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Users' Impact on Buildings' Energy Performance Gap

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Abstract. Prior to implementation of new building (or building retrofit) projects, buildings' future energy demand is regularly predicted for certification or optimisation purposes. However, there is often a deviation between the projected and actual energy use during buildings' operation. A number of different factors can contribute to this mismatch that is typically referred to as energy performance gap (EPG). These could be due to uncertainties regarding weather conditions, buildings' systems, construction, and geometry. Specifically, issues regarding occupants' behaviour and related control actions have recently been suggested to be a major cause for the EPG. However, evidence for such a claim is not conclusive. In this context, this contribution explores the impact of occupants' control-oriented behaviour (e.g., interactions with buildings' control components and systems, such as opening or closing windows or adjusting thermostats) on buildings' energy performance. The present contribution entails critical reflections on these issues. Moreover, strategies are discussed that could balance occupants' control opportunities and energy efficiency targets.

Keywords: Buildings, Energy Performance Gap, Occupant Behaviour, Simulation

1. Potential contributors to buildings' energy performance gap

A building-oriented energy performance gap (EPG) can be described as the deviation between prior estimations and the actual energy use during buildings' operation [1,2]. Estimations of buildings' energy use during design phase are typically performed using calculation methods or simulation tools. The actual buildings' energy use during operation is usually metered over a certain time period.

Different factors can contribute to the deviation between the projected and the actual energy use during buildings' operation [3,4]. Examples of such factors include: *i)* Energy performance predictions include assumptions regarding future weather circumstances, which can be highly uncertain; *ii)* Buildings' construction can deviate from initial design in the realization stage. Likewise, buildings' implemented systems (e.g., heating, cooling, ventilation, lighting) and their operation may not reflect the design-phase intentions; *iii)* Assumptions regarding the interaction between future building users and environmental control elements are seldom accurate; *iv)* Mistakes may occur in the usage of computational tools (e.g., input data could be false or settings could be incorrectly assigned) and the tools themselves could be insufficiently scrutinized with regard to their fidelity and validity; v) Deficient monitoring infrastructure and inconsistent documentation may lead to errors in the accounting of actual consumed energy magnitudes.

It has to be noted that, given the stochastic characteristics of occupants' behaviour and weather conditions, the results of energy performance calculations must be always evaluated in the context of assumed model input data. As such, in order to isolate the impact of occupants' behaviour on EPG, one must account for the other potential influencing factors via normalization techniques [5].

The presence of occupants in buildings and their control actions within buildings, such as operation of windows, lights, shading elements, heating or cooling systems, have been recently suggested to be a main cause of the EPG. In this context, it has been frequently argued that the steady improvement in quality of both building's envelope as well as in efficiency of control systems has diminished the impact of purely technical factors on energy use. This has been suggested to augment the role of the occupants with regard to the EPG [6-9]. In the subsequent section, recent investigations of these assertions are discussed in light of available empirical evidence.

2. Empirical clues regarding occupants' role in the EPG

A recent study focused on the availability of evidence for the claim that occupants are the main reason for the energy performance gap [10]. Thereby, 144 relevant scientific articles were assessed with regard to quality and content. These included studies that focus on the EPG in both residential and non-residential buildings located in different climatic regions. The review results indicate that building's actual energy use has been both under and overestimated. According to the reviewed studies, the median value of EPG was +30% in case of residential buildings, +14% in case of non-residential buildings (see Figure 1). Note that here positive numbers of EPG indicate that calculations underestimated buildings' actual energy use, whereas negative numbers indicate an overestimation. Around 70% of the reviewed studies indicate some instance of EPG linked to buildings' envelope, internal heat gains, lighting, plug-loads, and mechanical equipment. For instance, some reviewed studies report that actual indoor temperatures deviate from the assumed model input. Likewise, the assumed durations for heating or cooling of buildings' spaces may have been both shorter and longer than the actual intervals, thus contributing to the magnitude of the EPG.

Frequent EPG causes listed in the reviewed studies were plug-load schedules (reported in 40%), window operation (reported in 36%), and set-point temperature (reported in 33%). Multiple studies report some form of an occupant-related EPG. However, evidence for occupants' role in the EPG is not consistently provided. The review results also show that only 14% of the studies include data concerning both energy use and user behaviour. A subsequent research effort specifically focused on this qualitative aspect of the reviewed studies [11]. Thereby, quality labels were assigned to the individual studies on the basis of three different criteria, that is quality of data, extent of normalisation, and applied method to identify the cause of the EPG. Figure 2 shows the distribution of the EPG magnitude as a function of data quality in the respective studies results. Thereby, three quality levels are defined, namely low ("L"), medium ("M"), and high ("H"). The results of this study suggest that the documented EPG magnitudes were considerably higher in lower quality studies.

As such, these critical observations regarding past research on EPG underline the need for and importance of more robust approaches toward a more reliable assessment of buildings' energy performance and the associated predicted challenges. In this context, it would be beneficial not only to improve the fidelity of simulation models, but also to assemble a richer repository of empirically-based data on the patterns of users' presence and behaviour in buildings [12,13]. Such a repository could offer the routine possibility of calibrating simulation models on the basis of monitored data on user behaviour and energy use. Likewise, the inclusion of occupant-related social, cultural, and demographic information can further contribute to a better understanding of the scope and variety of their behavioural tendencies, thus refining the quality of respective representation in simulation models.

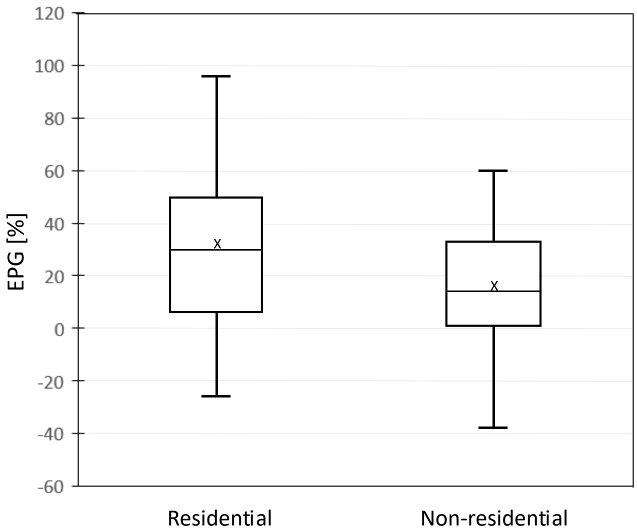

Figure 1. *Evaluation results of EPG magnitude (in %) in the reviewed publications separated for residential and non-residential buildings [14].*

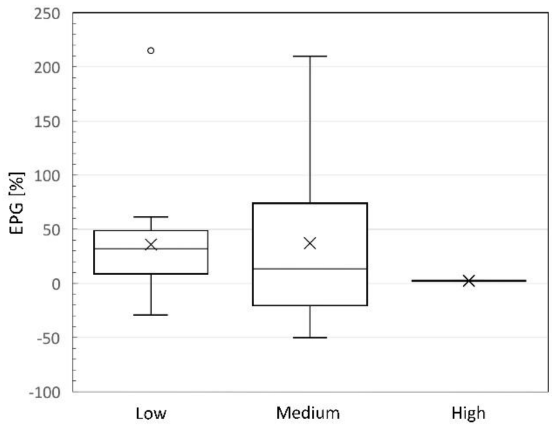

Figure 2. *Distribution of EPG magnitude as a function of the data quality in the respective studies [11].*

3. Mitigation of the potentially negative user behavior effects

As outlined above, previous research has not provided definitive empirical evidence to support the claim regarding the prevalence of occupants' responsibility for EPG. Nonetheless, existing case reports do suggest that, in specific cases, occupants' behaviour may adversely affect buildings' energy performance. This motivated the search for and implementation of strategies that could help obviating respective negative implications. In this context, two specific strategies are worth elaborating: i) the first strategy addresses features of building design and technology adjustments; ii) the second strategy focuses on targeted and timely provision of information to building users. Aspects related to both strategies are outlined in the following:

- Consideration of certain features of the adopted building design and technology can be critical. These included especially the pursuit of a high level of zonal granularity or smart zoning. A high level of zonal granularity can be beneficial to better represent the differentiated coverage of indoor environmental control systems (such as those for heating, ventilating, cooling, and lighting, as well as windows and shading elements) in different spaces of a building. In that way, the provision of control services can be linked to occupants' presence in the space.

- Occupants' satisfaction with and understanding of environmental control opportunities can be enhanced by including intuitive and responsive user interfaces as well as providing personal control opportunities to offer the possibility to maintain preferred environmental conditions in the users' immediate surroundings. As such, this contributes to an increased level of user satisfaction without significant consequences on buildings' energy performance.
- The implementation of smart zoning supports an energy-efficient operation of environmental systems as it facilitates the detection of users' presence and absence and the respective adjustments of the systems' operation. For instance, in case of users' absence, lights can be switched off or dimmed down to reduce electrical energy use, blinds can be operated to cut solar gains, and thermostat can be adjusted to reduce heating or cooling demand.
- The inclusion of intelligent building automation can further support the energy-efficient operation of buildings. Thereby, automated systems can be fed with real-time monitored data (e.g., regarding both indoor and outdoor environmental conditions) to bring about the building users' preferred conditions while maintaining energetically optimal operation modes. This helps to ensure acceptable levels of thermal, visual, and air quality conditions for building users while reducing the need for and number of potentially counterproductive control actions.
- Another strategy toward energy performance improvement involves the targeted and timely provision of information to building users. Specifically, occupants should be supplied with information on how to operate available interfaces, systems, and equipment in an appropriate manner.
- Finally, information campaigns and real-time feedback regarding sources and magnitude of energy consumption can improve occupants' awareness towards buildings' energy performance. Specifically, real-time feedback can support users' understanding of the way their behaviour (i.e., their interactions with buildings' control systems and devices) can influence buildings' energy consumption.

Overall, the above list of strategies can be suggested to provide an overview of the kinds of rational (technical and behavioural) options that can contribute not only to improving indoor environmental conditions (and hence occupants' satisfaction) but also to enhancing buildings' energy performance.

4. Concluding remark

In this contribution, we critically discussed the phenomenon of the energy performance gap (EPG) as related to the building design and operation domain. This phenomenon pertains to the frequently observed deviation of buildings' actual energy performance from calculations performed prior to building construction and retrofit projects. We specifically addressed certain tendencies in the past research in this area, which have identified occupants and their behaviour (control actions) as the central contributor to the EPG. However, a close scrutiny of these studies, and the evaluation of the respective empirical evidence do not conclusively establish the validity of an occupant-centric EPG explanation. In fact, the contributing factors to the EPG can be manifold and include, among others, monitoring issues (with respect to both occupant and energy data), uncertainties related to assumptions in simulation models regarding future weather conditions, and issues regarding the proper usage of simulation tools. It is of course conceivable logically, and has been empirically demonstrated in specific cases, that user-related assumptions in simulation models can also be an important contributing factor to the EPG. Specifically, occupants' interactions with building control elements can negatively impact the energy performance of buildings. In this context, it is important to emphasize that, whereas the EPG is not likely to be precluded in the course of energy use estimation procedures, strategies are available to mitigate potentially negative implications of building users' behaviour on buildings' energy efficiency. Accordingly, future research should focus on taking a simultaneous look at both building technology advancements and occupant-centric information measures so as to positively influence indoor environmental conditions while preserving optimal levels of energy performance.

Data availability statement

This contribution is not based on data beyond information entailed in the provided references.

Author contributions

Conceptualization: C.B. and A.M.; Writing - original draft: C.B. and A.M., Writing – review & editing: C.B. and A.M.

Competing interests

The authors declare that they have no competing interests.

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