostat is assigned to control the temperature in the entirety of large office floor area. In such a case, the entire area would have to be cooled or heated even if only one occupant is present. To facilitate the efficient and differentiated provision of indoor-environmental services to the occupants, achieving a high zonal granularity of the pertinent control systems would be advantageous (Mahdavi et al. 1995).
- Provision of personal control opportunities for the occupants, particularly in office-like settings, has the potential to bring about higher degrees of occupant satisfaction with respect to indoor-environmental conditions without adverse consequences for energy efficiency objectives (Hellwig and Boerstra 2017; 2018). There can be significant inter-individual differences in occupants' indoor-environmental preferences. Personal control over their immediate spatial surroundings enables occupants to adjust conditions according to

their preferences, without imposing those on the entire space. The aforementioned high zonal granularity provides a suitable technical infrastructure for the provision of personal control opportunities.

- Simple monitoring methods such as the detection of occupants' presence facilitate the energy efficient operation of building systems during time periods when spaces are not occupied. This includes implementation of thermostat setbacks, turning off (or dimming down) the lights, modulation of supply air volumes and operation of shades for solar control.
- To be properly operated by occupants, relevant building elements, components and systems (from windows and blinds to switches and thermostats for heating and cooling systems) must have user interfaces that are intuitive and responsive (Mahdavi et al. 2021). For instance, windows that do not support fine-grained dosage of the effective opening area and blinds that cannot be comfortably operated (or not operated at all under certain – e.g. windy – outdoor conditions) arguably deter occupants from using them effectively. The resultant improperly modulated magnitudes of air flow and solar gains can also engender negative consequences in view of energy efficiency.
- The automated operation of building components and systems such as windows, shades, luminaires and HVAC components can make use of information on indoor-environmental conditions (e.g. ambient air temperature and humidity, CO_2 concentration, illuminance level) as well as outdoor conditions (e.g. solar irradiance, wind speed) to proactively accommodate occupants' needs and preferences. Thus the probability of counterproductive actions (such as system overrides) could be reduced.

The second category, that is the mitigation of potentially negative effects of occupant behaviour, pertains to provision and dissemination of information. The following briefly discussed instances of such common-sense measures are suggested to contribute to both occupants' satisfaction and buildings' energy efficiency.

- It has been suggested that more could be done to provide occupants with more accessible and concise instructions regarding the most important features of buildings' systems, equipment and their interfaces (Mahdavi et al. 2021). Such instructions could guide occupants toward a better understanding of the functionality of buildings' control systems and how they could be most effectively operated. The timely provision of well-prepared user-friendly instructional content can support occupants to bring about their preferable indoor-environmental conditions while avoiding pitfalls in view of energy wastage.
- If thoughtfully conceived and properly implemented, broad information campaigns regarding ways in which energy can be conserved, may have the potential to encourage energy-conscious user behaviour. Such initiatives could raise occupants' awareness level concerning general environmental issues on the one side and specific opportunities (such as those afforded by adaptive behaviour) on the other side to not only act in a manner that is energy-conscious, but also to maintain adequate personal comfort. Moreover, technology can be used to provide regular or real-time feedback regarding the past record and current trends of energy use and to which activities and behaviour the respective magnitudes can be attributed to. Again, such feedback may provide incentives to avoid, among other things, habits that are inefficient energy-wise, without necessarily improving comfort conditions.

Note that, independent of the strength of empirical evidence for the role of occupants in the EPG, efforts to improve the computational methods, models and procedures for the estimation of buildings' energy demand can be beneficial, including better models of occupants' presence and behaviour in buildings. To this end, it is important to assemble larger and higher quality sets of empirical data sets regarding buildings occupants' indoor-environmentally relevant behaviour (Dong et al. 2022; Huebner and Mahdavi 2019; Mahdavi 2020). Larger-scale availability of cross-sectional data facilitates, amongst other things, the consideration of demographic, socio-economic, and cultural traits of different populations and how the variance of such traits can support the creation of differentiated – context-sensitive – behavioural models in computational applications. The reliability of the predictive performance of computational models can be further enhanced via model calibration using monitored energy use data. However, the main utility of this possibility pertains mainly to building retrofit projects and building operation scenarios.

Conclusion

The projection of buildings' future energy demand frequently deviates from their actual use, a phenomenon referred to as the EPG. Arguing that the buildings' envelope and systems have become increasingly efficient, it has been suggested that the occupants' behaviour is the main factor behind the EPG. The 10 questions posed and treated in the present contribution intended to contribute to a more systematic treatment of the EPG discourse in the context of buildings. Starting from basic terminology, these questions addressed the contributing factors to the EPG as well as the existence and quality of the related empirical evidence for the EPG. Generally speaking, the EPG may stem from performance modelling and monitoring deficiencies, as-designed versus as-implemented building construction and systems installation, and the stochastic nature of weather conditions and occupancy-related processes. Concerning the latter factor, the supposition that occupants are the main contributors to the EPG has not been conclusively substantiated. Consequently, a central question pertained to the specification of the necessary conditions for conducting a systematic causal study of the purported role of occupants in the EPG. Notwithstanding the paucity of empirical evidence and definitive causal studies, it stands to reason that interactions of occupants with buildings' control components and systems are among the factors that can undesirably influence buildings' energy performance. Hence, the final question in our treatment considered the implications of the EPG discussion for future research and development effort, focusing specifically on the evidence-based modelling-supported building design and operation methods. This highlighted the need to pursue several concurrent measures, both in terms of technology-centric strategies (e.g. zonal granularity, personal control, occupancy monitoring, building automation and intuitive user interfaces for building control systems) as well as information provision and dissemination measures. Thus win–win situations could be created benefiting both occupant satisfaction and energy efficiency.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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