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TECHNISCHE UNIVERSITÄT WIEN
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DIPLOMARBEIT

A critical study of the suggested role of occupants in the building-related energy performance gap

unter der Leitung von

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KURZFASSUNG

Zwischen der berechneten Gesamtenergieeffizienz von Gebäuden und dem tatsächlichen Verbrauch besteht häufig ein erheblicher Unterschied. Während mehrere Faktoren zu diesem Unterschied (der so genannten Energieleistungslücke) beitragen können, wird er häufig auf das Verhalten der Bewohner zurückgeführt. Im Rahmen dieser Arbeit wird die Rolle der Bewohner bei der Energieleistungslücke analysiert. Einschlägige Studien wurden identifiziert, um den Stand der Technik detailliert darzustellen. Darüber hinaus wird eine Methode zur Bewertung der Beweise für die behauptete Ursache vorgeschlagen. Die Bewertung umfasst eine quantitative Analyse einer Punktebewertung, die für einzelne Studien vergeben wird. Die meisten Studien deuten darauf hin, dass das Nutzerverhalten einen wesentlichen Anteil an der Energieleistungslücke hat. Zusammen mit dem Temperatursollwert erweisen sich die Nutzung von Geräten und die Belegung als die wichtigsten Faktoren des Nutzerverhaltens, die die Lücke verursachen. Die Ergebnisse der Bewertung zeigen jedoch, dass die in den überprüften Studien vorgelegten Beweise nicht ausreichen, um die ermittelten Ursachen zu stützen. Die Ergebnisse dieser Arbeit zeigen einige wichtige Überlegungen auf, die in zukünftigen Untersuchungen berücksichtigt werden sollten, um die Stärke der Beweise für die Rolle der Bewohner bei der Energieleistungslücke zu bewerten.

Keywords

Leistungslücke, Energieverbrauch, Nutzerverhalten, Datenqualität, Normalisierung, Energiemodellierung, quantitative Bewertung, Gebäude

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ABSTRACT

There is often a significant difference between the calculated energy performance of buildings and the actual consumption. Whereas multiple factors may contribute to this difference (the so-called energy performance gap), it is often attributed to the occupant behavior. Within this work, the role of occupants in the energy performance gap is analyzed. Relevant studies were identified for a detailed review of the related state of the art. Moreover, a method of assessing the evidence is proposed for the claimed cause. The assessment entails a quantitative analysis of a point rating given to individual studies. The majority of studies suggest that occupant behavior is a major contributor to the energy performance gap. Together with the temperature set-point, equipment use and occupancy are shown to be the main identified factors of occupant behavior causing the gap. However, the results of the assessment shows that the evidence presented in the reviewed studies is not sufficient to support the identified cause. Findings from this work identifies some key considerations that should be addressed in future investigations to assess the strength of evidence for the occupant role in the energy performance gap.

Keywords

Performance gap, energy use, occupant behavior, quality of data, normalization, energy modelling, quantitative assessment, buildings

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The research presented in this thesis is based on a collective work for a recently published review study, which I was privileged to contribute to. I would like to additionally thank each one of the involved colleagues for their valuable input, and my supervisor for introducing me to the topic through this chance of contribution.

Many thanks to my class mates for their genuine presence for one another. And my most gratitude, is to those who seek and share knowledge for the sake of understanding our universe, and providing an inspiration to dream.

Thanks to my parents for their trust, encouragement and ultimate belief in me.

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CONTENTS

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1 INTRODUCTION

1.1 Motivation

One of the questions relevant to meeting the energy efficiency targets is the deviation of the buildings' real energy consumption from the calculated energy demand. This is referred to as the Energy Performance Gap (EPG). There is a growing concern in the building sector regarding this phenomenon. In the European context, the Energy Performance Building Directive (EPBD) has developed a legislative framework to promote more energy saving potential from the building sector, as it is estimated to consume around 40% of the total EU energy consumption (fernbas, 2019). Hence, several forms of energy ratings were developed to predict the energy use of buildings. For new and retrofitted buildings, the magnitude of deviation; actual energy from predicted, can go up to 380% and 780% more electricity and fossil fuel consumption, respectively (Jain et al., 2020). The literature points out a variety of causes contributing to the EPG. The physical characteristics of the building envelope is identified as one of those causes. Occupant Behaviour (OB) is identified to be responsible for a larger share of the EPG. A commonly mentioned reason for that is the rebound effect; which can be described as an increase in the energy-related comfort level as a result of improved energy performance of buildings (O. Guerra Santin, 2013). Nevertheless, other studies reported only 5% more energy consumption than calculated (van Dronkelaar, Dowson, Spataru, Burman, & Mumovic, 2019). One of the reasons researchers found limited evidence for the influence of OB on the performance gap is the lack or uncertainty of available occupant data and modelling (Belazi, Ouldboukhitine, Chateauneuf, & Bouchair, 2018). Yet, few were focusing on assessing the evidence provided for the claimed cause. The evidence presented in literature uncovers a range of variations in the quality of energy and occupant' data. Moreover, the methods of predicting energy use raise questions regarding the occupant-related magnitude of gap.

1.2 Objectives

In order to conduct a well-grounded assessment of the identified cause of the EPG, there is a need to have a closer look on the explicit proofs presented for the assumed occupant-related EPG. The work reported in this thesis varies from, and is complementary to the existing literature: it quantifies the evidence for the claimed

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OB share of the EPG, and provides some qualitative considerations to better assess the evidence.

The current work aims to answer the following questions:

1. Does the OB contribute to the so-called EPG?
2. In case statement 1 applies, what are the OB factors that mostly contributes to the EPG?
3. Is there a sufficient evidence that OB is responsible for the majority of the EPG?
4. What are the possible uncertainties in energy and occupants' data, along with modelling approaches, which can affect the evidence assessment?
5. To which extent can an improved energy use prediction based on empirical evidence reduce the EPG?

1.3 Overview

This thesis is organised as follows: Section 2 provides information about the approach carried out which is, a review of existing studies, and assessment of the evidence for the identified cause of gap with a detailed description of the assessment criteria. Section 3 presents the results of individual assessments of studies and a general synthesis of all studies' assessment results. Section 4 includes the scientific contribution of the research through an interpretation of the results. Section 5 is a summary of the main results and findings.

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2 APPROACH

2.1 Defining the hypothesis

As building systems and thermal envelope properties are improving, occupant behaviour is suggested to cause the bigger share of effect on the EPG in buildings. However, the extent of this effect is uncertain due to the lack of a conclusive evaluation of the evidence provided for this assumption in literature. According to the state of the art, there are several ways to test this statement. One way is through conducting an experiment on a sample of buildings and measure the gap between energy predictions and energy use based on actual energy and occupants' data. Another way, is a review of a number of scientific studies which address the role of occupants in the EPG. The proposed work addresses the contribution of OB to the EPG through: 1. A review of relevant literature; 2. Conducting a quantitative and qualitative assessment of evidence provided in literature for the occupant-related cause of gap.

2.2 Identifying relevant publications

The selection process of the literature in the present work is based on a collective review carried out in a recently published article (Mahdavi et al., 2021). The aim was to select papers which identify the causes of the EPG and in particular address occupant behaviour as a major cause. First, a search was carried out to include scientific publications investigating the EPG: meaning, causes, reduction potentials using keywords: performance gap, rebound, prebound, gap. The number of papers identified were 70 articles, some were classified as 'secondary category'. The reason for that was the absence of the role of occupants in the EPG, which is the main cause addressed in the hypothesis of the current work. However, the need to include all articles in the dataset and not only the articles addressing occupants, provides insights to the topic of the EPG and the various causes contributing to it. This is addressed in the fourth section of this chapter: Rationale of assessment.

Second, a search of literature was performed that only includes the role of occupants' behaviour in the EPG. The search words contained "buildings" AND "occupants". The result of this search was classified mostly as 'Main category'. The articles included occupants and other causes for the EPG (e.g., physical envelope characteristics, building systems, weather). Database resources used were mainly

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Scopus and Web of Science. The method used for identifying the relevance of the second dataset was through reviewing titles, keywords and abstracts. This resulted in additional 102 articles. Most of the articles were accessible through the TU-institution account. Duplicates in 'main' and 'secondary' categories were identified using Zotero and thus removed from the literature collection. Further filtering took place to remove 28 articles for the reason of being less relevant including review articles, studies addressing the topic in a broader sense or in a very specific context, which makes it more difficult to generalize the experiments carried out (e.g., specific construction type). All articles were selected to include only the ones published in English language. The total number of relevant articles were 144 (Figure 1).

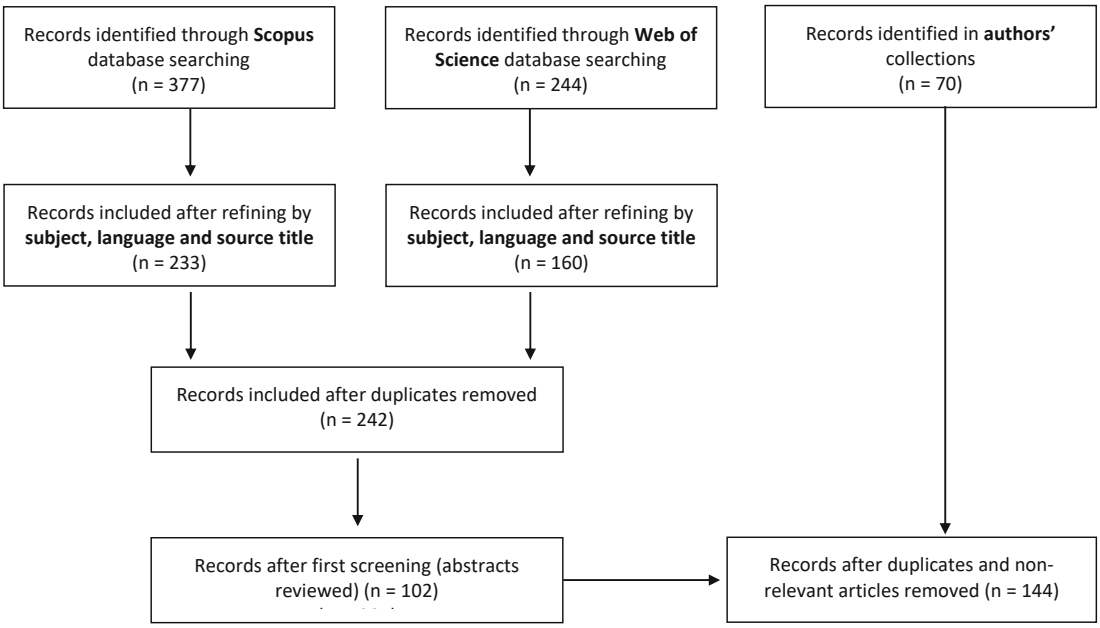

Figure 1 Process of identifying relevant publications (Mahdavi et al., 2021)

2.3 Review structure

The identified articles were reviewed according to the following criteria: 1. *Publication information* which includes the year of publication, and the type of study addressed in the present work. Three types were identified according to the quality of data presented: 'Gold' category includes data on energy and occupants, 'Silver' contains data on energy only, 'Bronze' does not include empirical data on either energy or occupants. The reason for this classification: gold, silver, and bronze is to include 'data quality' as a major criterion for the evidence assessment of the EPG (Section 2.4). 2. *Building-related information* refers to basic data about the location where the study is carried out, building typology with a detailed description (e.g.,

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multi-family residential building), an indicator for the building physical characteristics (e.g., new, retrofitted, existing), number of spatial units investigated and the year of construction. 3. *Source of occupant-related model assumptions* refers to the source of input variables of OB used in the prediction model. 4. *Predicted energy* contains the energy type (e.g., heating load), the type of energy (e.g., electricity, gas), the purpose (e.g., space heating & hot water), the energy magnitude and unit (e.g., $kWh.m^{-2}.a^{-1}$) and the method used for the energy predictions (e.g., simulation). 5. *Measured energy data* includes the monitoring period, the energy type and the purpose, magnitude of energy use, source of data, data resolution: spatial & temporal granularity; variables measured for indoor and outdoor conditions and the method of monitoring, occupants' actions and the source of data. 6. *Normalised energy data* contains the variable affecting the energy consumption (e.g., weather) and the method of normalisation. 7. *Deviation (%)* describes the energy gap defined as the deviation of actual energy use from predicted. 8. *Main findings* encompass the occupant-causes identified by the study to the EPG and the recommendation to better predict OB in energy models. Three examples for the three study types: 'Gold', 'Silver' & 'Bronze' are presented in (Table 1).

Table 1 Structure of the review of articles

Publication information		**Building-related information**						
Ref.	**Type**	**Location**	**Type**			**Nr. of objects**	**Year of construction**	**Source of occupant-related model assumptions**
			Residential/ Non-residential	**Single/multi family; office, etc**	**Retrofit/ New /Existing**			
(Mahdavi & Berger, 2019)	Gold	Switzerland	Residential	Multi-family	New building	8 apartments	2009	Swiss Society of Engineers and Architects (SIA) standard
(de Wilde, 2014)	Silver	Britain (Plymouth)	Non-residential	Education	NA	1	NA	NA
(Roetzel, Tsangrassoulis, Dietrich, & Busching, 2011)	Bronze	Athens, Greece	Non-residential	Office	NA	3	NA	Literature review, survey

Predicted energy					**Measured data**				
Predicted energy-related variable	**Type**	**Purpose**	**Predicted magnitude**	**Method of energy use prediction**	**Observation period**		**Energy (including assessment method)**		
					From	**To**	**Measured energy type**	**Purpose**	**magnitude**
Heating load	Electricity, pellet combustion, solar energy	Space heating and hot water	19 kWh/m2. annual	Simulation	2010-07	2012-06	Electricity, pellet combustion, solar energy	Space heating, hot water, ventilation system	38 kWh/m2. annual
Energy demand	Gas, electricity	Heating, HVAC, plug loads	6000 - 8000 kWh/month (electricity), 3000-15000 kWh/month (gas)	Simulation	2011	2012	Gas consumption, electricity consumption	Heating, HVAC, plug loads	9000 - 12000 kWh/month (electricity), 3000-18000 kWh/month (gas)
Energy demand	Gas, electricity	Heating, cooling, lighting, office	50-200 kWh/m2. annual	Simulation	NA	NA	NA	NA	NA

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		equipment							
Measured data									
Energy (including assessment method)			**Indoor conditions**		**Outdoor conditions**		**Occupant behaviour**		
Source of energy data	**Spatial granularity**	**Temporal granularity**	**Indoor conditions**	**Source of indoor data**	**Outdoor conditions**	**Source of outdoor data**	**Occupant characteristics**	**Observed occupant behaviour**	**Source of user behaviour data**
Energy meters, energy bills, in-situ measurements	Building	Annual	Air temperature	NA	NA	NA	Household composition	Occupancy, window opening behaviour, use of shades	72 observations during several days in winter
Energy metering	Building	Monthly	NA	NA	Air temperature	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Normalized energy data		**Deviation %**	**Main findings**	
Normalized variables	**Method of normalization**	**(actual energy use from predicted)**	**Identified/ assumed occupant-related cause of gap**	**Recommendations for better people models of the future**
Energy consumption for heating and hot water	Adjusted for degree days, HDD16/20 basis	-1% (simulation) 81% (SIA calculation)	Higher occupancy and indoor temperature than assumed, window opening, obstruction of solar gains	Regular monitoring to technical installations, explaining technical solutions to users, feedback to planners and constructors
NA	NA	30% (electricity) - 5% (gas)	Plug loads, occupancy, control issues	Deeper look into BEMS
NA	NA	NA	Operation of office equipment and lighting	Holistic assessment is required to understand the contextual interdependencies. Key factors in the study are building design, window size, type of office equipment and use as well as tasks performed, type of lighting system and its use.

Further refinement took place to include only the 'Gold' category of studies. Consequently, 57 articles were selected according to the availability of empirical data for energy and occupants. The resulting sample was further reduced to 52 articles in order to strictly include a clear comparison between energy predictions and actual energy use.

2.4 Rationale of assessment

The assessment of the EPG causes presented in the selected sample of studies is carried out using a quantitative method of point rating system. And, a qualitative reasoning of the rating assigned to each study which contains 1. a detailed description of the exact causes of the EPG identified by each study; 2. A brief description of the building typology, the number of investigated sample of buildings and the location where the study carried out; 3. A detailed reasoning of the strength of the evidence and information about variables normalised and the method carried out. The reason for developing this method of assessment emerged from the review of studies. It was observed that many studies seem to assume the causes rather than proves them through an empirical process.

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The points' weight of the selected criteria of assessment has a ratio of 2:2:1 for quality of data: normalisation coverage: variable match (cause vs measurement). It is subjectively perceived that the quality of data and the number of factors normalised in the study are more important for identifying the causes of the EPG than the variable mismatch (cause vs measurement). First, quality of data is divided into energy and occupants' data, each has a rating of 'low', 'medium', & 'high' with points 0, 0.5, 1 respectively. Second, normalisation coverage has three levels for evaluation: none resembles that there is no normalisation carried out, the other two levels describe the number of factors normalised with a rating of 1, 2. Third, the variable mismatch (cause vs measurement) states whether or not the identified cause are directly or indirectly measured, so it's either yes or no interpreted as 0 and 1. Last, points are summed up to a total value, and accordingly the assessment is derived to be whether 'low', 'medium', or 'high' with a range of values 0 - 2 for 'low', 2.5 - 4 for 'medium', and 4.5 - 5 for 'high'. The range for the three ratings gets smaller approaching 'high' rating, which contributes to a narrower window of evaluation towards the higher assessments. In other words, it makes it more challenging for studies to have a higher evidence evaluation than a lower one, which can contribute to a better filtering process (Table 2).

Table 2 Assessment criteria

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	0 - 2
Medium	½	Medium	½	1 factor	1	No	0	Medium	2½ - 4
High	1	High	1	2 or more factors	2	Yes	1	High	4½ - 5

½: Half point; 1: Full point

In order to decide upon the rating for each criterion (e.g., 'low', 'medium', 'high'), a number of detailed quantitative and qualitative aspects for assessment had to be developed, as follows:

1. **Quality of data:**
   - *Energy data:*
   a. Data resolution: temporal & spatial granularity.
   b. Duration of monitoring.
   c. Data source (e.g., energy metering, energy bills, questionnaire, previous study).

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d. Using more than one method of data collection to confirm the data credibility (e.g., in-site observations + energy bills).
e. Separate measurements for separate energy types (e.g., space heating, hot water, electricity). This can be done by initially obtaining separate measurements (separate meters) or by estimations (e.g., 15% increase of space heating consumption in winter months to summer months). The first method is considered more credible.
f. Providing an argument for why a certain number of data points are considered a representative sample (e.g., 4 rooms/spaces out of 33 are chosen for the experiment).

– *Occupants' data*

a. Number of occupant behaviour variables monitored (e.g., window operation, temperature set point, use of shades).
b. Duration of monitoring.
c. Data source (e.g., sensor measurements, survey, in-site observations).
d. Using more than one method of data collection to confirm the data credibility (e.g., sensors + questionnaire).
e. Providing an argument for why a certain number of data points are considered a representative sample (e.g., occupants, observations).
f. Interdependency of monitored variables increase the credibility of data for both variables (e.g., occupancy and illuminance. Measuring both variables strengthen the identified cause: light operational hours outside occupancy hours. Since both variables are measured, not one is measured (occupancy) and the other is concluded (use of lighting) from energy consumption measurements).

2. Normalisation coverage:

Number of variables considered/adjusted for energy consumption.

3. Variable match (cause vs measurement)

This criterion addressed whether the identified cause was directly or indirectly measured in the study.

- *Directly:* is when the identified cause is occupancy and the measured variable is occupancy.
- *Indirectly:* is when the identified cause is occupancy and the measured variable is use of artificial lighting or CO_2 concentration (an occupant can be present but

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shutting off the light or opening the window such that CO_2 concentration would not be correlated with occupancy).

For the purpose of synthesizing the studies in a single assembled structure, a code system of naming is assigned according to three aspects: the candidate cause of the EPG, the typology of the building, and the evaluation of the evidence presented by each paper (Table 3). An example of a study which has occupant behaviour as a candidate cause, office as the typology of the addressed building, and an evidence evaluation of 'medium' for the identified cause of the EPG; is C1T3E2 (Table 3). This should allow an electronic search function of the identified aspects across the selected studies in the assembled structure (*Table 5*).

Table 3 Coding system of individual studies

Code	C	T	E
1	Occupant behaviour	Residential	Low
2	Weather	Commercial	Medium
3	Building systems	Offices	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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3 RESULTS

In this section, the results of the assessment are presented. First, in subsection 3.1, individual studies are assessed separately following the identified criteria (Table 2). Accordingly, the conclusive evidence assessment ('low', 'medium', 'high') is added to (Table 3) to generate the individual study codes (e.g., C1T1E2). The coding system only allows limited possible combination of names, it does not distinguish different studies with similar assessment. Thus, a sequential reference number is assigned to identify each study. Second, in subsection 3.2, qualitative review results are presented for the studies. It includes a description of the approaches presented to investigate the role of occupants in the EPG. A statistical analysis is carried out to present a collective overview of the results. Quantitative results are presented in (*Table 5*), to allow a quick and easy way to read the results.

3.1 Assessment results of individual studies

Assessment Study **C1T1E2**:

1. *Actual energy performance of student housing: Case Study, benchmarking and performance gap analysis* (Lehmann, Khoury, & Patel, 2017)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**3 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause of the EPG refers to the occupant behaviour; higher occupancy than assumed, higher average indoor temperature than assumed, window opening, obstruction of solar gains. Typology: The addressed buildings consist of eight residential student apartments in Geneva, built in 2009.

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Strength of evidence: Two years monitoring of energy data for space heating, hot water and ventilation systems took place. The data resolution for energy can be categorised as 'low'; annual values. Window opening, use of shades, occupancy and indoor temperature were monitored (72 observations) during several days in winter. The quality of the data for occupant behaviour is evaluated as 'medium' due to the number of observations and the method of monitoring; no details given about the method of reporting those observations. Neither fixed time interval is mentioned for the data observations nor why those 72 observations is a representative sample. The Identified causes are directly monitored for occupancy, window opening, indoor temperature and use of shades. Normalisation: Energy consumption for heating and hot water is adjusted for weather: heating degree days (HDD), internal heat gains, and U-value of the roof. Solar heat gain by shading of neighbouring buildings and closed shades was reduced. Indoor temperature was raised by 1K. After normalising energy use for those variables, simulation results seem to match the actual consumption when applying a higher ventilation rate than assumed (1m3/m2.h instead of 0.3m3/m2.h). Which indicates that the main contribution to the heating energy gap is due to exchange loss; ventilation and windows opening. The overall assessment of the mentioned points categorizes the strength of evidence as 'medium'.

Assessment Study **C1T1E1**:

2. *Low-energy dwellings: The contribution of behaviours to actual performance* (Gill et al. 2010)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1 ½**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

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Assessment summary:

Candidate causes of the EPG: The identified causes are temperature set point, window opening and lack of user control on programmer settings for the temperature set-point. Typology: 26 dwellings; single and multi-family low energy buildings in the UK, built in 2007.

Strength of evidence: Actual values for heating and electric energy are obtained through energy metering as annual values. Therefore, the energy data resolution is evaluated as 'low'. Despite the possible uncertainty in the occupant data monitoring method; survey. In addition to a sample size of 60%; 18 occupants in 15 of the dwellings are included, where the average behaviour score is used. The quality of occupants' behaviour data is categorised as 'medium' due to the level of detail gathered in the survey about the use of each appliance, occupancy schedules and insightful qualitative comments obtained from interviews that helped rationalize findings from the survey. Design values of electrical consumption includes only regulated use and not the use of appliances (which are included in the measured electricity) which can explain a big part of the gap. The identified causes are directly monitored in the survey; temperature setpoints, window behaviour, MVHR (mechanical ventilation with heat recovery) use, user ability to set the programmer control for the temperature set-point. Normalisation: No information about normalization is mentioned because no calibration for specific parameters took place in a model. Actual energy values are compared to design targets. The study presents a POE (post-occupancy evaluation) to identify the potential behavioural attributes affecting the energy gap. The result of the assessment of evidence is 'low'.

Assessment Study **C1T1E2**:

3. *A case study on household electricity uses and their variations due to occupant behavior in Chinese apartments in Beijing* (Jian et al. 2015)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are operational; use of equipment such as lighting, appliances and room air conditioners. Typology: 44 apartments were investigated in Beijing, built in 2007.

Strength of evidence: The data resolution for energy is categorised as 'medium'; one year of monitoring of electrical energy consumption; lighting, electrical appliances, air conditioners took place with a temporal granularity of two times a week (every 3 or 4 days) reported by manual reading of energy meters. Further data collection was carried out only on two apartments out of the 44 with a data resolution of 10-minute interval, indoor air temperature was measured. The occupant data includes length and frequency of daily use of lighting and appliances. Normalisation: No normalisation of variables is carried out. The identified causes of occupant behaviour were directly monitored using a paper questionnaire. The evidence assessment is 'medium'.

Assessment Study **C1T2E3**:

4. *Towards measurement and verification of energy performance under the framework of the European directive for energy performance of buildings* (Burman, Mumovic, and Kimpian 2014)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	**4 ½**

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are 75% relates to operational use; longer hours of operation for heating and ventilation systems, higher heating set points and lower cooling set points in classrooms. Procurement gap of poor installation of mechanical ventilation systems accounts for 25% of the gap. Typology: one educational building was investigated in England, built in 2008.

Strength of evidence: Electricity and natural gas are monitored for two years. The quality of energy data is categorized as 'high' with an hourly resolution often aggregated to yearly values. Occupant's data; occupancy, temperature set points, ventilation rates, schedules of operation for heating & ventilation systems are assessed as 'medium' due to the range of uncertainty of data collected from the POE (interviews and on-site observations). Normalisation: gas consumption for heating is adjusted for heating degree-days. The model is calibrated with the measured variables including all loads; heating, domestic hot water (DHW), lighting, fans/pumps, cooling, equipment and electricity consumption for external lights and lifts. The results are adjusted to obtain a valid comparison between modelling results and actual performance. The Identified causes were directly monitored in the POE. The case study confirms that calibrated thermal models could match the actual performance. The overall assessment of the evidence is categorised as 'high'.

Assessment Study **C4T1E1**:

5. *The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock* (Guerra Santin, Itard, and Visscher 2009)

Code	C	T	E
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	1 ½
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: Building characteristics; insulation, age of the building, the presence of a bath, the presence of a thermostat and temperature setting, dwelling size and number of rooms are identified to have a contribution of 42% to the gap compared to occupant behaviour; which is 4.2%. The occupant-related causes of gap are identified to be occupancy, number of heated rooms, temperature set-point, household size. Typology: The sample of the addressed buildings are 15,000 of the housing stock, in the Netherlands.

Strength of evidence: The data for occupants includes: occupancy, heating and ventilation behaviour; acquired from a national survey, which can be categorised as 'medium' due to the size of the sample despite the uncertainty of the method of data collection. The data for the characteristics of the building is obtained through inspection, it includes the percentage of insulation per surface, type of materials, or type of heating system. Energy data (gas and electricity) for space and water heating are obtained from energy bills for 3 years duration as annual values, which is assessed as 'low'. Normalisation: No normalisation of variable took place. The identified causes of the EPG are directly monitored in the survey. The assessment of the evidence is 'low'.

Assessment Study **C1T1E2**:

6. *The influence of energy performance levels on the heating demand in dwellings: Case-study analyses on neighbourhoods* (Delghust et al. 2013)

Code	C	T	E
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are occupant-related, referring to occupancy, number of heated rooms, thermostat use; setpoint & frequency, ventilation behaviour; mechanical system and window opening. Typology: 62 single-family residential buildings are examined in Belgium. One case study for new buildings built in 2008. Another case study for older buildings built in the 1960s.

Strength of evidence: The energy data resolution of gas and electricity consumption for space heating and hot water is obtained from energy bills as annual values per building; therefore, evaluated as 'low'. A survey is carried out to obtain occupant behaviour data; occupancy, thermostat use (setpoint & frequency), ventilation behaviour (mechanical system and window opening). Occupant data is categorized as 'medium' because the sample is quite large but the method of data is uncertain compared to monitoring using sensors. Normalisation: gas consumption for heating and hot water is normalised for heating degree days. Heating hours and temperature set-points were estimated from the heating period data from the surveys and temperature measurements. The identified causes are directly monitored in the survey. The assessment of the overall evidence is 'medium'.

Assessment Study **C1T1E2**:

7. *Comparison between predicted and actual energy performance for winter heating in high-performance residential buildings in the lombardy region (Italy)* (Dall'O' et al. 2012)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**3 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are occupancy, temperature setting, use of windows and shutter. Typology: three identical residential flats in Italy.

Strength of evidence: Energy data: ground water supply heat, electricity, solar energy, gas is obtained as annual values per apartment. The quality of energy data is categorised as 'medium' due to the availability of separate energy data for heating and domestic hot water using separate energy meters. Occupancy, temperature setting, use of windows and shutter is monitored using sensors. Indoor conditions such as air temperature and relative humidity were also measured using data loggers. Due to the method of measurement and the parameters chosen, occupant data quality is categorized as 'high'. Normalisation: Energy consumption for heating and DHW is normalised for actual degree days. The identified causes are directly monitored using sensors. The evidence assessment is 'medium' because only 1 factor: weather is normalised for the energy consumption.

According to the addressed definition of the EPG, the identified causes should reflect the gap between predictions and actual performance not the gap between actual performance of different flats; therefore, different users. The study results display consistency between the predicted model produced during the certification procedure and the actual energy performance of the three selected flats. However, the identified causes refer to the potential variation in energy use as a result of different users.

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Assessment Study **C1T1E2**:

8. *A Comparison of projected and actual energy performance of buildings after thermal retrofit measures* (Housez, Pont, and Mahdavi 2014)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**4**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The cause is identified to be user related, which is window opening behaviour. Typology: seven retrofitted residential buildings in Austria. Five multifamily residences in Vorarlberg, the upper level of a duplex house in Lower-Austria, and a residential complex for the elderly in Styria.

Strength of evidence: Energy data including electricity, gas, oil, district heating is obtained from energy bills as annual values per building. Oil demand was documented by the inhabitants on the monthly basis. Energy data quality is assessed as 'medium'. The monitoring period was 6-months (winter season). Window opening, heating behaviour and occupancy data is obtained from interviews with 22 users. The quality of occupant data is categorised as 'medium' due to the method of data gathering. Normalisation: The energy consumption is adjusted for the monitored monthly mean indoor temperatures. Air change rate is considered higher than the energy certificate assumptions by a factor of 4-6. The share of warm water from the total heating demand was estimated based on standard values. For the final estimation of actual space heating demand, the estimated contribution of solar collector units as well as the assumed system efficiencies was taken into account. The identified cause for the EPG: window opening, is directly monitored in the interviews. The assessment of evidence is 'medium'.

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Assessment Study **C1T1E2**:

9. *A study of the impact of occupant behaviors on energy performance of building envelopes using occupants' data* (Yousefi, Gholipour, and Yan 2017)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**4**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The causes are identified to be the ventilation rate and simulation assuming all floor area conditioned, but real use omits 10%.

Typology: One multi-family residential building in Iran is investigated; eight apartments in total.

Strength of evidence: Energy data for electricity and gas is obtained from energy bills as annual values for 3 years and is categorized as 'medium'. Occupancy schedule, usage of appliances, lighting, heating and cooling appliances are monitored using interviews and field studies. Occupants' behaviour data is categorized as 'medium' because of the number of factors measured. Normalisation: Energy use is normalised for weather. Fenestration and shading geometry data; detached building shadings and parapet walls are considered. Construction characteristics, heating and cooling system specifications are obtained from the building contractor's archive. Occupancy, window opening behaviour, activity level, electric plug, gas equipment, and lighting behaviour are adjusted in the base case simulation model. The calibrated model with the real measurements minimises the gap from 90% to15%. The identified causes for use of windows and cooling behaviour are directly monitored in the interviews. The assessment of the evidence is 'medium'.

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Assessment Study **C1T1E2**:

10. *Evaluating the influence of building fabric, services and occupant related factors on the actual performance of low energy social housing dwellings in UK* (Gupta, Kapsali, and Howard 2018)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**3**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The causes are identified to be related to physical performance of the fabric, services and systems: lack of proper commissioning of MVHR and heating systems; and occupants: higher temperature demand, opening of windows in winter, and over-use of heating systems.
Typology: 6 case studies (3 developments; A, B, C) of low energy social housing dwellings in the UK, built in 2011-2012.

Strength of evidence: The quality of energy data is categorised as 'high' due to its temporal granularity; 5-min interval. The energy data is obtained per apartment from energy bills for the duration of one year and it includes gas consumption, PV solar energy consumption and electricity consumption. Occupants' data is categorised as 'high' due to the number of factors monitored: occupancy, opening and closing of doors and windows, washing and showering regimes and thermostat settings as well as indoor temperature, relative humidity and CO_2 concentration; and the method of data monitoring: sensors and self-logging activity of occupants. Normalisation: No normalisation information is mentioned. The identified causes for the EPG are directly monitored by sensors and survey. The overall assessment of the evidence in 'medium'.

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Assessment Study **C1T1E3**:

11. *Performance gap and occupant behavior–review and analysis of high-efficiency residential buildings in Germany* (Hahn et al. 2020)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	**4 ½**

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is occupant-related: temperature set-point. Typology: one multi-family new residential building with 8 apartments is examined in Germany, built in 2011.

Strength of evidence: The quality of energy data is evaluated as ‘high’ due to its data resolution: 5-min interval aggregated to annual values; and the duration of monitoring: 4 years; and the measurements of net energy for space heating, electricity, and domestic hot water. Data is obtained through research technical monitoring, values per apartment. Operational data (occupant behaviour) is categorised as ‘medium’ because it is based on surveys and not a real time measured data. Normalisation: Heating energy is adjusted for weather and location (heating degree days to same location (code is "reference location" in Germany)), square meter normalized vs. person normalized for DHW use. The identified cause was directly monitored. The overall assessment of the evidence is ‘high’.

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Assessment Study **C1T1E2**:

12. *Energy Performance gap of a nearly zero energy building (NZEB) in Denmark: The influence of occupancy modelling* (Carpino et al. 2020)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**3 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is occupancy through internal gains, interacting with systems and modified indoor conditions. Typology: one single-family residential building (nearly Zero Energy Building) is addressed in Denmark, built in 2017.

Strength of evidence: The quality of energy data is assessed as 'medium' since the data resolution is monthly values per appliance or whole building. Data for electricity consumption and district heating is monitored by power meters for the duration of 6-months. Occupancy and appliance usage is monitored using CO_2 sensor for occupancy and power meter per appliance. Indoor conditions: air temperature, humidity, ventilation speed is also monitored using sensors. The data for occupants can be assessed as 'high' due to the method of monitoring: sensors and the relevance of factors chosen which affects electricity and district heating consumption. Normalisation: heating is adjusted for real occupancy profiles, electricity for the use of appliances: lighting and equipment, ventilation and DHW. The identified cause for appliance usage is directly monitored; however, for occupancy it was concluded from the CO_2 concentration in the room. The overall assessment result is 'medium'.

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Assessment Study **C1T1E2**:

13. *Comparing the impact of presence patterns on energy demand in residential buildings using measured data and simulation models* (Cuerda et al. 2019)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**3 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes refer to the user behaviour; presence profile and its effect on the internal heat gains. Typology: two multi-family residential buildings in Spain were addressed, built in 1972.

Strength of evidence: The quality of energy data: gas consumption for heating and domestic hot water is 'high' due to its time resolution, hourly values per apartment, obtained through energy metering. Also, electricity consumption for individual appliances and electronic devices are measured. The monitoring period is one year. Occupants' data are measured for appliances use, opening window behaviour, boiler setpoints, indoor air temperature using sensors and individual energy meters. A mixed-method approach is used to develop actual occupancy profiles through interviews with the users and the measured data. The quality of data is categorised as 'medium' because of the number of factors measured and the uncertainty of data synthesis using a qualitative method. Normalisation: energy data is adjusted for weather; data is obtained from a meteorological station located within the neighbourhood. geometry data is obtained from the original architectural design team. Energy is adjusted for building constriction elements where some characteristics of the dwelling were monitored and occupant behaviour: heating and cooling, mechanical ventilation, lighting and appliances corrected based on the actual occupancy profiles. The identified cause is not directly measure but

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synthesized from energy measurements and interviews. The assessment for evidence is 'medium'.

Assessment Study **C1T1E1**:

14. *Domestic energy consumption patterns in a hot and humid climate: A multiple-case study analysis* (Aldossary 2014)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1 ½**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is the use of air conditioning by occupants. Typology: A multiple case-study analysis is carried out for three single-family houses and three typical flats built in 2011 in Saudi Arabia.

Strength of evidence: Electricity consumption is monitored for one year. The quality of energy data is 'medium' because it has a resolution of monthly data and obtained from energy bills. The study says that 'details of where this energy was consumed are vague'. Use of air conditioning is monitored through interviews of the occupants. The quality of data is 'low' because the method of monitoring is uncertain and only one factor of occupant behaviour is measured. Normalisation: the simulation model adopts the user profile obtained from the interviews (household composition, age and work status). The identified cause is directly measured by interviewing users about their use of air conditioning. The overall assessment of the evidence is 'low'.

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Assessment Study **C1T1E1**:

15. *The applicability of energy models to occupied houses: Summer electric use in Davis* (Vine 1982)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**2**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are thermostat setting, appliance use patterns, movable window shading, and air conditioner schedules. Typology: 74 single-family detached houses in Davis, California is examined.

Strength of evidence: electricity and cooling loads for a three-month cooling season (July-September, 1980) are obtained from energy bills. Energy data is evaluated as 'medium' for the data resolution of monthly values and short monitoring period. Data concerning occupant behaviour is monitored for frequency of use of household appliances and air conditioning use using interviews and surveys. Indoor conditions: air temperature is monitored using thermographs and survey. Occupant data quality is 'medium' due to the number of factors measured. Normalisation: No information about normalisation is mentioned. The study predicts the electricity use by incorporating results from a sensitivity calculation into a model of a house. The identified causes are directly monitored in the interviews. The overall assessment of evidence is 'low'.

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Assessment Study **C1T4E2**:

16. *Assessment of energy consumption in existing buildings* (Brady 2017)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**3**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is the presence of occupants. Typology: A university workshop building is investigated in the UK.

Strength of evidence: Electricity and gas consumption for space heating/cooling, hot water, lighting, equipment, small power, fans, pumps, controls and auxiliary, server rooms and lifts are obtained from utility bills for the whole campus (several buildings) as hourly values. The monitoring period is seven years. Energy data is evaluated as 'medium' due to its broad spatial granularity. Yet the monitoring period is long and the data resolution is 'high'. Occupants' behaviour is measured for occupancy and frequency of equipment use using a survey. Occupant data is evaluated as 'medium', as there are two factors measured on a long-time span. However, the method of data collection is uncertain. Normalisation: Energy consumption is normalised for weather conditions; method is not mentioned. The identified cause is directly measured in the study. The overall assessment of the evidence is 'medium'.

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Assessment Study **C1T1E2**:

17. *Energy performance evaluation of a passive house built to Scottish building standards* (Bros-Williamson, Stinson, and Currie 2015)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are occupancy, services control systems and number of appliances in the household. Typology: Two single-family new houses are studied in Scotland.

Strength of evidence: Gas and electricity consumption for space & water heating, lighting, fans, pumps & appliances are measured from energy meters per building with a time resolution of hourly values. The duration of energy monitoring is one year. Quality of energy data is evaluated as 'high'. Indoor conditions are measured for air temperature, surface temperature, air, pressure and volume flow rate of air using thermograms, sensors. Occupancy, service control systems and use of appliances data are obtained from a user survey. Occupants' data is evaluated as 'medium' because several factors are considered. Normalisation: electricity consumption is normalised for making a comparative evaluation. However, the variable normalised is not specified. Therefore, the factors normalised is set to none. The identified cause is directly measured in the survey results. The evidence evaluation is 'medium'.

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Assessment Study **C1T1E2**:

18. *Regulatory Energy calculations versus real energy use in high-performance houses* (Delghust 2015)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is the number of heated rooms. Typology: 537 high performance houses were investigated in Belgium.

Strength of evidence: Electricity and gas consumption is obtained from energy bills per buildings for a duration of one year. The resolution of data intervals is not mentioned. Energy data is evaluated as 'low'. Occupancy, heated rooms, heating hours, temperature set-points, number of baths/showers per week & duration are measured using a survey. Occupants' data is categorized as 'medium' due to the uncertain method of data collection and the number of variables measured. Normalisation: Energy use for space heating and DHW is adjusted to heating degree days. The Identified cause is directly monitored in the survey. The overall evaluation of evidence is 'medium'.

Assessment Study **C1T1E2**:

19. *Targeting 'behavers' rather than behaviours: A 'subject-oriented' approach for reducing space heating rebound effects in low energy dwellings* (Galvin 2013)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is thermostat setting and window opening. Typology: Two retrofitted residential buildings (60 apartments) were examined in Germany.

Strength of evidence: Energy consumption for space heating and domestic hot water were measured using a principal meter per apartment. The quality of data is evaluated as 'medium' because they are monthly values and a monitoring duration of one year. Occupants' behaviour is measured for window use and thermostat settings using sensors for the same monitoring period. Occupant behaviour data is categorised as 'high' because of the number of variables measured and the accuracy of the monitoring method. Normalisation: No information about normalisation mentioned. The identified cause is directly monitored. The overall evaluation of the evidence is 'medium'.

Assessment Study **C1T3E2**:

20. *A Methodology for estimating rebound effects in non-residential public service buildings: Case study of four buildings in Germany* (Grossmann et al. 2016)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are window opening, heating technique (adjustment frequency, temp setpoint). Typology: Four mixed-use retrofitted buildings were investigated in Germany.

Strength of evidence: Thermal energy is measured for space heating using on site measurements and energy metering per building for a duration of 2-5 years before & after retrofit. The energy data is evaluated as 'low' due to the data resolution. The temporal granularity of energy data is annual values. Occupancy, window opening, heating control/set-point are measured through interviews. Occupants' data is categorised as 'medium' due to the uncertainty of the monitoring method despite the number of variables measured. Normalisation: Energy consumption for space heating is adjusted for weather. The identified cause is directly measured. The overall evaluation of the evidence is 'medium'.

Assessment Study **C1T1E3**:

21. *Occupant behaviour in energy efficient dwellings: Evidence of a rebound effect* (Guerra Santin 2013)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	**4 ½**

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are use of heating system (adjustment frequency, temp setpoint) and use of ventilation system (hours of ventilation per room). Typology: 4724 Multi-family and Single-family old buildings are investigated in the Netherlands.

Strength of evidence: Gas consumption for space heating is obtained from energy providers. The data resolution is measured as hourly values per room. Energy values is evaluated as 'high' due to the data resolution. Occupants' behaviour is measured for use of heating and ventilation systems using a survey (questionnaires). Occupant behaviour is evaluated as 'medium' due to the method of data collection. Normalisation: Two factors are normalised: standard deviations from the mean are used for temp set-point, ventilation hours consider the type of ventilation with most hours (grills, windows, mechanical systems). The identified cause is directly monitored. The overall evaluation of evidence is 'high'.

Assessment Study **C1T1E1**:

22. *Meta-study of the energy performance gap in UK low energy housing* (Gupta, Howard, and Kotopouleas 2019)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	1
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is occupancy patterns. Typology: A sample of 48 – 92 single-family and multi-family buildings were investigated in the UK.

Strength of evidence: Energy consumption for space heating, water heating, ventilation systems, lighting, cooking, small appliances is measured through energy metering per apartment and per building. Energy data is evaluated as 'low' because it is annual values and the duration of monitoring is not mentioned. Occupancy schedules, occupancy type (working adults, retired, stay at home with children) is measured. The Method of data monitoring is not mentioned. Occupants' data is evaluated as 'low'. Normalisation: No normalisation took place, the calculations used fixed occupancy schedules instead of the actual occupancy patterns. The identified cause is directly monitored. The overall evaluation of evidence is 'low'.

Assessment Study **C1T1E1**:

23. *Exploring the Performance Gap in UK Homes: New Evidence from Smart Home and Smart Meter Data* (Kane et al. 2015)

Code	C	T	E
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	1 ½
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is temperature set-points. Typology: 20 single-family retrofitted buildings were examined in the UK.

Strength of evidence: Gas and electricity consumption for heating, hot water, lights and appliances are obtained through energy metering per house. Energy data is evaluated as 'low' since the monitoring period is only one month and the temporal granularity of data is not mentioned. Temperature set-points are measured using indoor sensors. Indoor and outdoor air temperature is also measured using Hobo sensors and a weather station 20 km away, respectively. Occupant behaviour data is categorised as 'medium' because of the absence of the monitoring period information despite the accuracy of the monitoring method. Normalisation: No information about normalisation is mentioned. The identified cause is directly monitored. The overall evaluation of evidence is 'low'.

Assessment Study **C1T1E1**:

24. *Occupant Interaction with As-Designed Smart Heating: Impacts upon Energy Use & Thermal Comfort* (Littlewood and Smallwood 2019)

Code	C	T	E
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	**1**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are higher temperature setpoints, interaction with smart indoor control systems. Typology: 13 multi-family and single-family residential buildings are examined in the UK.

Strength of evidence: Electricity consumption for heating and hot water is measured using power meters per building. Monitoring period is one year; however, time intervals of data is not mentioned, therefore energy data is evaluated as 'low'. Window opening and temperature set-point is measured. The method of data measurement is not mentioned; therefore, the quality of occupant behaviour data is categorised as 'low'. Normalisation: no information about normalisation of variables is mentioned. The identified cause is directly monitored. The evidence for the EPG is evaluated as 'low'.

Assessment Study **C1T3E2**:

25. *Statistical model of the heating prediction gap in Dutch dwellings: Relative importance of building, household and behavioral characteristics* (Majcen 2015)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2** ½
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

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Assessment summary:

Candidate causes of the EPG: The identified causes are occupancy, temperature setpoints, number of taking showers. Typology: Two data sets were investigated in this study: dataset 1: 4800, dataset 2: 460, consists of mixed-use buildings in the Netherlands.

Strength of evidence: Gas consumption for space heating and domestic hot water data is obtained from energy bills for one year per apartment/building as annual values; therefore, energy data is evaluated as 'low'. Occupancy, heating and ventilation practices, showering as well as occupants' characteristics: number, age of occupants, ability to pay energy bill is obtained from a survey. Occupant's data is categorised as 'medium' because of the number of factors measured despite the uncertainty of the data source. Normalisation: Gas consumption is normalised for degree days. The identified causes are directly measured. The overall evidence evaluation is 'medium'.

Assessment Study **C1T2E2**:

26. *Eight-month experimental study of energy impact of integrated control of sun shading and lighting system based on HDR vision sensor* (Motamed, Deschamps, and Scartezzini 2019)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**4**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes relate to the control behaviour of lighting and blinds position. Typology: two non-residential office buildings were investigated in Switzerland.

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Strength of evidence: Electric lighting energy consumption for dynamic shading & artificial lighting is measured using energy metering per room. The data resolution has hourly values for the duration of six months. Energy data is evaluated as 'high' also due to measuring a specific type of energy consumption for a specific use. Occupancy, blinds position, electric lighting behaviour is monitored using sensors for the same duration; indoor conditions: air temperature, illuminance, luminance is monitored using sensors. Occupants' data is evaluated as 'high'. Normalisation: electrical lighting consumption is normalised by considering the impact of different occupancy rates. The identified cause is directly monitored. The overall evidence evaluation is 'medium'.

Assessment Study **C1T2E1**:

27. *Post-occupancy performance of five low-energy schools in the UK* (Pegg, Cripps, and Kolokotroni 2007)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are lighting and Heat ventilation air conditioning (HVAC) usage outside of core occupancy hours. Typology: Five non-residential educational buildings were examined in the UK.

Strength of evidence: Electricity and gas consumption is measured using principal meter. Data are collected per building with a time interval of 30-min. Energy data is evaluated as 'medium' because the duration of monitoring is short and potential errors in data correction. The logging took place for 1320 consecutive hours (55

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days), and the results from the sample have been scaled to represent a full year. Occupant behaviour is measured for lighting control: on/off status using observations and sensors (e.g., lighting control sensors). Despite using multiple methods with high certainty for collecting occupant data but it is evaluated as 'medium' because of the short monitoring period. Normalisation: No data about normalisation is mentioned. The identified cause is directly monitored for the use of lighting but not for the use of the HVAC systems outside of core occupancy. The overall evidence evaluation is 'low'.

Assessment Study **C1T2E2**:

28. *A case study: The energy performance gap of the center for interactive research on sustainability at the University of British Columbia* (Salehi 2015)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is occupancy. Typology: one newly built educational building is examined in Canada.

Strength of evidence: Electricity for heating, cooling, fans, pumps, lighting and equipment is measured using power meters per room. The quality of data is evaluated as 'medium' as the data resolution has a monthly time interval and the monitoring period is one year. Occupancy, window status, temperature set-points are measured using sensors. Indoor conditions: air temperature, setpoints, CO_2, total Volatile Organic Compounds (tVOC) are monitored using sensors as well for the same duration. Occupants' data is categorised as 'high' because more than one variable is measured and the certainty of the data collection method. Normalisation:

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No information about normalisation is mentioned. The identified causes of the EPG are directly monitored. The overall evaluation of evidence is ‘medium’.

Assessment Study **C1T1E2**:

29. *Apartment related energy performance gap–how to address internal heat transfers in multi-apartment buildings* (Moeller et al. 2020)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**4**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are indoor temperatures, window opening rate (low or high ventilation rate). Typology: 6 new residential buildings (8 apartments each) built in 2010, in Munich, Germany.

Strength of evidence: Thermal energy for heating, domestic hot water is measured using energy metering per apartment/building with a temporal granularity of monthly values. The monitoring period is one year. Energy data is evaluated as ‘medium’. Occupant behaviour is measured for the frequency of window opening using sensors. Indoor conditions: air temperature is measured using sensors. Occupants’ data is evaluated as ‘medium’ because only one variable is measured despite the certainty of the method of data collection. Normalisation: heating energy is normalised for weather and adjusted for additional component from domestic hot water (60% losses). The identified causes for the EPG is directly monitored. The evidence evaluation is ‘medium’.

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Assessment Study **C1T2E2**:

30. *Building energy model calibration with schedules derived from electricity use data* (Kim et al. 2017)

Code	C	T	E
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**3**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is occupancy. Typology: Three non-residential (office, education) retrofitted buildings are examined in Philadelphia and University Park, PA, USA.

Strength of evidence: electricity consumption is measured using energy metering per building with a data resolution of 15-min time interval. The duration of monitoring is 10 months. Therefore, energy data is evaluated as 'high'. Occupancy patterns data is obtained from IR and video-based sensors for the same monitoring period. Occupants' data is evaluated as 'high' because of the using two methods of data collection, both have high certainty. Normalisation: No information about normalisation is mentioned. The identified cause of the EPG is directly monitored. The evidence evaluation is 'medium'.

Assessment Study **C1T3E1**:

31. *Mind the Gap: Studying actual versus predicted performance of green buildings in Canada* (Mallory-Hill and Gorgolewski 2018)

Code	C	T	E
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

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Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	**1**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is occupancy. Typology: 9 newly built mixed-use buildings are addressed in Canada.

Strength of evidence: Electricity consumption for heating/cooling, lighting, ventilation is obtained from utility bills per building as annual values. Therefore, energy data is evaluated as 'low'. Occupancy data is collected using a survey. Occupants' data is categorised as 'low' because only one variable is monitored and the method has high uncertainty. Normalisation: no information about normalisation is identified. The identified cause of the EPG is directly monitored. The general assessment of the evidence is 'low'.

Assessment Study **C1T1E2**:

32. *The influence of user behaviour on energy use in old dwellings: Case-study analysis of a social housing neighbourhood* (Delghust et al. 2012)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								Assessment	
Quality of data				Normalisation coverage		Variable match (cause vs measurement)			
Energy		Occupants							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

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Assessment summary:

Candidate causes of the EPG: The identified causes are occupancy, use of heating devices (set point temperatures and daily heating periods) and window opening.
Typology: 36 single-family residential buildings, built in the 1960s are addressed in Belgium.

Strength of evidence: gas consumption for heating is obtained using energy metering as annual values per room. Energy data is evaluated as 'low'. Occupancy is measured using surveys, household compositions (gender & age), employment is included as well. Indoor conditions: heat flux, air tightness, CO_2, air temperature, relative humidity is measured using sensors. Occupants' data is evaluated as 'medium' because several methods of data collection is included and several variables are measured. Normalisation: gas consumption is adjusted to heating degree days. The values for set-point temperatures are deducted from the average point of stabilization of the indoor temperature during occupancy. The identified causes are directly monitored only for occupancy. The use of heating devices and window opening are monitored using indirect measures: CO_2 concentration and indoor air temperature. The overall evaluation of evidence is 'medium'.

Assessment Study **C1T4E2**:

33. *Optimizing the performance of energy-intensive commercial buildings: Occupancy-focused data collection and analysis approach* (Azar and Menassa 2016)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

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Assessment summary:

Candidate causes of the EPG: The identified causes are occupancy, lighting and equipment afterhours/unoccupied use patterns. Typology: One non-residential building, built in 2010 is examined in Madison, WI, USA.

Strength of evidence: Energy consumption measurements for HVAC, lighting, and equipment are obtained through energy metering per room, with a data resolution of 15-min for the duration of one year. Energy data is evaluated as 'medium' because the data resolution is high for spatial and temporal granularity. Yet, different types of energy: electricity/thermal is not measured separately. Occupancy and equipment usage is measured using sensors. Occupants' data is evaluated as 'high', because more than one variable is monitored and the method of monitoring is highly certain. Normalisation: No information about normalisation is included. The identified causes are directly monitored. The overall evidence evaluation is 'medium'.

Assessment Study **C1T2E1**:

34. *Quantifying the underlying causes of a discrepancy between predicted and measured energy use* (van Dronkelaar et al. 2019)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1 ½**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are occupancy, equipment power density, heating and cooling set-points. Typology: Four non-residential university and office buildings are examined in London, UK.

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Strength of evidence: Gas and electricity consumption for lighting, equipment, heating and cooling, plug loads is measured using energy metering. Data is gathered separately for each energy type per floor as hourly values. Energy data is evaluated as 'high'. Occupancy is monitored using swipe card & WIFI data. Occupants' data is categorised as 'medium' because only one variable is measured. Normalisation: no information about normalisation is mentioned. The identified cause is directly monitored for occupancy data only, equipment power density, heating and cooling set-points is not directly monitored. The overall evaluation of evidence is 'low'.

Assessment Study **C1T2E1**:

35. *Buildings energy consumption generation gap: A Post-occupancy assessment in a case study of three higher education buildings* (Bourdeau, Guo, and Nefzaoui 2018)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1 ½**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is occupancy. Typology: 5 non-residential educational buildings, built in 1987-1997 are examined in France.

Strength of evidence: Electricity and gas consumption is monitored for specific & non-specific electricity uses, heating using energy bills and built-in smart meters. Data is obtained as annual to 10-min interval values. Energy data is evaluated as 'medium' because data is measured for separate energy types, yet values are obtained per building. Occupancy data is obtained using course schedules with absence factor. Occupants' data is evaluated as 'low' because no real-time

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measured occupancy took place. Normalisation: Energy consumption is adjusted for Heating degree days. The identified cause of the EPG is not directly monitored for occupancy. Instead, course schedules. The overall evidence assessment is 'low'.

Assessment Study **C1T1E1**:

36. *Usability of the EPC tools for the profitability calculation of a retrofitting in a residential building* (Caceres and Diaz 2018)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**0**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is heating set-point. Typology: One residential building, built in 1987 is examined in Norway.

Strength of evidence: Energy consumption for heating is obtained through site inspection, per room as annual values. Energy data is categorised as 'low', since the observation period is not specified and the temporal granularity is annual values. Occupancy is monitored using site inspection and surveys. Indoor conditions: lighting and equipment were measured but the method of monitoring is not specified. The quality of occupants' data is evaluated as 'low' because only one variable is measured, the method of monitoring is not certain, and the duration of monitoring is not specified. Normalisation: No information about normalisation is included. The identified cause: heating set-point is not directly monitored, instead occupancy. The overall evaluation of evidence is 'low'.

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Assessment Study **C1T1E1**:

37. *Understanding the performance gap in energy retrofitting: Measured input data for adjusting building simulation models* (Cuerda et al. 2020)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are the control of heating and cooling, and window opening behaviour. Typology: Two multi-family residential buildings: one retrofitted and one is an existing building, built in 1972, are investigated in Madrid, Spain.

Strength of evidence: Electricity consumption for heating & cooling is measured using energy metering per apartment with a time step of hourly values. Energy data is categorised as 'high' for its spatial and temporal granularity on the duration of one year. Use of heating boiler (on/off) and window opening is measured using a questionnaire; actual occupancy data is compiled from the electric energy consumption timetable of electric devices which do not have continuous consumption (e.g., the fridge) from which the occupancy presence schedules are obtained. Indoor conditions: air temperature and humidity are monitored using sensors. Occupants' data is categorised as 'medium' due to the uncertainty of the monitoring methods. Normalisation: no information about normalisation is mentioned. The identified causes of the EPG are directly monitored. The evidence evaluation is 'medium'.

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Assessment Study **C1T2E1**:

38. *Energy Performance certification of faculty buildings in Spain: The gap between estimated and real energy consumption* (Herrando et al. 2016)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**0**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are occupancy and office equipment outside operating hours. Typology: 21 existing office buildings, built or refurbished between 1990-2013 are examined in Spain.

Strength of evidence: Electricity and gas consumption is measured for space heating, cooling, lighting, hot water, appliances, IT, laboratories. Energy data is obtained from energy bills per building as annual values. The monitoring period is not identified, data is evaluated as 'low' due to the data resolution. Occupants' behaviour is measured for office equipment operation (on/off) when not in use through site visits and informal user interviews. Data is evaluated as 'low' due to the uncertainty of the monitoring method and the number of variables measured for occupant behaviour: one variable. Normalisation: No information about normalisation is identified. The identified cause is directly monitored only for office equipment use, but occupancy data is concluded and not directly measured. The overall evidence evaluation is 'low'.

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Assessment Study **C1T1E1**:

39. *Energy evaluation of residential buildings: Performance gap analysis incorporating uncertainties in the evaluation methods* (Allard, Olofsson, and Nair 2018)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is occupancy. Typology: one single-family existing residential building is investigated in Umeå, Sweden.

Strength of evidence: Energy consumption for heating is measured per building with time intervals of daily values. Energy data is evaluated as 'low' because the source of data and the type of energy monitored is not identified. The duration of monitoring is only 2 months. Occupancy data is measured using observations. Indoor conditions: air temperature is also measured, but the method of measurement is not identified. Occupants' data is categorized as 'low' due to the uncertainty of the source of data. Normalisation: No information about normalisation of energy is mentioned. The identified cause is directly monitored. The overall evidence evaluation is 'low'.

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Assessment Study **C1T1E2**:

40. *Energy Performance gap in refurbished German dwellings: Lesson learned from a field test* (Calì et al. 2016)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**3**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are window opening, indoor temp set-point and higher domestic hot water temperature. Typology: Three multi-family retrofitted buildings (each 30 apartments), built in the 1950s, are investigated in Germany.

Strength of evidence: Energy consumption: electricity, gas, district heating is measured for heating and domestic hot water using energy metering per apartment. Data resolution is monthly values. The observation period is three years, Energy data is categorised as 'high'. Occupancy data, light on the ceiling (Lux), Infrared/visible light ratio (to recognize the light source), window opening (open/closed) is measured using sensors. Indoor conditions: air temperature relative humidity, CO_2, volatile organic compounds (VOC) is also monitored using sensors. Occupants' data is categorised as 'high' because more than one variable of OB is monitored and the method of data collection has high certainty. Normalisation: Indoor air temperature is corrected by - 2.5 Kelvin. The identified causes are directly monitored for occupancy; However, indoor temp set-point is indirectly obtained from the air temperature and the district heating energy measurements, same for domestic hot water temperature. The overall evidence evaluation is 'medium'.

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Assessment Study **C1T2E1**:

41. *ObepME: An online building energy performance monitoring and evaluation tool to reduce energy performance gaps* (Jradi et al. 2018)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**2**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are occupancy and energy systems set-points. Typology: New non-residential educational building, built in 2015 is investigated in Odense, Denmark.

Strength of evidence: Energy consumption for ventilation, heating and lighting is monitored using energy metering. Data resolution is measured per building as monthly values. The energy data is evaluated as 'low' because of the data resolution and the monitoring period is only 3 months. Occupancy is monitored using cameras. Indoor conditions: Air temperature, humidity, CO_2, illuminance, radiator valve position, ventilation damper position, blinds position and multiple temperature and pressure along the energy supply scheme, are measured using sensors. Occupants' data is evaluated as 'high' because more than one occupant-related variables measured and the high certainty of the source of data. Normalisation: No information about normalisation is included. The identified causes of the EPG are directly monitored. The overall evaluation of evidence is 'low'.

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Assessment Study **C1T2E2**:

42. *Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap* (Menezes et al. 2012)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**3**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are lighting and equipment use. Typology: A new office building is investigated in London, UK.

Strength of evidence: Electricity consumption for lighting and appliances are measured using energy metering. The energy data is evaluated as 'high' due to the data resolution: spatial granularity per floor/certain appliances, temporal granularity as half-hourly values. Occupants' data is measured for the use of appliances & equipment, and occupancy using sensors. Data is categorised as 'high' because of the certainty of the monitoring method and that more than one occupant-related variable is measured. Normalisation: No information about normalisation is included. The identified causes are directly measured. The overall evaluation of evidence is 'medium'.

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Assessment Study **C1T1E1**:

43. *Improving the energy performance certificate recommendations' accuracy for residential building through simple measurements of key inputs* (Gonzalez-Caceres et al. 2019)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1 ½**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is heating set-point. Typology: One residential building, built in 1987, is investigated in Norway.

Strength of evidence: electricity consumption for space heating is measured using energy metering. Data is monitored per building with an hourly time interval. The observation period is one year. The quality of energy data is 'medium' because the temporal granularity is high and the data is measured for a specific type of energy for a specific purpose. Heating set point is monitored using visual inspection. Indoor conditions: air temperature, mechanical ventilation rate is monitored using sensors. Occupants' data is categorised as 'low' because only one variable is measured and the source of data is not certain, since no data is provided on how often those visual inspections took place and how many times. Normalisation: no information about normalisation of data is included. The identified cause is directly measured for heating set-point. The overall quality of evidence is 'low'.

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Assessment Study **C1T1E1**:

44. *Evaluating the 'as-built' performance of an eco-housing development in the UK* (Gupta and Kapsali 2016)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes relate to usability of controls: temperature set-point, misuse of heating system, lack of understanding of operation of heating and ventilation systems. Typology: 23 multi-family new buildings, built in 2012 are examined in the UK.

Strength of evidence: electricity consumption for heating, ventilation, lighting, appliances and cooking are measured using Ewgeco energy monitoring devices. Data is categorised as 'medium' since the data resolution is measured per room as monthly values for the duration of one year. Operation of thermostats data is monitored using surveys and interviews. Indoor conditions: air temperature, relative humidity and CO_2 are measured wirelessly from a data-hub. Occupants' data is evaluated as 'medium' as only one variable of OB is measured, however the air temperature is measured using sensors which can reflect – to an extent – the temperature set-point data collected from the surveys, this acts as a further confirmation to the data. Normalisation: no data about normalisation is included. The identified cause is directly measured for the temperature set-points, but the misuse of heating system and lack of understanding of operation of heating and ventilation systems is concluded as further reasons of the occupant-related EPG. The overall assessment of evidence is 'low'.

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Assessment Study **C1T2E2**:

45. *Comparative building performance evaluation of a 'sustainable' community centre and a public library building* (Gupta, Kapsali, and Gregg 2017)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are occupants' use of the building controls: e.g., window opening, temperature controls, ventilation controls, lighting. Typology: two non-residential new buildings: library and a community centre, built in 2009, 2008 are investigated in the UK.

Strength of evidence: electricity, biomass, solar energy and gas consumption are monitored using energy metering and Ewgeco energy monitoring devices. Data is collected per building with a data resolution of 5-min for the duration of one year. Despite the high time resolution, data is evaluated as 'medium' because of the low spatial granularity. Occupancy, window opening, temperature controls, ventilation controls and lighting are monitored through sensors and questionnaires. Indoor conditions: air temperature, relative humidity and CO_2 are measured using sensors. Occupants' data is categorised as 'high' because more than one variable of OB is monitored and several methods of data collection are included. Normalisation: no information is included regarding normalisation. The identified causes of the EPG are directly measured. The overall evaluation of evidence is 'medium'.

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Assessment Study **C1T1E1**:

46. *Realisation of energy performance targets of an old apartment building renovated to NZEB* (Hamburg et al. 2020)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are occupancy, higher indoor temperature, supply air temperature, window airing, and higher ventilation airflow rates, higher DHW consumption. Typology: One multi-family retrofitted building, built in 1986, is investigated in Estonia.

Strength of evidence: electricity and district heating consumption are measured using energy metering. Data is obtained on the apartment level as annual values for the duration of one year. The quality of energy data is categorised as 'low'. Occupants' data is obtained for occupancy; indoor conditions: air temperature and ventilation air flow are also measured, but the data source is not included. Therefore, occupants' data quality is categorised as 'low'. Normalisation: no information about normalisation is included. The identified causes for the EPG are directly measured. The overall assessment of the strength of evidence is 'low'.

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Assessment Study **C1T1E2**:

47. *Consumer behavior in energy-efficient homes: The limited merits of energy performance ratings as benchmarks* (Heesen 2018)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**3 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are indoor temperature and opening windows. Typology: 60 multi-family retrofitted buildings are investigated in Germany.

Strength of evidence: Energy consumption for space heating is measured using energy metering. Data is obtained per apartment as monthly values. The quality of energy data is evaluated as ‘medium’ because the duration of monitoring is only 6-months. Window opening is monitored using sensors. Indoor conditions are measured for carbon dioxide concentration. room humidity, air temperature, volatile organic compounds. Occupants’ data is evaluated as ‘high’ due to the certainty of the monitoring method. Normalisation: heating energy consumption is adjusted for weather conditions. The identified causes are directly monitored for the window opening behaviour and the indoor temperature. The overall evaluation of evidence is ‘medium’.

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Assessment Study **C1T2E1**:

48. *Building performance evaluation: Balancing energy and indoor environmental quality in a UK school building* (Jain et al. 2020)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1 ½**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is occupancy beyond regular hours. Typology: eight educational buildings: new and retrofitted are investigated in London, UK.

Strength of evidence: electricity and gas consumption are measured for space heating, lights, small power, lifts, server, pumps and fans. Data are collected using energy metering per building; temporal granularity of 30-min for electricity and monthly values for gas. The quality of energy data is assessed as 'high' because of the high data resolution and an observation period of 3 years. Occupancy patterns is obtained from weekly schedules. Indoor conditions are measured for air temperature, relative humidity, CO_2, VOCs, reverberation time and illuminance using sensors. The quality of occupants' data is categorised as 'medium' because the method of monitoring occupancy is not certain. Normalisation: no information about normalisation is included. Illuminance is measured using sensors which can be an uncertain way to strengthen the occupancy patterns obtained from the weekly schedules. yet in both cases the identified cause: occupancy, is not directly monitored. The overall evidence evaluation is 'low'.

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Assessment Study **C1T3E2**:

49. *Energy monitoring of a low temperature heating and cooling district network* (Vetterli, Sulzer, and Menti 2017)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	
Medium	½	Medium	½	1 factor	1	No	0	Medium	**2 ½**
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are higher set point temperature and windows operation for ventilation. Typology: One newly built district, 2012-2013 is investigated in Switzerland.

Strength of evidence: energy consumption for heating: space heating, domestic hot water, electric demand: operation of heat pumps, circulating pumps, auxiliaries, is measured, the source of data is not included as it was not part of the current study. Data has a resolution of 15-min time interval over 5-years observation period. The quality of the energy data is evaluated as 'medium' since the data is not directly measured in the study. Temperature setpoints and operation of the ventilation system are monitored through observations. Indoor temperature is measured, method is not identified. The quality of occupants' data is evaluated as 'low' because no detailed information is provided for the method of observation and how often data points is recorded. Normalisation: energy consumption is adjusted for weather conditions. The identified causes are directly measured for temperature set-points and window opening. The overall evaluation of evidence is 'medium'.

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Assessment Study **C1T1E1**:

50. *Occupants' behavior and activity patterns influencing the energy consumption in the Kuwaiti residences* (Al-Mumin et al 2003)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1 ½**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is the use of lights and appliances.

Typology: 30 single-family buildings are examined in Kuwait.

Strength of evidence: electricity consumption measurements for lighting, appliances, hot water and air conditioning is obtained from a survey per building. Energy data is evaluated as 'low' because of the uncertainty of the data source and the duration of monitoring is not explicitly mentioned. Occupancy patterns, occupant activity, operation of lighting and appliances, hot water and air conditioning is measured using a survey. Data is categorised as 'medium' due to the number of variables measured. Normalisation: no information is included for normalisation. The identified causes for the EPG are directly measured for the use of lighting and appliances. The evidence assessment result is 'low'.

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Assessment Study **C1T2E1**:

51. *Calculating the lighting performance gap in higher education classrooms* (van Someren, Beaman, and Shao 2018)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**2**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified cause is light operational hours outside occupancy hours. Typology: 13 classrooms in 3 retrofitted buildings are examined in the UK.

Strength of evidence: electricity consumption for lighting is measured per room using energy metering. The quality of energy data is assessed as 'low' because the time resolution is not included and the observation period is only 6 months. Occupancy and illuminance measurements is collected from Sensors: photocells and absence detection. Occupants' data is evaluated as 'high' because of the certainty of the data source and the interdependence of the two variables measured: occupancy can - to a large extent - confirm illuminance data and vice versa. Normalisation: no information about normalisation is included. The identified causes are directly measured for both occupancy and lighting use. The overall evaluation of evidence is 'low'.

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Assessment Study **C1T1E1**:

52. *The building performance gap: Are modellers literate?* (Imam, Coley, and Walker 2017)

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial/Offices	Medium
3	Building systems	Mixed-use	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Strength of evidence assessment								**Assessment**	
Quality of data				**Normalisation coverage**		**Variable match (cause vs measurement)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	**1**
Medium	½	Medium	½	1 factor	1	No	0	Medium	
High	1	High	1	2 or more factors	2	Yes	1	High	

½: Half point; 1: Full point

Assessment summary:

Candidate causes of the EPG: The identified causes are temperature set-point, occupancy schedules, internal gains from appliances and lighting, and external door opening. Typology: one multi-family retrofitted building is investigated in the UK.

Strength of evidence: electricity and gas consumption for heating is measured on building level. The duration of monitoring is one year, data is obtained as hourly values. Energy measurements is evaluated as 'medium' because the source of data is not identified. Indoor temperature set-point and occupancy data is obtained from a survey. Occupants' data is categorised as 'medium' because the method of data monitoring is not certain. Normalisation: no information about normalisation is included. The identified causes are directly monitored for temperature set-point and occupancy schedules. However, internal gains from appliances and lighting, and external door opening is not directly measured. The overall assessment of evidence' strength is 'low'.

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3.2 General assessment

3.2.1 Overview

The reviewed studies examine the role of occupants in the EPG through several approaches. Hence, it is necessary to clearly explain the ones relevant to the present work. The studies include - but not limited to - one or more of the following:

1. A comparison between predicted energy demand and actual energy use. Predictions are carried out using either simple calculation methods or dynamic simulation models. The source of energy and occupant' model assumptions are usually standard values. In some cases, it can be based on databases of energy use and actual occupancy schedules using surveys if the building is already existing.

2. A comparison between actual energy data of similar spatial units (e.g., apartments) with different occupants. OB is likely to differ. If different occupants showed similar energy use to each other within one unit, but different across different 'similar' units, then it can be concluded that OB is not the reason for the EPG (Sonderegger, 1978). 3. A comparison between actual energy data for a single apartment with different occupants at different times, in order to determine a range for user profiles: high, medium and low energy use.

4. Sensitivity analysis to examine the predictive capability of different variable inputs (e.g., occupancy, ventilation rate) on the energy demand.

5. Assessment of occupants' assumptions used in energy prediction models (e.g., qualitative insights about OB through surveys). This aims to determine a good representation of the occupant real behaviour to optimise model assumptions.

6. Assessment of different calculation methods for energy and OB predictions (e.g., dynamic vs static method).

7. A comparison between normalisation approaches and the associated effect on the total energy demand. In the present work, the EPG is described as the difference in energy magnitude between predicted and actual energy use with a specific focus on the contribution of occupants' behaviour. Therefore, studies include only comparisons between: actual energy use of similar apartments with different occupants, or comparing multiple prediction scenarios, were discarded.

3.2.2 Location distribution and typology of buildings

The reviewed articles exhibit a diversity in locations with different weather conditions and building standards. Nevertheless, the majority of studies still pertain to Europe

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(78%), followed by the USA, Canada, China and Australia. According to the present literature search (144 articles), most studies investigating the EPG were carried out in western countries. Few studies were conducted in Pakistan, Saudi Arabia, Kuwait and South Africa (Mahdavi et al., 2021). In the selected sample of studies (52 articles), the dominating typologies of buildings are residential (64%) and office buildings (25%). The remaining (11%) are distributed among mixed use and other typologies.

3.2.3 Identified causes of the EPG

The majority of studies reported OB as the major cause of the EPG (98%), presented in the form of the identified code 'C1' (*Table 5*). Few studies documented building physical characteristics (e.g., Installation of systems, envelope characteristics) as one of the reasons of the EPG. One study identified building characteristics (e.g., insulation, age of the building, the presence of a bath, the presence of a thermostat, dwelling size and number of rooms) as the major cause for the EPG (42%), in comparison to OB contribution (4.2%) (Guerra Santin et al. 2009). It is worth mentioning that the overall evidence assessment of this study is 'low' (1.5 points). The identified causes of the EPG can be summarised as follows: presence of occupants, temperature set-points, operation of windows, use of shades, number of heated rooms, use of equipment and building physical characteristics. The majority of studies identify more than one OB actions causing the occupant-related gap. 20% of the studies documents a single OB factor, mostly occupancy or equipment use (Table 4). Temperature set-point (58%) and equipment use (52%) are the most frequent occupant actions identified, followed by occupancy (44%), window opening (33%), use of blinds (8%) and number of heated rooms (6%).

Table 4 Identified causes of the EPG

Ref. nr	Occupants-related						Building envelope
	Occupancy	Set-point temperature	Window opening	Use of Shades	Nr. of heated rooms	Equipment use	
1	x	x	x	x			
2		x	x				
3						x	
4		x				x	x
5	x	x			x		x
6	x	x	x		x	x	
7	x	x	x	x			
8			x				
9						x	

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10		x	x			x	x
11		x					
12	x	x				x	
13	x						
14						x	
15		x		x		x	
16	x						
17	x					x	
18					x		
19		x	x				
20		x	x			x	
21		x				x	
22	x						
23		x					
24		x				x	
25	x	x				x	
26				x		x	
27						x	
28	x						
29		x	x				
30	x						
31	x						
32	x	x	x			x	
33	x					x	
34	x	x				x	
35	x						
36		x					
37		x	x			x	
38	x					x	
39	x						
40		x	x				
41	x	x					
42						x	
43		x					
44		x				x	
45		x	x			x	
46	x	x	x			x	
47		x	x				
48	x						
49		x	x				
50						x	
51						x	
52	x	x	x			x	

Equipment use is further represented by its end-use: lighting, appliances, heating, ventilation and air conditioning. A comparison was made between different end-uses of the equipment (Figure 2). A small variation is observed. Heating is the most common end-use (41%). Ventilation and air conditioning were the least identified end-use (26%).

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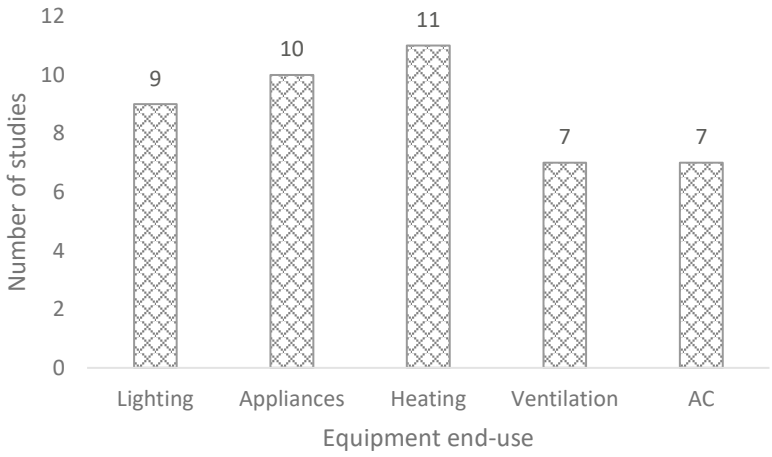

Figure 2 Distribution of studies with regard to equipment end-use

3.2.4 Energy and occupant data

There are several methods used to measure energy and occupants' data. In the majority of studies, energy data is obtained from energy meters or utility bills. Few studies carried out a site inspection, interviews with occupants or used energy auditing equipment to obtain energy data. Some studies used a combination of the above-mentioned methods for a higher data credibility. The most common energy types measured were electricity, natural gas and district heating. In some studies, it was possible to obtain separate energy data for different types using separate energy meters. The duration of monitoring ranged between 3 months to 5 years. On average, it was one year. The data resolution for energy was mostly per building, apartment or room. Few studies measured energy data on the scale of appliances, floor and several buildings (Figure 3). Time resolution for energy data ranged from annual values to 5-min intervals. Annual values are the most common (33%), followed by hourly and sub-hourly (29%), and monthly values (21%). Few studies had a data resolution of 5-min to 10-min interval. Only two studies documented daily and weekly values for energy measurements (Figure 4). The assessment of energy data for all studies is distributed as follows: 'low' (37%), 'medium' (38%), and 'high' (25%) (*Table 5*).

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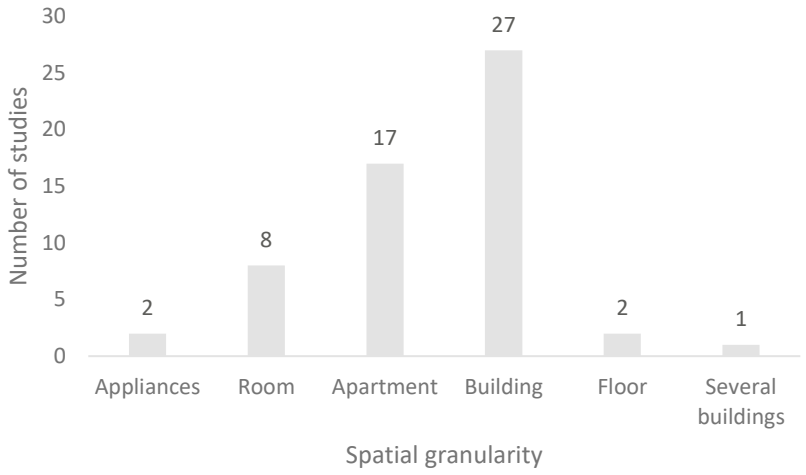

Figure 3 Distribution of studies with regard to the resolution of energy data (Space)

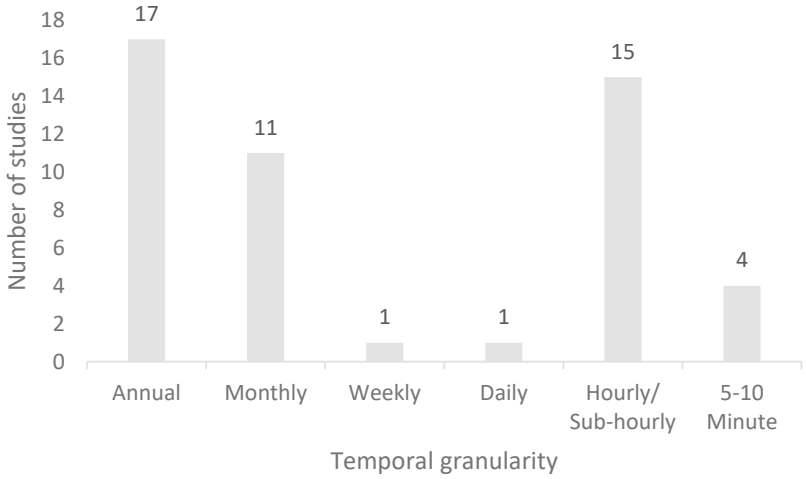

Figure 4 Distribution of studies with regard to the resolution of energy data (Time)

Occupants' data displays more variety in sources compared to energy data. Sensors (e.g., absence detection, lighting control) were the dominant method used for gathering OB data in the selected sample (38%). Almost the same number of studies used survey questionnaire (37%). Fewer studies used site inspection observations (15%), Interviews (12%) and occupancy time schedules (6%) (Figure 5). In a number of studies (23%), two or more methods of data collection were used to achieve a higher certainty of occupants' data. In the majority of studies, the identified causes correspond to the variables measured. Therefore, the distribution of the identified causes (Table 4) can represent the distribution of the OB variables measured (Figure 6). The assessment of occupants' data is distributed as follows: 'low' (11%), 'medium' (50%), and 'high' (29%) (*Table 5*).

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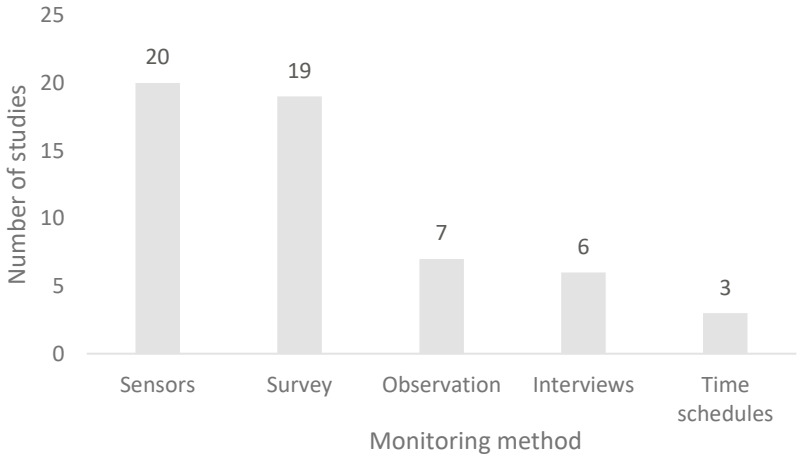

Figure 5 Distribution of occupants' data collection methods

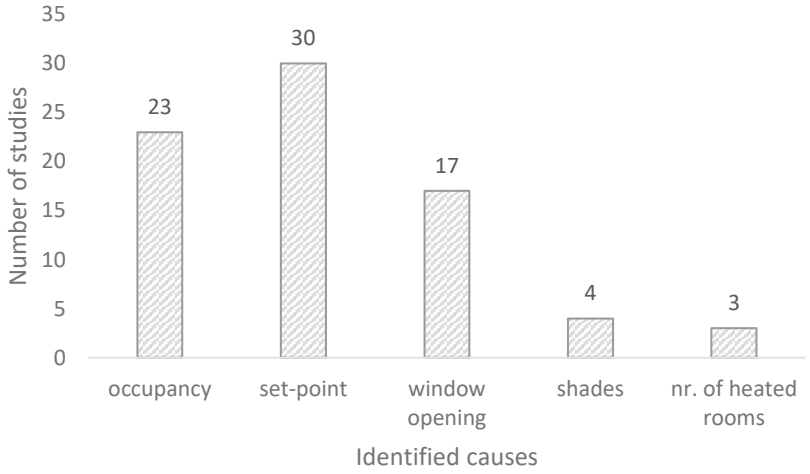

Figure 6 Distribution of the occupant-related measured variables

3.2.5 Normalisation

There is no single definition of the term normalisation. Thus, it is necessary to clarify what is meant by normalisation in the addressed context. In order to make a valid comparison between the predicted energy demand and the actual energy use, normalisation of energy consumption is necessary. The aim of normalisation is to separate the influence of the assumed cause on the EPG, which in this case is OB. It includes the actual contribution of all other potential causes (e.g., weather, construction) in the energy calculations (Mahdavi et al., 2021). In the present assessment, the quality of normalisation is measured based on the number of variables included. The most common is weather (21%). It is mostly carried out by adjusting the number of heating/cooling degree days, which are calculated from the actual weather data and accordingly the energy use is modified. Some studies

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consider variables like temperature set-point (Delghust et al. 2012; Guerra Santin 2013) and ventilation hours (O. Guerra Santin, 2013). Only 20% of the reviewed studies normalised energy consumption for 2 or more variables. While 60% did not include data about normalisation (*Table 5*).

3.2.6 Evidence assessment

The evaluation of evidence is presented in two forms. First, the numerical value per study: from 0 to 4.5 points (*Table 5*). Second, the general qualitative assessment of 'low', 'medium', and 'high' presented in each study' assessment (section 3.1) (Figure 7). Only 6% of the reviewed studies are assessed to have a 'high' quality of evidence (4.5 points). No study earned the full 5 points. 42% of the selected articles were evaluated as 'low', from which two studies had a numerical value of 0 points. The most frequent numerical evidence assessment is 2.5 points (52%) (Figure 8).

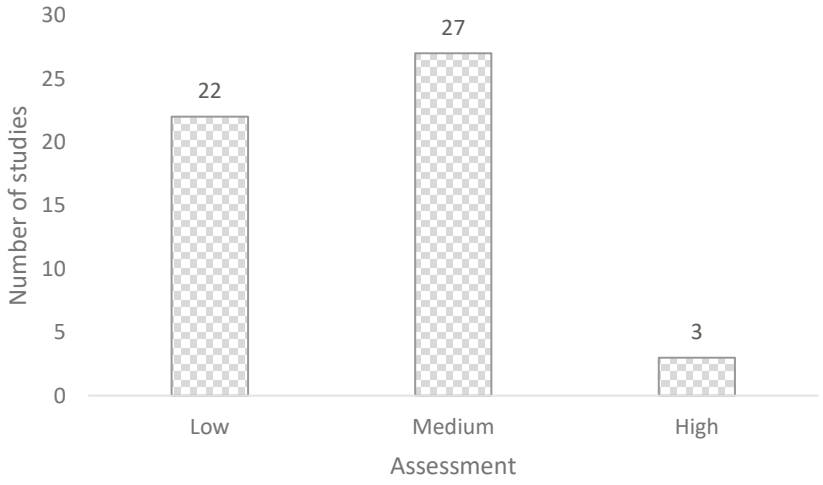

Figure 7 Distribution of the qualitative evidence assessment

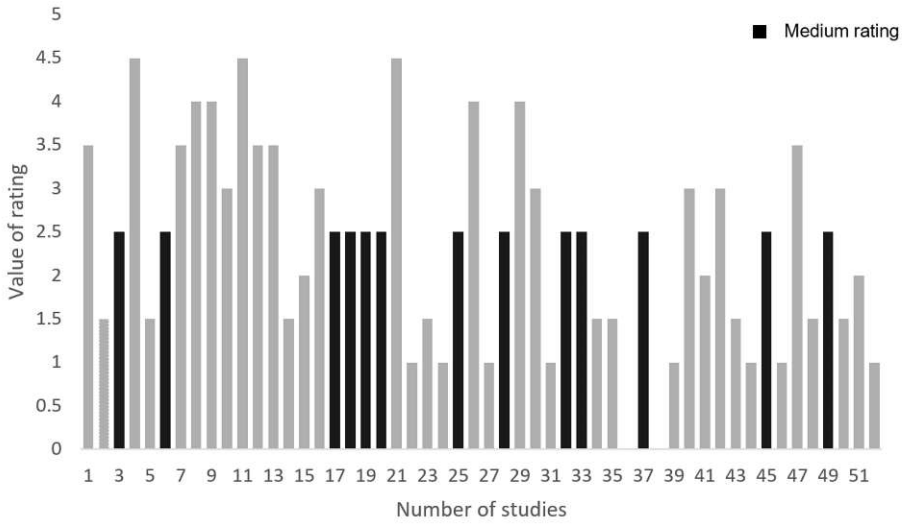

Figure 8 Numerical assessment of evidence

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Table 5 Assessment of studies

Ref. nr.	Code	Quality of data		Normalisation coverage (nr. of factors)	Variable match (cause vs measurement)	Assessment (Numerical value)
		Energy	Occupants			
1	C1T1E2	Low	Medium	>=2	Yes	3.5
2	C1T1E1	Low	Medium	0	Yes	1.5
3	C1T1E2	Medium	High	0	Yes	2.5
4	C1T2E3	High	Medium	>=2	Yes	4.5
5	C4T1E1	Low	Medium	0	Yes	1.5
6	C1T1E2	Low	Medium	1	Yes	2.5
7	C1T1E2	Medium	High	1	Yes	3.5
8	C1T1E2	Medium	Medium	>=2	Yes	4
9	C1T1E2	Medium	Medium	>=2	Yes	4
10	C1T1E2	High	High	0	Yes	3
11	C1T1E3	High	Medium	>=2	Yes	4.5
12	C1T1E2	Medium	High	>=2	No	3.5
13	C1T1E2	High	Medium	>=2	No	3.5
14	C1T1E1	Medium	Low	0	Yes	1.5
15	C1T1E1	Medium	Medium	0	Yes	2
16	C1T4E2	Medium	Medium	1	Yes	3
17	C1T1E2	High	Medium	0	Yes	2.5
18	C1T1E2	Low	Medium	1	Yes	2.5
19	C1T1E2	Medium	High	0	Yes	2.5
20	C1T3E2	Low	Medium	1	Yes	2.5
21	C1T1E3	High	Medium	>=2	Yes	4.5
22	C1T1E1	Low	Low	0	Yes	1
23	C1T1E1	Low	Medium	0	Yes	1.5
24	C1T1E1	Low	Low	0	Yes	1
25	C1T3E2	Low	Medium	1	Yes	2.5
26	C1T2E2	High	High	1	Yes	4
27	C1T2E1	Medium	Medium	0	No	1
28	C1T2E2	Medium	High	0	Yes	2.5
29	C1T1E2	Medium	Medium	>=2	Yes	4
30	C1T2E2	High	High	0	Yes	3
31	C1T3E1	Low	Low	0	Yes	1
32	C1T1E2	Low	Medium	>=2	No	2.5
33	C1T4E2	Medium	High	0	Yes	2.5
34	C1T2E1	High	Medium	0	No	1.5
35	C1T2E1	Medium	Low	1	No	1.5
36	C1T1E1	Low	Low	0	No	0
37	C1T1E2	High	Medium	0	Yes	2.5
38	C1T2E1	Low	Low	0	No	0
39	C1T1E1	Low	Low	0	Yes	1
40	C1T1E2	High	High	1	No	3
41	C1T2E1	Low	High	0	Yes	2
42	C1T2E2	High	High	0	Yes	3
43	C1T1E1	Medium	Low	0	Yes	1.5
44	C1T1E1	Medium	Medium	0	No	1
45	C1T2E2	Medium	High	0	Yes	2.5
46	C1T1E1	Low	Low	0	Yes	1
47	C1T1E2	Medium	High	1	Yes	3.5
48	C1T2E1	High	Medium	0	No	1.5
49	C1T3E2	Medium	Low	1	Yes	2.5
50	C1T1E1	Low	Medium	0	Yes	1.5
51	C1T2E1	Low	High	0	Yes	2
52	C1T1E1	Medium	Medium	0	No	1

C: Candidate cause; T: Typology; E: Strength of evidence

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4 DISCUSSION

4.1 Evidence assessment

The present review tackles the question of whether the OB is responsible for the majority of the EPG in buildings or not. As presented in results, OB is identified as the main contributor to the EPG in 98% of the studies. However, it is necessary to point out that the cause indicated to is based on what is 'identified' by the studies and not necessarily what is empirically evident. The assessment carried out provides a method to quantify the strength of evidence in order to make a tangible conclusion about the role of OB in the EPG. The majority of studies were assessed as 'medium' (52%), followed by 'low' assessment (42%). Almost 50% of the 'medium' studies has a numerical assessment of 2.5 points, which is the lowest numerical value for 'medium' points (Figure 9). Only 3 out of 52 studies showed a 'high' assessment of evidence (6%). These results indicates that the majority of studies provide rather insufficient evidence with regard to the purported cause. Therefore, the role of OB in the EPG is more likely 'assumed' rather than conclusively established. In order to gain more insight about this claim, the distribution of each assessment criteria (e.g., quality of data, normalisation coverage) across all studies is explored in the following in more detail.

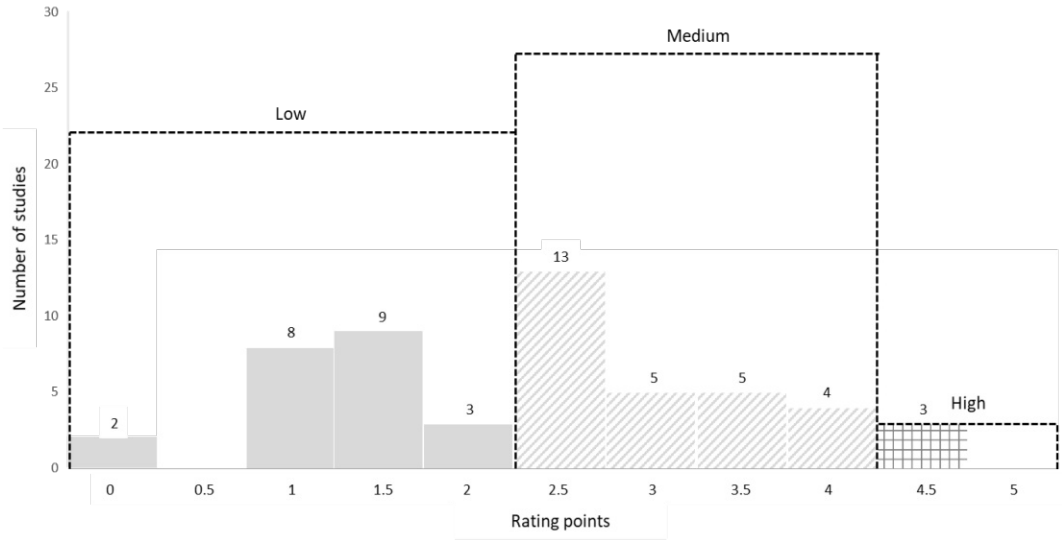

Figure 9 Distribution of studies according to the assessment value.

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4.2 Quality of data

Due to the challenging nature of predicting human actions with regard to OB in buildings (e.g., window opening, thermostat settings, occupancy), it is often the case that energy predictions are based on standard assumptions and not empirical data. In the current review, quality of data (energy and occupants) is identified as a major criterion in assessing the evidence of the identified EPG causes. Across all studies, a normal distribution is observed with regard to the quality of data assessments (Figure 10). The 'medium' assessment exhibits the bigger percentage for both energy and occupants' data assessment (44%), which can influence the evidence assessment towards the 'medium' category. The remaining studies were almost equally distributed between 'low' and 'high' data assessments, showing equal influence on the evidence assessments towards both 'low' and 'high' categories (Figure 10). A comparison between the distribution of data quality for both energy and occupants seperately is carried out in order to explain the factors shaped the data assessment distribution.

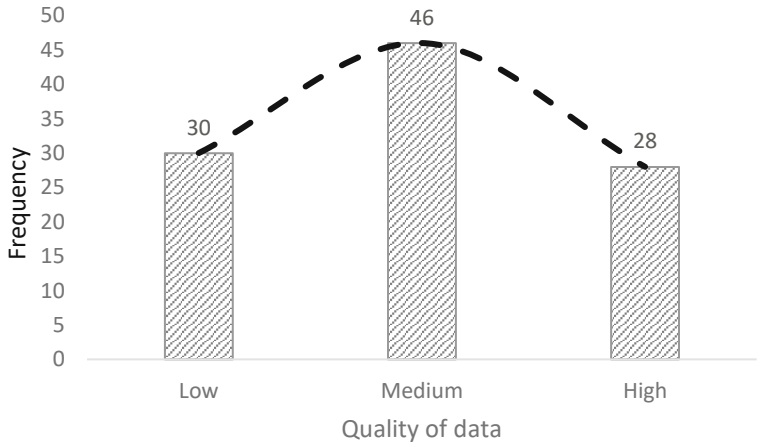

Figure 10 Classification of studies with regard to the quality of data

Both types of data (energy and occupants) still shows a normal distribution when analysed seperately (Figure 11). However, more dispersion is observed for occupants' data compared to energy data. 'Medium' assessment represents 38% of energy data and 50% of occupants' data. This indicates that the 'medium' percentage in (Figure 10) is more influenced by occupants' data assessment rather than energy data assessment. The reason for the domination of 'medium' assessment is mainly due to the monitoring methods used to collect occupants' data. Only 38% of the data sources were empirical (e.g., sensors). The majority of

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studies used less certain methods (e.g., survey, observation, interviews, time schedules), which shifted most of the studies from ‘high’ assessment of data quality to ‘medium’ assessment. Concerning occupants’ data distribution, both ‘low’ and ‘high’ assessments represent a much lower percentage compared to ‘medium’. Nevertheless, studies with a ‘high’ assessment for occupants’ data exceeds those with ‘low’ assessment. This is due to the fact that most studies that used empirical methods of measuring OB (38%), actually measured more than one factor of OB as well. This increased the overall assessment of the occupants’ data quality to the ‘high’ assessment. While studies assessed as ‘low’ are only the ones that have measured one factor of OB, and often the method of monitoring either has low certainty (e.g., survey) or is not mentioned.

Considering energy data, studies are almost equally distributed between ‘low’ and ‘medium’ assessments. The reason for that is the influence of the time resolution of energy data on the quality of data assessment. In most of studies, annual and monthly values are the most frequent. Despite the fact that the number of studies measuring hourly and sub-hourly values is comparable to the number of studies measuring annual values (Figure 4), yet the quality of data assessment was not much affected by this high resolution of hourly and sub-hourly values. One reason for that can be the low spatial granularity of energy data, which is mostly measured on building scale (Figure 3). This contributes to a decrease in the overall energy data assessment, shifting more studies towards the ‘low’ assessment. It is worth mentioning that studies based on database sources for occupants and energy data have the most uncertainty because usually energy data is documented as annual values and occupants’ data is not based on empirical measurements of the OB but rather through questionnaire surveys.

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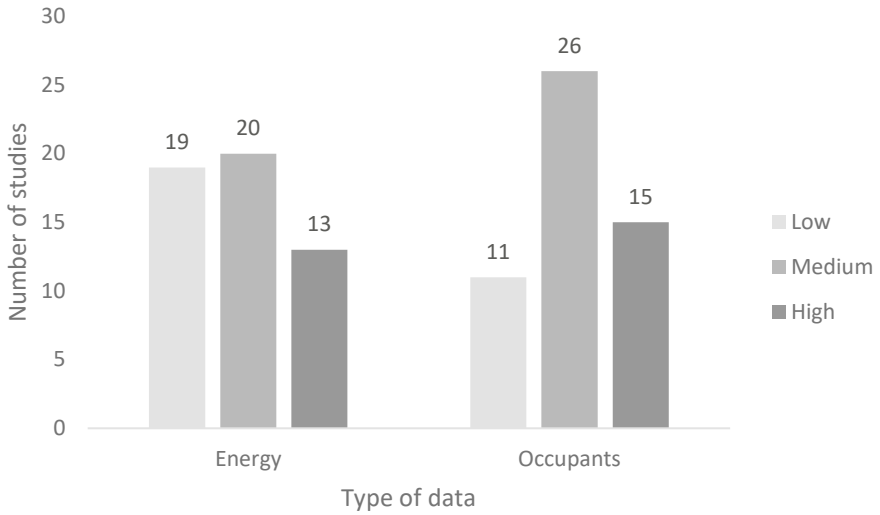

Figure 11 Classification of studies with regard to the type of data

It can be observed that the energy and occupants' data display opposite percentages for 'low' and 'high' assessments. This explains the equal distribution for both assessments when data is combined (energy and occupants) in the quality of data distribution (Figure 10).

4.3 Interdependency of variables

In addition to the above-mentioned quantitative assessment, some qualitative considerations are worth mentioning when assessing the quality of data, for instance: the interdependency of variables measured. It explains how the assessment of data quality can differ when two or more interdependent variables are assessed separately vs together. An example can be when measuring the use of thermostat, window opening and indoor temperature in a room. A valid scenario is if a window opening action takes place, the indoor temperature must experience a change (setting aside the scenario where the indoor and outdoor air temperature are exactly the same), unless the use of thermostat also changed or any other variable interfered (e.g., increased occupancy). If a certain variable change is observed without being explained by the other interdependent variables, then the data quality of all the variables should be questioned. Because the interdependent measured variables do not confirm each other. Thus, it is necessary to analyse the measurements for those variables collectively and not separately. The assessment carried out in the current work does not consider the interdependency of variables for assessing the data quality, only the number of variables measured.

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4.4 Normalisation

Normalisation coverage was identified as another main criterion considered in the evidence assessment. As explained before, the quality of the normalisation coverage is measured according to the number of factors included for normalising the energy use. The majority of studies did not provide any information about normalisation, while studies normalised energy use for 2 or more factors represents the smallest number (17%) (Figure 12). However, most of those 17% showed a 'low' to 'medium' assessment of data quality. This contirubuted to the increase in the number of studies with an overall 'medium' evidence assessment. It is worth mentioning that normalisation coverage has similar weight of points on the evidence assessment as the quality of data. It can be observed that the normalisation distribution (Figure 12) was the factor that shifted the evidence assessment towards the 'low' rather than the 'high' category (Figure 9).

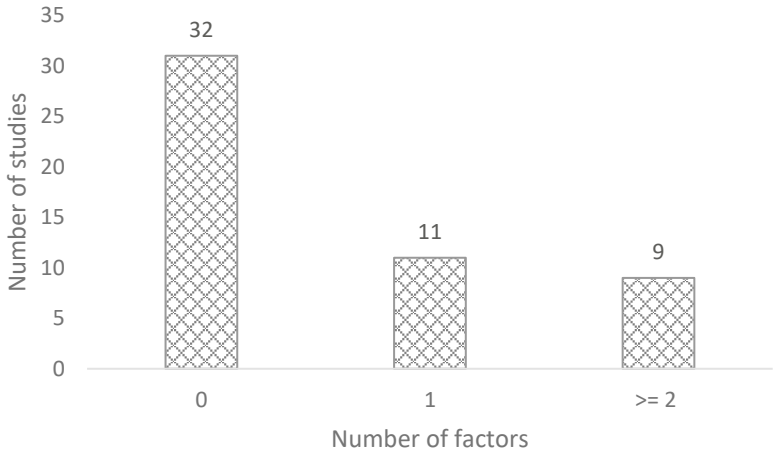

Figure 12 Distribution of the normalisation coverage

In most studies, the identified causes of the EPG were directly measured (Figure 13). This finding should push the overall evidence assessment towards the 'high' category. Yet, this did not happen because the weight of points provided for this criterion was half the wieght of either data quality or normalisation coverage, which minimized its influence on the evidence assessment.

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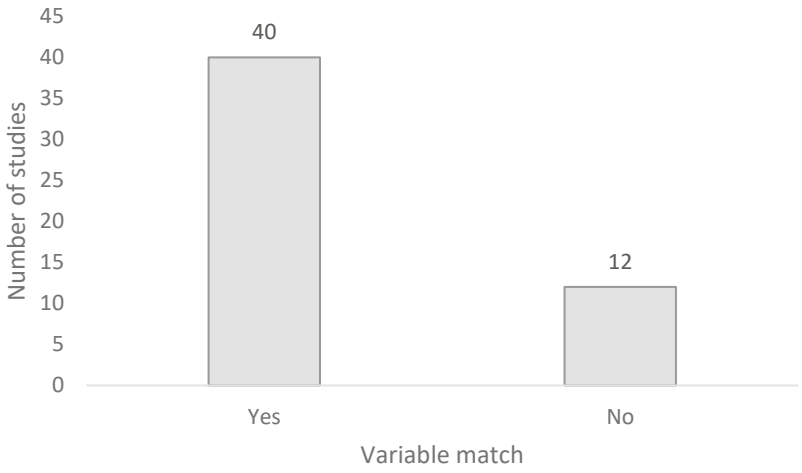

Figure 13 Distribution of the variable match (cause vs measurement)

Another instance of co-dependency of variables is between the third criteria of assessment: variable match (cause vs measurement) and the typology of the building investigated. In (Menezes et al. 2012), occupancy is measured and lighting use is obtained from the occupancy hours because the typology of the building is office space. So, it is assumed that no one will occupy the space in an office building without turning on the lights. In residential buildings, on the other hand, spaces can be occupied while the lights are turned off, for instance during sleeping or sitting activities.

4.5 EPG distribution

Another factor should be considered when addressing OB as the major cause of the EPG is the gap magnitude in relation to the evidence assessment. The average reported magnitude of gap across all studies suggests 56% more energy use than predicted energy demand. However, when looking at the gap percentage in each assessment category (Figure 14), it can be observed that there is a negative correlation between the EPG percentage and quality of evidence. The EPG percentage gets significantly smaller when evidence assessment rankings are higher. On average, the magnitude of the EPG is reported in the 'low' assessment as 266%, in the 'medium' assessment as 225%, and in the 'high' assessment as 3%. This implies that, among all reviewed studies, the EPG appear to be smaller when the identified cause relies - to a large extent - on empirical evidence.

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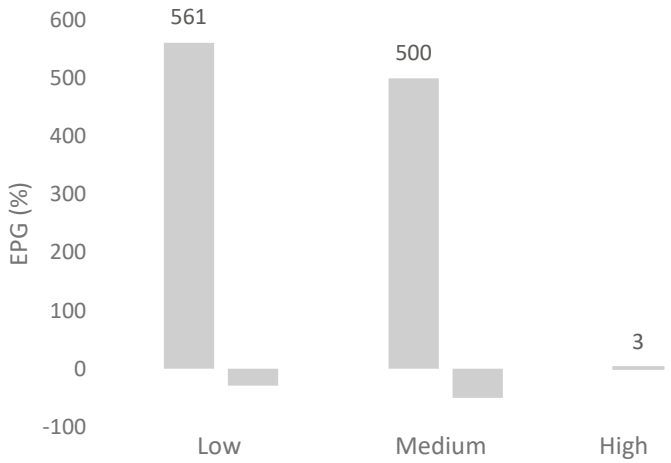

Figure 14 Distribution of EPG magnitude (in %) with regard to the assessment categories

Nevertheless, looking at the EPG distribution with regard to evidence assessment as separate data points and not as a range of values, some outliers can be identified (Figure 15). When outliers are excluded, a normal distribution is observed. In contrast to the previous distribution (Figure 14), the EPG magnitude seems to be highest in the 'medium' evidence assessment, followed by the 'low' and the 'high'. This distribution matches the distribution of the overall evidence assessment (Figure 9). This indicates that in the current case, the magnitude of the EPG magnitude might correlate with the evidence assessment strength. But it does not confirm that the EPG decreases with a higher evidence assessment as presented in (Figure 14). A reason for the second distribution can be that the sample of studies is not representative. Perhaps in another dataset, the number of outliers in the 'low' assessment would increase, expanding the dataset to match the distribution in (Figure 14).

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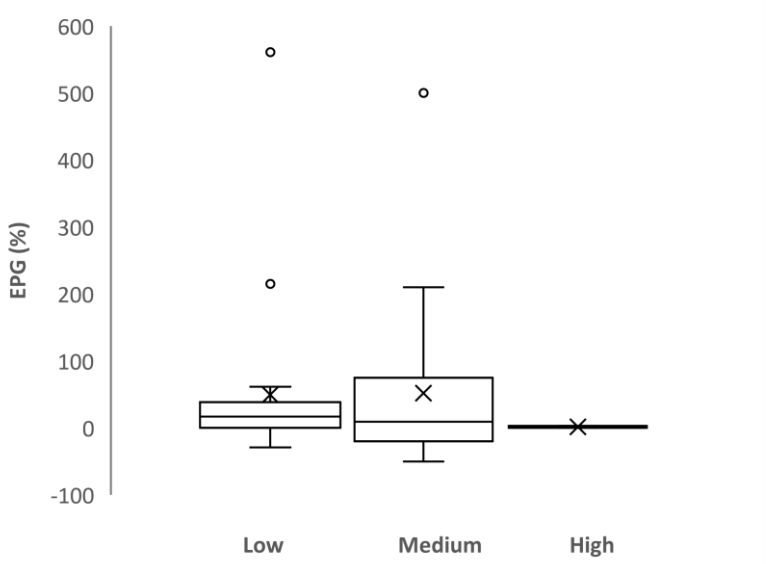

Figure 15 Distribution of EPG with regard to the assessment categories

4.6 Synthesis

Potential correlation between the three criteria: candidate cause (C), typology (T) and strength of evidence (E) is analysed. The case C1T1E2 is the most frequent (*Table 6*). This distribution reflects the distribution of each criterion separately: C1 (98%), T1 (64%), and E2 (52%). Most studies identified OB as the major candidate cause investigated residential buildings, and had a 'medium' evidence assessment, followed by a 'low' assessment. This highlights a need for further investigation of the role of occupants in the EPG in building typologies other than residential buildings and based on empirical data.

Table 6 Number of studies identified with the corresponding code

Code	Nr. of studies
C1T1E1	13
C1T1E2	17
C1T1E3	2
C1T2E3	7
C1T2E2	5
C1T2E3	1
C1T3E1	1
C1T3E2	3
C1T4E2	2
C4T1E1	1

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4.7 Optimization potential

It is now clear that the studies address the EPG from two main perspectives. First, from a view of a data problem. Second, as a problem of method of handling the data (e.g., normalisation of data, prediction calculation method). The identified OB action distribution in (Table 4) indicates the optimisation potential in the model assumptions, which is a data problem. It shows a need for adjusting the data for temperature set-point, equipment uses and occupancy as the major OB causes affecting the EPG. Building characteristics shows a small contribution to the gap. However, it is necessary not to overlook that the sample of studies was mainly targeting the role of occupants in EPG. A reason of the current distribution of causes can be because the sample is not focusing on investigating the role of other factors in the EPG (e.g., building characteristics).

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5 CONCLUSION

The energy performance gap, or the discrepancy between predicted energy demand and actual energy use, was explored in the reviewed studies, with an emphasis on the role of occupants. Several approaches were adopted in this investigation. Energy performance predictions for buildings are carried out using simplified calculation methods or dynamic simulation models. Model assumptions for energy and occupants are mostly based on standard values. Few studies relied on measured energy and occupants' data for model assumptions, aside from some studies that investigated retrofit cases of existing buildings. Most studies examined the typology of residential buildings. Energy measurements were usually of electricity and natural gas consumption. There was a consistency in the sources of data, namely energy meters or utility bills. A variation in the factors measured for indoor and outdoor conditions was observed across all studies. The most common factor was air temperature, which usually reflected the desired temperature set by occupants inside the building. Occupants' data was obtained from several sources. Only 38% used empirical methods (e.g., absence detection sensors, lighting control sensors), other sources included surveys and interviews. The majority of studies measured temperature set-point, equipment-use behaviour, occupancy, and window opening. Those variables were identified as the most common occupant-related factors causing the gap.

In order to provide proper conditions for the assessment of evidence presented in literature, studies selected for the assessment are the ones include measurements for both energy and occupants, namely the 'Gold' category. This strict requirement provided a 'medium' for a quantitative assessment of the evidence of the EPG. In the majority of studies, occupant behaviour was identified as the primary cause of EPG (98%). However, according to the assessment carried out, only 6% of the studies showed a 'high' strength of evidence. The strength of the majority of studies was assessed as 'medium' and 'low'. A numerical assessment of 2.5 points is seen in nearly half of the 'medium' studies. This is the lowest numerical value for 'medium' points, which shows high tendency towards the 'low' assessment. The assessment distribution indicates that the evidence provided in most studies is not sufficient to identify OB as the major cause of the EPG.

Across all reviewed studies, the EPG appears to get smaller when the cause is largely based on empirical evidence. However, this finding was not supported when

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some studies showing the highest EPG percentage were excluded. In the latter case, the EPG's magnitude correlates with the evidence assessment, showing a normal distribution. This can be a result of a sample bias, which raises a demand for further investigation using a larger sample of studies to investigate if indeed a higher evidence assessment is associated with a lower EPG magnitude.

One way of addressing the problem of the EPG is through dedicating more efforts in developing monitoring tools for a more targeted and automated way of data acquisition regarding occupant behaviour (Guerra-Santin, 2017; Mojic, Lehmann, van Velsen, & Haller, 2019; van Dronkelaar et al., 2019). Another way is addressing the problem as a model limitation, which should guide more efforts to improve occupants' modelling. What is suggested here is that it is preferable to address the EPG from the perspective of a data and/or modelling rather than prematurely identifying "wasteful occupants" as those mainly responsible for EPG.

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6 INDEX

6.1 Abbreviations

EPG	Energy performance gap
OB	Occupant behavior
HDD	Heating degree days
HVAC	Heating ventilation air conditioning
MVHR	mechanical ventilation with heat recovery
POE	Post-occupancy evaluation
DHW	Domestic hot water
tVOC	total volatile organic compound
VOCs	Volatile organic compounds

6.2 List of Figures

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6.3 List of Tables

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