Serious games for energy applications in the built environment: A systematic review

Energy Research & Social Science 138 (2026) 104826

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Review

Serious games for energy applications in the built environment: A systematic review

Abdollah Baghaei Daemei [a,b,*], Nima Izadyar [c], Ehsanolah Assareh [d], Heide Karen Lukosch [a], Matthaios Santamouris [e], Mona Abd Al Salam [f], Amirhosein Ghaffarianhoseini [g], Ali GhaffarianHoseini [g]

[a] HIT Lab NZ, University of Canterbury, Christchurch, New Zealand
[b] Energy Performance Analysis Lab, Tech Innovation Experts, Auckland, New Zealand
[c] School of Built Environment, College of Engineering and Science, Victoria University, Melbourne, VIC, Australia
[d] Asia Pacific University of Technology & Innovation (APU), Technology Park Malaysia, Kuala Lumpur, Malaysia
[e] School of Built Environment, Faculty of Arts, Design & Architecture, University of New South Wales, Sydney, 2052, Australia
[f] School of Built Environment, University of Technology Sydney, Sydney, Australia
[g] School of Future Environments, Auckland University of Technology, 55 Wellesley Street East, Auckland CBD, Auckland, 1010, New Zealand

A R T I C L E I N F O

Keywords:
Serious games
Gamification
Built environment
Energy behavior
Energy efficiency
Energy-related decision-making
Energy literacy

A B S T R A C T

Energy use in buildings is a major global challenge because it depends not only on technologies, but also on how people understand, operate, and respond to building systems. Serious games and gamified applications have been used to improve energy literacy, encourage energy-saving behavior, and support energy-related decision-making. However, evidence remains fragmented across building contexts, user groups, technologies, design approaches, and evaluation methods. It is still unclear how these interventions are designed, who they serve, and whether they produce measurable energy outcomes in real built-environment settings. This systematic literature review examines serious games and gamified applications for energy-related purposes in the built environment. The review analyses 69 empirical studies published between 2008 and 2026. Studies were examined according to application context, target users, learning objectives, game design features, interaction mechanisms, technologies, evaluation approaches, reported outcomes, and limitations across residential, educational, professional, and urban energy contexts. Findings show that most interventions target non-professional users, especially students and household residents, and are mainly evaluated in educational or controlled settings. Game design is dominated by accomplishment- and social-influence-based mechanisms, including challenges, points, feedback, progression, badges, competition, leaderboards, collaboration, and social comparison. More advanced approaches, including real-time building data, adaptive feedback, artificial intelligence, immersive environments, and professional decision-support tools, remain limited. Some studies reported short-term energy reductions, but evidence of sustained and independently verified real-world energy impact remains weak. The review contributes a hierarchical taxonomy linking system purpose, motivational design, user-building interaction, technological integration, and evaluation strategy, supporting future real-world, data-driven, and longitudinally validated interventions.

1. Introduction

Energy consumption in the built environment is a major contributor to global energy demand and greenhouse gas emissions [1,2]. Residential and commercial buildings account for a substantial share of this energy use [3,4]. Improving energy efficiency in buildings and influencing user behavior are, therefore, central priorities in addressing sustainability challenges [5–7]. While technological solutions, including smart systems, sensors, and building automation, have advanced considerably, evidence demonstrates that human behavior continues to

* Corresponding author at: HIT Lab NZ, University of Canterbury, Christchurch, New Zealand.
E-mail addresses: abdollah.baghaeidaemei@canterbury.ac.nz, abdollah.baghaei@tinx.co.nz (A.B. Daemei), Nima.Izadyar@vu.edu.au (N. Izadyar), heide.lukosch@canterbury.ac.nz (H.K. Lukosch), m.santamouris@unsw.edu.au (M. Santamouris), Mona.AbdAl-Salam@uts.edu.au (M.A. Al Salam), amirhosein.ghaffarianhoseini@aut.ac.nz (A. Ghaffarianhoseini), ali.ghaffarianhoseini@aut.ac.nz (A. GhaffarianHoseini).

https://doi.org/10.1016/j.erss.2026.104826
Received 4 May 2026; Received in revised form 17 June 2026; Accepted 24 June 2026
Available online 8 July 2026

play a critical role in determining actual energy performance [8,9].

This means that building energy performance depends not only on technical systems, but also on how people understand, use, and respond to them. As a result, there is growing interest in approaches that can engage users more effectively and support informed energy-related decision-making in everyday and professional contexts [10,11]. In this context, serious games and gamification have emerged as promising tools for influencing energy-related behaviors and enhancing user engagement [12]. Serious games are commonly understood as game-based systems developed for purposes beyond entertainment, such as education, training, and behavior change [13].

Serious games have already been applied in diverse fields, including health and medical education [14,15], rehabilitation [16,17], disaster education [18,19], indoor air quality and air pollution [20,21], and environmental learning [22,23], where they have demonstrated value in supporting knowledge acquisition, skills development, engagement, and decision-making. This broader evidence base provides a useful foundation for the energy domain, where serious games and gamified approaches are already established as tools for encouraging energy-efficient practices, improving awareness of consumption, and supporting more sustainable user–building interactions [24,25]. However, recent developments have shifted attention toward more data-driven, adaptive, and context-sensitive applications that are increasingly connected to smart buildings, user feedback, and real-world energy systems.

In this review, serious games refer to complete game-based systems designed for purposes beyond entertainment, while gamification refers to the use of game elements in non-game systems to support engagement, learning, or behavior change. Game-based learning, gamified applications, and game-based interventions are used as broader terms when the intervention involves either a full game or selected game mechanics. Therefore, the scope of this review includes both full serious games and gamified systems, provided they address energy-related applications in the built environment and report empirical evaluation.

Despite the expanding body of research, the field remains conceptually and methodologically fragmented [12,26]. There is a lack of a focused synthesis addressing energy-related applications within the built environment [24]. Consequently, evidence on whether these interventions lead to measurable, real-world energy outcomes remain limited [27]. Existing studies vary widely in their application contexts, target users, game design approaches, technological features, and evaluation methods [26].

Previous reviews have provided valuable foundations for understanding serious games and gamification in energy-related contexts; however, they do not fully address the built environment as an integrated application domain. Johnson et al. [12] systematically reviewed applied games in domestic energy consumption, but their scope was restricted to household energy use and excluded other built-environment settings such as workplaces, schools, public buildings, and professional contexts. Wu et al. [26] reviewed serious games as an engaging medium for building energy consumption and classified trends, categories, and engagement approaches, but the review was based on a smaller body of selected projects and did not systematically synthesize user profiles, interaction mechanisms, technological integration, evaluation approaches, and empirical evidence across the wider built-environment domain.

Delemere and Liston [28] made an important contribution by examining behavior change techniques within serious games for energy efficiency, but their focus was on behavioral mechanisms rather than the broader relationships between game design, built-environment context, user–building interaction, and energy-performance evidence. More recently, Abdurahmanovic [24] reviewed gamification and serious games in energy systems, with a particular emphasis on district heating systems and customer engagement, rather than the full range of building, household, educational, urban, and professional settings. A separate systematic review is needed for the built environment because energy-related decisions in this domain are shaped by the interaction between users, buildings, technologies, and operational contexts.

Unlike broader energy or sustainability interventions, built-environment applications involve specific conditions such as occupancy patterns, HVAC systems, appliances, lighting, smart meters, sensors, automation, and user–building feedback loops. These factors influence both serious game design and evaluation. For example, games aimed at household awareness require different interaction models and evidence standards from those designed for retrofit decision-making, demand response, or smart-building operation.

To address these gaps, this study aims to systematically review the application of serious games in energy-related research within the built environment, with a focus on their purposes, design characteristics, and reported outcomes. To be specific, it examines how the games are designed to support user interaction and decision-making across households and building professionals and assesses the extent to which they contribute to measurable energy performance outcomes.

Therefore, this study makes four distinct contributions to the literature on serious games for energy-related applications in the built environment. First, it extends previous reviews by moving beyond domestic energy consumption, behavioral techniques, or district heating systems to provide a built-environment-specific synthesis across residential, educational, public, workplace, urban, and professional contexts. Second, it integrates multiple analytical dimensions that are often examined separately, including application context, user profile, learning objective, game elements, delivery method, user–building interaction, technological features, evaluation approach, and reported outcomes.

Third, it proposes a hierarchical taxonomy that organizes the field through a dependency-based structure linking system purpose, motivational and game design, user–building interaction, technological integration, and evaluation strategy. Fourth, it identifies evidence gaps that are particularly important for the built environment, including the underrepresentation of professional users, limited real-world data integration, short-term evaluation designs, reliance on self-reported outcomes, and weak evidence of measurable energy-performance impact.

2. Materials and methods

This study employed a systematic literature review following the multi-stage framework proposed by Khan et al. [29]. The review process comprised four stages: (i) formulation of research questions, (ii) systematic search of relevant databases, (iii) study selection through predefined screening criteria, and (iv) data extraction and synthesis. A structured search strategy was applied across major academic databases, and identified records were screened using explicit inclusion and exclusion criteria at title/abstract and full-text levels. Relevant studies were then coded to extract information on application context, user profiles, game design, technological features, and evaluation methods. The extracted data were synthesized using a structured comparative approach to identify patterns, gaps, and relationships across studies, enabling the development of a taxonomy and research directions.

2.1. Defining research questions

This study aims to provide a comprehensive understanding of the application of serious games and gamification in energy-related studies within the built environment. To achieve this, a set of research questions (RQ1-RQ4) was developed to capture the various dimensions of this interdisciplinary field (Table 1). The formulation of these research questions was informed by existing classifications and review studies in the field of serious games and gamification, particularly those that examine key dimensions, including application context, learning objectives, game design elements, delivery methods, learning theory, and user characteristics [11,30,31]. Prior research has highlighted the importance of structuring serious game studies based on these

Table 1
Research questions and analytical focus.

No.	Main questions	Primary focus
RQ1	What are the contexts, objectives, and design features of serious games for energy-related applications in the built environment?	Application scope and design characteristics
RQ2	Who are the target users, and how do these games enable user–building interactions through technological features?	Users, interactions, and technological integration
RQ3	How are these games evaluated, and what outcomes are reported regarding their real-world impact effectiveness?	Evaluation approaches and reported outcomes
RQ4	What theoretical frameworks are used, and what limitations and future research opportunities are identified?	Theoretical grounding, limitations, and future directions

dimensions to enable systematic comparison and synthesis across different application domains [32,33]. Accordingly, the research questions in this study were designed to capture these core aspects, while being adapted to the specific context of energy-related applications in the built environment.

2.2. Identifying the relevant works

This study followed the PRISMA approach to identify, screen, and select relevant studies for inclusion in the review (Fig. 1). Relevant records were retrieved from multiple academic databases, including Scopus, Web of Science, IEEE Xplore, ACM Digital Library, ScienceDirect, ProQuest, EBSCOhost, and ASCE Library. These databases were selected to provide broad interdisciplinary coverage across engineering, computer science, energy, sustainability, and built environment research [34,35].

The search strategy was developed using three concept blocks aligned with the scope of the review: (i) serious game and gamification intervention terms, (ii) energy-related application terms, and (iii) built-environment context terms. The first block captured serious games, gamification, game-based learning, digital games, simulation games, and educational games. The second block captured energy use, energy efficiency, energy saving, building energy, household energy, HVAC, thermal comfort, ventilation, and building performance. The third block restricted the search to built environment contexts, including buildings, residential settings, households, smart homes, smart buildings, and the built environment. These blocks were combined using Boolean operators to ensure that included records addressed all three domains: game-based intervention, energy relevance, and built-environment application. This structure was used to improve conceptual coherence and reduce retrieval of studies outside the review scope.

The database search was conducted in 2026 using a structured keyword string applied to the title, abstract, and keyword fields, where supported by each database. In this regard, the "TS" field in Web of Science was treated as broadly comparable to the "TITLE-ABS-KEY" field in Scopus. The final search string was defined as follows:

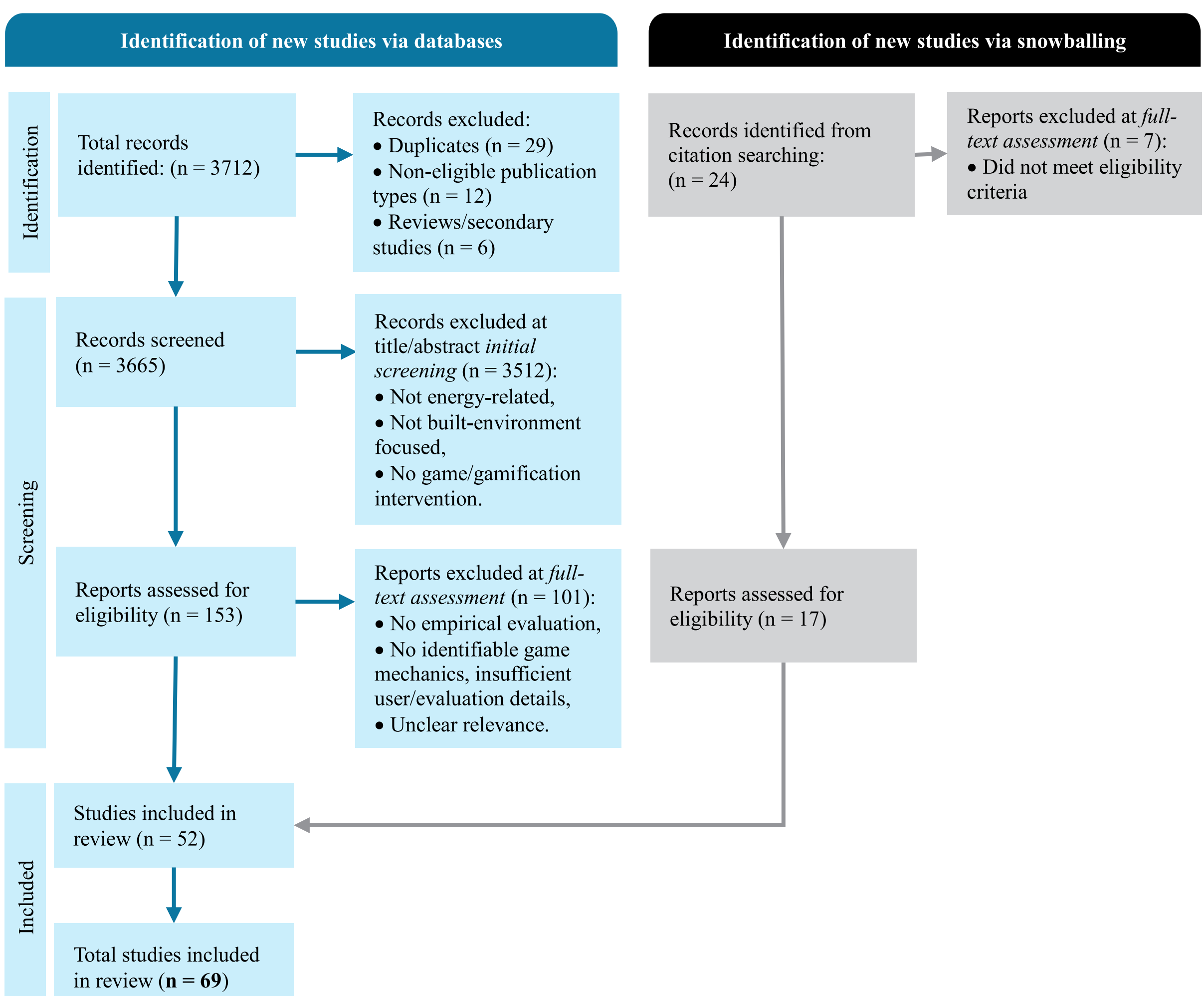


Fig. 1. PRISMA flow diagram showing the identification, screening, eligibility assessment, and inclusion of studies from database searching and backward/forward citation searching. Detailed eligibility criteria are provided in Table 2.

("serious game*" OR gamif* OR "game-based learning" OR "digital game*" OR "video game*" OR "simulation game*" OR "educational game*") AND ("energy consumption" OR "energy use" OR "energy efficiency" OR "energy saving*" OR "energy conservation" OR "building energy" OR "residential energy" OR "household energy" OR HVAC OR "thermal comfort" OR ventilation OR "building performance") AND (building* OR residential OR household* OR "built environment" OR "smart home*" OR "smart building*").

The asterisk (*) operator was used to capture multiple variations of key terms, such as gamification, gamified, and gaming, thereby increasing the inclusiveness of the search. No additional restrictions related to time frame, subject area, or publication type were applied during the initial search phase to avoid premature exclusion of potentially relevant studies. However, during screening, only peer-reviewed journal articles, conference papers, and book chapters reporting original research were considered eligible.

The database search identified 3712 records. All retrieved records were exported and merged into EndNote. Before title and abstract screening, 47 records were removed, including duplicate records (n = 29), non-eligible publication types (n = 12), and review or secondary studies (n = 6). After this initial removal, 3665 records were screened based on titles and abstracts. At this stage, 3512 records were excluded because they were not energy-related, were not focused on the built environment, or did not involve a serious game, gamification, or game-based intervention. Following full-text assessment, 101 reports were excluded, resulting in 52 studies included from the database search.

To improve the comprehensiveness of the review, backward and forward snowballing were then applied to the eligible studies. Backward snowballing involved examining the reference lists of selected studies to identify additional relevant works [36], while forward snowballing involved identifying newer studies that cited these key papers [37]. This process identified 24 additional records. After full-text screening, 7 reports were excluded, and 17 additional studies were included in review.

In total, the review included 69 studies: 52 studies identified through database searching and 17 studies identified through snowballing. The detailed inclusion and exclusion criteria are presented in Table 2, and the final list of selected studies is provided in the Supplementary Materials.

The eligibility criteria were applied progressively during study selection, according to the level of information available at each stage. The criteria did not change across stages; rather, title and abstract screening was used to remove clearly irrelevant records, while full-text assessment enabled a more detailed evaluation of intervention characteristics, game mechanics, empirical evaluation, and relevance to energy-related applications in the built environment. To improve clarity, the criteria are presented below according to the three main screening stages.

Although no restrictions on timeframe or subject area were applied during the initial database search, several eligibility criteria were used during screening to maintain the methodological quality and interpretability of the review. First, only peer-reviewed journal articles, conference papers, and book chapters reporting original research were included, because the review aimed to synthesize empirically evaluated serious game interventions rather than conceptual proposals, opinion pieces, or secondary literature. Second, review papers, editorials, theses, reports, and non-peer-reviewed publications were excluded to reduce duplication of evidence and ensure that the analysis was based on primary studies. Third, only studies available in English were included, as this allowed consistent screening, coding, and interpretation of game design features, user interactions, technological characteristics, and reported outcomes. While these criteria may have excluded some relevant grey literature or non-English studies, they were necessary to ensure transparency, comparability, and reliability across the selected evidence base.

To improve reproducibility, the search strategy was organized into three concept blocks: game-based intervention terms, energy-related terms, and built-environment terms (Table 3). The same conceptual search structure was applied across all databases, but field codes and syntax were adapted to the requirements of each database interface. Where exact title–abstract–keyword searching was not available, the closest equivalent metadata fields supported by the database were used. All records were exported to EndNote, merged into a single library, and screened using the same eligibility criteria. The same conceptual search structure was applied across all databases, consisting of three search blocks: game-based intervention terms, energy-related terms, and built-environment terms. Field codes and syntax were adapted to each database interface. The total excludes duplicate records removed before screening.

Table 2
Eligibility criteria applied during the screening stages.

Screening stage	Inclusion criteria	Exclusion criteria
Identification: database search	Peer-reviewed original research, including journal articles, conference papers, and book chapters, retrieved using the predefined search string covering serious games/gamification, energy-related terms, and built-environment terms.	Duplicate records; books, editorials, commentaries, theses, dissertations, reports, websites, white papers, and other non-peer-reviewed sources; review papers and other secondary studies.
Title and abstract screening	Studies addressing serious games, gamification, game-based learning, simulation games, or related interventions for energy-related applications in built-environment contexts, including buildings, households, smart homes, schools, campuses, workplaces, communities, districts, or urban energy systems. Digital and non-digital game formats were included.	Studies not explicitly focused on energy; studies limited to non-built-environment domains; studies that only mentioned games or gamification without applying them as an intervention.
Full-text eligibility assessment	Studies reporting an implemented or tested serious game, gamified system, or game-based intervention with identifiable game mechanics or simulation features, empirical evaluation, and at least one relevant outcome, such as energy awareness, knowledge, behavior, decision-making, usability, engagement, interaction, or energy-related performance.	Studies with no empirical evaluation; no identifiable game mechanics or simulation features; insufficient information about users, intervention design, or evaluation procedure; unclear relevance to energy-related applications in the built environment; or studies where the intervention was only conceptual and not implemented or tested.

Table 3
Database-specific search fields and retrieved records.

Database	Records retrieved
Web of Science	170
Scopus	571
IEEE Xplore	69
ACM Digital Library	681
ScienceDirect	1013
ProQuest	819
EBSCOhost	344
ASCE Library	26
Total	3665

2.2.1. Data extraction and coding procedure

Data extraction was conducted using a predefined extraction matrix developed from the research questions and the analytical dimensions of the review. For each included study, the following information was extracted: bibliographic details, publication year, publication type, built-environment context, energy application domain, target user group, sample size, learning objective, game elements, delivery method, user–building interaction type, technological features, evaluation approach, reported outcomes, theoretical or conceptual framework, reported limitations, and future research directions.

Game elements were extracted from the descriptions of the intervention, gameplay, feedback mechanisms, reward structures, social features, simulation components, and user interaction procedures. Similar terms were then normalized into consolidated element groups. For example, "points", "energy points", and "scores" were grouped as points/scores; "missions", "quests", and "challenges" were grouped as challenges/quests/missions; and "leaderboards" and "rankings" were grouped as leaderboards/rankings. These consolidated groups were then mapped to the Octalysis core drive that best represented their dominant motivational function. Further information is provided in the supplementary materials.

Outcome data were extracted according to the type of evidence reported in each study. Outcomes were coded into five non-mutually exclusive categories: energy-related performance, learning, behavioral, psychological and user-experience, and system or interaction outcomes. Where quantitative effects were reported, the direction and magnitude of the effect were extracted. Where only qualitative or descriptive findings were reported, the reported outcome type and evidence source were recorded. Because of the heterogeneity of study designs, interventions, measures, and reporting formats, the synthesis was conducted narratively and quantitatively by category rather than through meta-analysis.

2.2.2. Data extraction and coding procedure

A structured quality assessment was conducted to evaluate the strength and limitations of the included studies. Because the review included heterogeneous study designs, including experimental studies, quasi-experimental studies, field deployments, simulation-based evaluations, design-based studies, and mixed-method research, a single exclusionary quality scoring tool was not applied. Instead, studies were appraised using a structured set of methodological criteria relevant to serious game and gamification research.

The appraisal considered: (i) clarity of study aim and intervention description, (ii) clarity of user group and sample characteristics, (iii) appropriateness of the evaluation design, (iv) presence or absence of a comparison or control condition, (v) type of outcome measure used, (vi) use of objective, behavioral, or self-reported data, (vii) duration of evaluation and presence of follow-up, (viii) treatment of attrition or missing data, and (ix) transparency of reported limitations.

The quality assessment was not used to exclude studies after eligibility screening, because the aim of the review was to map the state of evidence across a fragmented and emerging field. Instead, the appraisal informed the interpretation of the results, particularly when distinguishing between short-term self-reported outcomes, simulated outcomes, and independently measured real-world energy outcomes. Studies relying only on post-intervention perceptions or short-term self-reported intentions were interpreted as providing weaker evidence than studies using control groups, longitudinal follow-up, system logs, smart-meter data, sensor data, or measured energy performance.

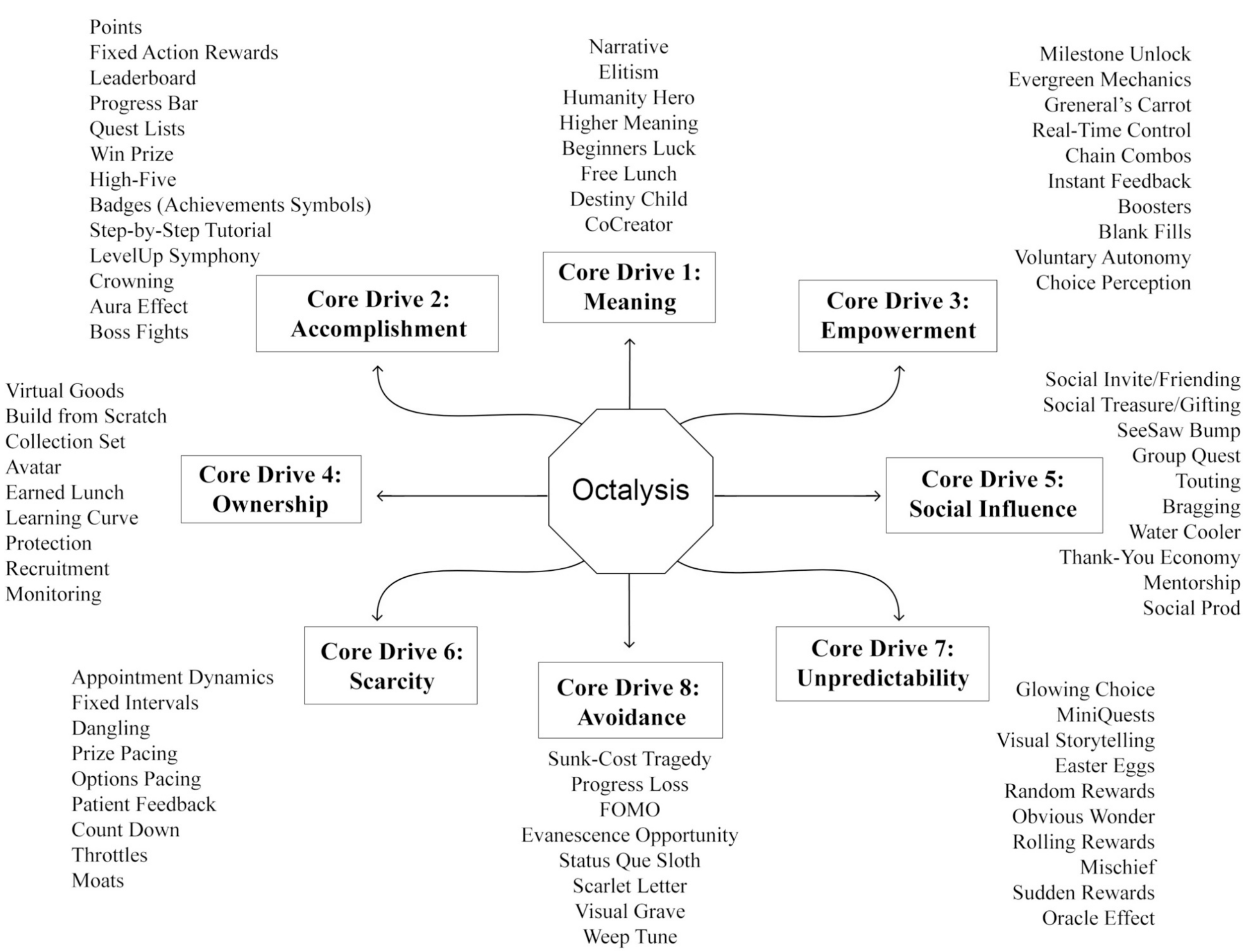


Fig. 2. The Octalysis Gamification Design Framework [32], modified from [43].

2.3. Analysis approach

The Octalysis Framework [38] was employed to systematically classify and interpret the game elements identified across the selected studies (Fig. 2). Octalysis is a gamification design framework that organizes user motivation into eight Core Drives (CDs), representing distinct psychological and behavioral forces that influence engagement, decision-making, and action [39]. Each Core Drive is linked to a set of game elements, such as points, scores, feedback, dashboards, challenges, quests, missions, competition, and leaderboards, which function as operational mechanisms through which motivation is activated.

The framework provides a structured and theory-informed approach for analyzing gamified systems by connecting observable design elements to underlying motivational drivers [39–41]. This makes it particularly suitable for systematic reviews, where diverse game features must be consistently classified and compared across studies. Unlike descriptive classifications of game mechanics, Octalysis enables interpretation of how and why specific elements may influence user behavior, rather than simply identifying their presence [42].

In this study, Octalysis was applied as an analytical model rather than a design tool, allowing the extracted game elements to be systematically mapped to their corresponding Core Drives. Each game element was mapped to the Octalysis Core Drive that best reflected its dominant motivational function in the reviewed study. Because some elements, such as competition, role-playing, feedback, and resource management, can align with multiple Core Drives depending on context, coding decisions were based on how each element was described and operationalized. For example, competition was classified under social influence when it involved comparison between users, leaderboards, teamwork, or peer interaction, while resource management and budgeting were classified under Empowerment when they required users to make strategic decisions, manage trade-offs, or test alternative energy-related choices. Elements such as avatars, virtual assets, virtual homes, virtual currency, and owned objects were classified under Ownership when they created a sense of possession or personal investment in the game environment.

Thus, the mapping should be interpreted as context-sensitive rather than as a fixed classification of game elements. This facilitated a consistent comparison of motivational strategies across the reviewed studies and supported the identification of dominant and underrepresented design patterns. As such, the framework provides both a unifying structure for synthesizing heterogeneous evidence and a theoretical basis for interpreting the effectiveness of gamification approaches in energy-related applications.

The Octalysis Framework was used in this review as a descriptive and interpretive framework for classifying motivational game design elements, not as a standalone behavioral theory or causal model of energy-related behavior change. Its purpose was to organize heterogeneous game mechanics according to their dominant motivational function and to identify which motivational design patterns were emphasized or underrepresented across the selected studies. Data extraction and initial coding were conducted by the first author using a predefined extraction matrix. The supervisory team reviewed the coding framework and discussed unclear classifications, particularly where game elements, interaction types, technological features, or learning theories overlapped. However, formal independent double coding and inter-rater reliability statistics were not conducted. This is a methodological limitation of the review because some coding decisions, particularly the mapping of game elements to Octalysis core drives, required interpretive judgement. To reduce this risk, the coding categories were defined in advance, ambiguous cases were discussed with the supervisory team, and the coding procedure is reported transparently.

3. Results

In this systematic literature review a total of sixty-nine studies published between 2008 and 2026 were identified, comprising forty-nine journal articles, eleven conference papers, and nine book chapters. A summary of all the eligible articles reviewed in this study is provided in the Supplementary Materials Section. Fig. 3 illustrates the temporal distribution of publications and their source types per annum. The temporal distribution of publications indicates that research on serious games for energy-related applications is relatively recent and has gained increasing scholarly attention, particularly in the past decade.

3.1. Keyword co-occurrence analysis

A keyword co-occurrence analysis was conducted to explore the conceptual structure of research on serious games for energy-related applications in the built environment. The analysis was performed using VOSviewer. The co-occurrence network was constructed based on author keywords, as these provide a more focused representation of the core themes defined by the authors. A thesaurus file was developed and applied to standardize terminology by merging synonymous terms (e.g., "energy saving" and "energy efficiency") and removing non-informative or out-of-scope keywords. In particular, terms related to indoor environmental quality and health (e.g., indoor air quality, asthma) were excluded to maintain alignment with the energy-focused scope of this review.

The analysis employed fractional counting, which distributes the weight of co-occurrence links proportionally across keywords within each document. This approach reduces bias associated with documents containing many keywords and is considered more appropriate for balanced network construction. A minimum occurrence threshold of 2 was applied, resulting in a final set of 48 keywords included in the network. Visualization was generated using the default layout and clustering algorithm in VOSviewer, with minor adjustments to improve readability. As shown in Fig. 4, the network is structured around three primary domains.

The co-occurrence analysis revealed a structured network consisting of several interconnected clusters, representing distinct but related research domains. The network is centered around the terms "serious game" and "gamification", which act as the primary conceptual anchors linking different areas of research. Three main thematic domains can be identified:

i) Game Design and Engagement Mechanisms: This central domain includes keywords such as *serious game* and *gamification*, reflecting the foundational role of game-based design principles in this field. These terms exhibit the highest connectivity, indicating that most studies frame their contributions within gamification strategies and interactive learning environments.

ii) Technology-Driven Systems and Smart Environments: A second domain is characterized by keywords, including *Internet of Things* (*IoT*), *sensors*, *environmental monitoring*, *virtual reality*, and *smart city*. This cluster highlights the integration of serious games with digital and sensing technologies, suggesting that many applications rely on data-driven environments and real-time interaction mechanisms.

iii) Energy Applications and Behavioral Interventions: The third domain includes *energy efficiency*, *eco-feedback*, *household consumption*, and related terms. This cluster represents the core application area relevant to this review, focusing on the use of serious games to influence user behavior and improve energy-related decision-making. However, compared to the other domains, this cluster appears smaller and less densely connected, indicating a more limited concentration of research explicitly targeting energy performance.

The structure of the network suggests that research on serious games in the built environment is primarily driven by gamification and technological innovation, rather than by domain-specific applications such as energy. Although energy-related topics are clearly present, they are positioned as a specialized subset within a broader interdisciplinary landscape. The relatively limited size and connectivity of the energy cluster indicates that the application of serious games for energy

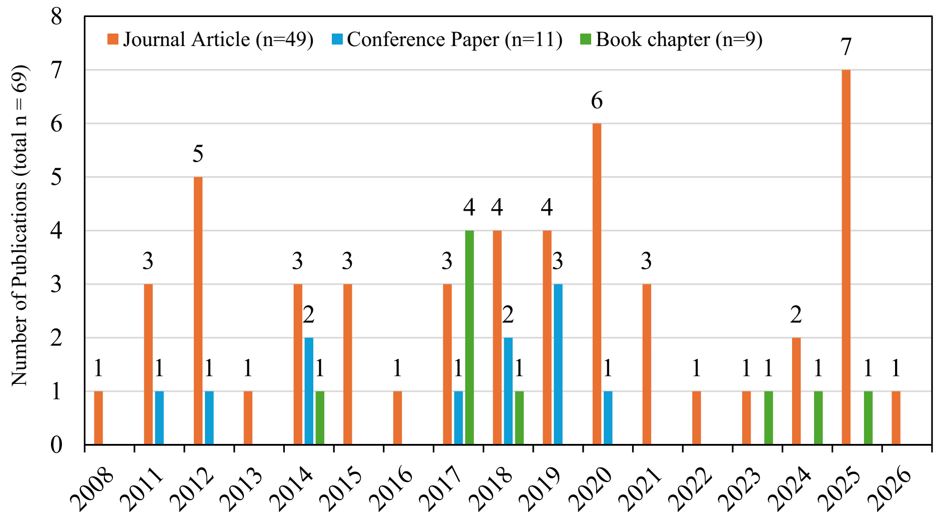


Fig. 3. Annual distribution of the 69 included studies by publication type, showing journal articles, conference papers, and book chapters published between 2008 and 2026.

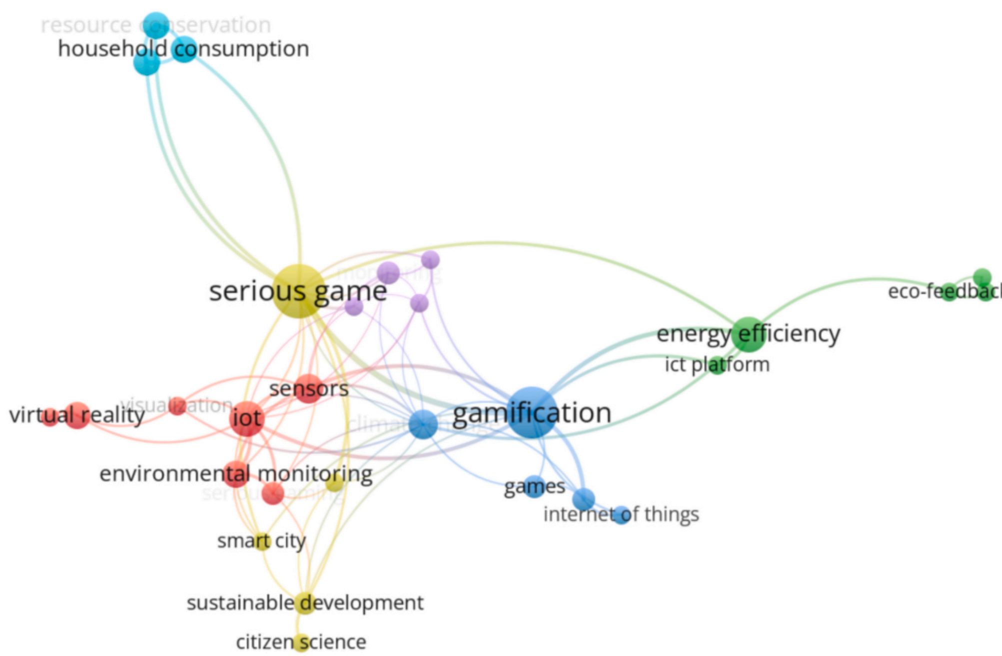


Fig. 4. Keyword co-occurrence analysis using VOSviewer.

efficiency and consumption remains less developed compared to technology-oriented and design-oriented research streams.

For instance, the keyword “energy efficiency” appears as part of a smaller cluster connected primarily to terms such as “gamification”, “ICT platform”, and “eco-feedback”, rather than forming a dense, independent network of energy-specific concepts. In contrast, technology-related keywords such as “IoT”, “sensors”, and “environmental monitoring” form a more interconnected cluster with multiple links to “serious game” and “gamification”, indicating a stronger integration of technological themes within the literature.

Furthermore, the network demonstrates that energy applications are often embedded within technology-driven contexts, such as IoT-enabled systems and smart environments, rather than being explored as standalone research themes. This suggests a reliance on digital infrastructures to support energy-related interventions.

3.2. Primary built-environment contexts

This section addresses RQ1 by examining the primary built-environment contexts in which serious games for energy-related applications have been developed and applied. This specifies where the game is situated (e.g., household, school, public building) and what type of built environment is explicitly addressed. Where studies explicitly refer to more than one built-environment context, they are reported as hybrid, and each stated context is counted. Among the selected studies, six primary context categories were identified. The categorization captures both the physical environment (e.g., residential buildings, schools, public facilities) and the scale at which energy-related activities are framed, ranging from individual households to urban or community-level systems. Table 4 summarizes the distribution of studies across these six categories, reporting the number of studies associated with each context. Because several studies explicitly describe more than one context (e.g., residential and urban, residential and educational), the

Table 4
Primary built-environment contexts addressed by serious games ($n = 69$).

Primary context category	Context definition	Example studies
Residential buildings (real or simulated)	Games are situated in residential homes, households, apartments, social housing, or smart homes, including both real occupied dwellings and simulated residential buildings.	[44–48]
Educational buildings	Games are explicitly situated in primary schools, secondary schools, universities, or educational buildings, including classroom-based and campus-level contexts.	[49–53]
Public and workplace buildings	Games are deployed in public, institutional, or workplace settings such as offices, museums, campuses, laboratories, or municipal buildings.	[51,53–56]
Urban / district / community-scale environments	Games are situated at the level of urban districts, neighborhoods, communities, cities, or energy communities, often combined with residential contexts.	[53,57–60]
Industrial / professional environments	Games are situated in industrial, service, or commercial organizations, or in professional energy-efficiency and investment decision-making contexts.	[50,56,61–63]
Hybrid contexts	Studies that explicitly reference more than one context, such as residential + urban or residential + educational.	[45,48,51,59,60]

counts are non-exclusive, and hybrid contexts are reported where applicable.

3.3. Primary learning objectives

This section addresses RQ1 by examining the primary learning objectives of the included serious games. Fig. 5 therefore represents the primary coded learning objective of each study, rather than all possible objectives reported across studies. The most frequently reported learning objective is awareness and knowledge building, representing the largest group of studies. These games aim to increase users' understanding of energy use, efficiency, and sustainability concepts, often targeting households or students [49,51].

For example, the EnerGAware serious game [45] was designed to improve household awareness of energy consumption by providing interactive feedback on daily energy use. The second most prominent category focuses on behavior change and habit formation, where games explicitly aim to reduce energy consumption or encourage sustained adoption of energy-efficient behaviors [10,47]. For instance, Geelen et al. [44] used a game-based intervention to encourage households to adopt energy-saving practices through repeated engagement and feedback. A substantial number of studies also emphasize motivation, engagement, and attitudes, seeking to influence users' willingness, intentions, or confidence to act on energy issues (e.g., [64–66]).

Decision-making and trade-off exploration appears as a distinct learning objective in several studies, particularly those addressing incentives, comfort trade-offs, or demand response [8,67]. For example, Garay Garcia et al. [68] developed a serious game to explore rebound effects by allowing users to experiment with energy-saving decisions and observe their consequences. A smaller subset of studies is explicitly aimed at professional training and skill development, such as improving competence in building design or energy-efficiency investment analysis [50,56,61]. Lastly, only a limited number of studies identify system-level understanding as their primary objective, addressing energy transitions and community-scale dynamics [58,59]. For instance, the GO2Zero simulation game [58] supports stakeholders in understanding energy transition processes at the district level.

3.4. Game elements and motivational design

This section addresses RQ1 by analyzing the game design elements used across the selected studies. The game elements reported in the summary spreadsheet were extracted, normalized, and categorized according to the Octalysis Gamification Framework [38], which organizes motivational design into eight core drives. Similar elements were consolidated into broader element groups, and each group was mapped to its primary motivational function within the framework. The resulting mapping is shown in Fig. 6.

The distribution of game elements shows a clear concentration in Core Drive 2, which appeared in 94.2% of the reviewed studies. This was the dominant motivational category, with commonly used elements including challenges, quests, missions, points, scores, feedback, dashboards, levels, progression, badges, achievements, goals, commitments, and pledges. This indicates that most studies relied heavily on achievement-oriented mechanisms that support measurable progress, performance feedback, task completion, and recognition.

The second most frequent category was Core Drive 5, which appeared in 75.4% of the studies. This core drive included competition,

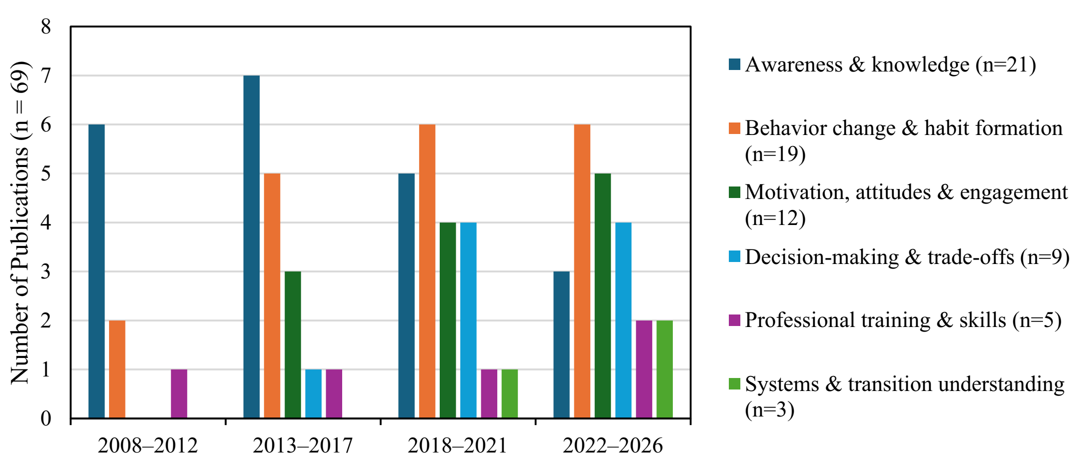


Fig. 5. Temporal distribution of the primary learning objectives included serious games for energy-related applications in the built environment. Each study was coded according to its dominant learning objective. Broader objectives, such as systems understanding, decision-making, motivation, or professional training, were included only when explicitly linked to energy use, energy efficiency, building performance, household energy behavior, demand response, smart-building operation, or related built-environment energy systems.

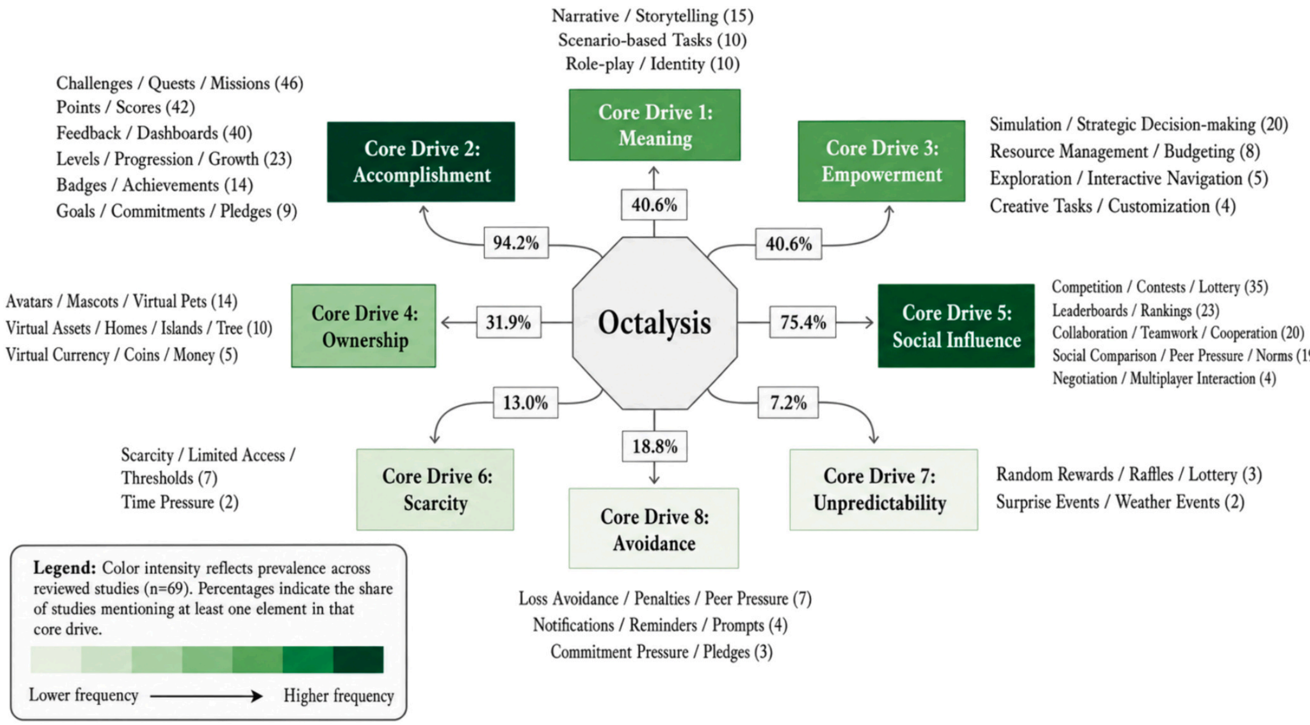


Fig. 6. Mapping of identified game elements to the Octalysis framework.

contests, leaderboards, rankings, collaboration, teamwork, cooperation, social comparison, peer pressure, social norms, negotiation, and multiplayer interaction. The prominence of this category suggests that many studies used peer interaction, comparative feedback, and collective participation as motivational strategies for encouraging energy-related engagement and behavior change.

Core Drive 1 and Core Drive 3 were each identified in 40.6% of the reviewed studies. Core Drive 1 was mainly represented through narrative, storytelling, scenario-based tasks, role-play, and identity-based design. These elements were used to provide users with contextual meaning, purpose, or a role within the learning environment. Core Drive 3 included simulation, strategic decision-making, resource management, budgeting, exploration, interactive navigation, creative tasks, and customization. These elements enabled users to test decisions, explore scenarios, and learn through interactive feedback, particularly in serious games, virtual homes, city-building environments, and simulation-based activities.

Core Drive 4 appeared in 31.9% of the studies. This category included avatars, mascots, virtual pets, virtual assets, homes, islands, trees, virtual currency, coins, and money. These elements were used to create a sense of personal investment, control, attachment, or ownership within the game environment. By contrast, the remaining core drives were much less frequently represented. Core Drive 8 appeared in 18.8% of the studies and included loss avoidance, penalties, peer-pressure-related avoidance, notifications, reminders, prompts, commitment pressure, and pledges. Core Drive 6: Scarcity and Impatience appeared in 13.0% of the studies and was mainly represented through scarcity, limited access, thresholds, and time pressure. Core Drive 7 was the least represented category, appearing in only 7.2% of the studies, mainly through random rewards, raffles, lotteries, surprise events, and weather events.

3.5. Delivery methods and application platforms (games)

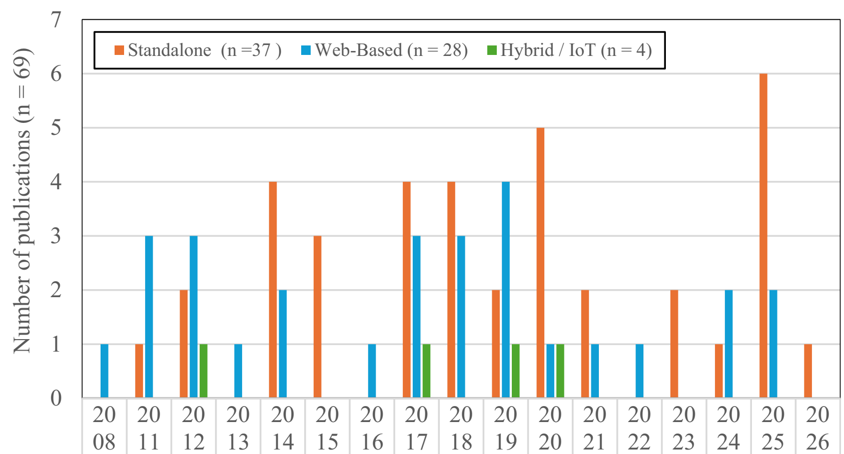
This section addresses RQ1 by examining the delivery methods used in the reviewed studies. In this review, delivery method refers to the medium or platform through which a serious game or game-based intervention is implemented and experienced by users, including digital, web-based, immersive, hybrid, and non-digital formats. The selected studies were categorized into four main delivery methods: standalone digital applications, web-based platforms, hybrid or IoT-integrated systems, and immersive environments. Standalone applications included locally installed desktop, mobile, or simulation-based games that did not require continuous internet connectivity [8,26,52]. Web-based platforms included browser-based games, online dashboards, and cloud-hosted learning systems [53,55,64]. Hybrid or IoT-integrated systems combined gameplay with real-world data sources, such as smart meters, sensors, dashboards, smart thermostats, or cloud-based infrastructures [45,48,51,60]. Immersive environments referred to systems using VR, AR, or MR technologies.

The results show a clear dominance in conventional screen-based delivery methods, particularly standalone and web-based applications, which accounted for most studies. These platforms were commonly accessed through desktops, laptops, tablets, or mobile devices and were mainly used in educational and residential contexts. Standalone applications appeared consistently across the reviewed period, especially from 2014 onwards, while web-based platforms were present from the earliest identified study in 2008 and continued across later years. By contrast, hybrid or IoT-integrated systems were reported in only a small number of studies and appeared intermittently over time. Fully immersive delivery methods, such as VR, AR, or MR, were not classified as a major delivery category under the applied criteria. Overall, the findings indicate that serious games in this field remain largely dependent on conventional screen-based formats, with limited use of real-world data integration or immersive technologies (Table 5).

This temporal distribution is further illustrated in Fig. 7, which shows the annual frequency of each delivery method. As shown in the figure, standalone applications demonstrate a consistent presence over time, while web-based platforms exhibit moderate variation across years. In contrast, hybrid or IoT-integrated systems appear only in a limited number of studies and at low frequencies.

Table 5
Delivery methods and application platforms.

Category	Description	Typical technologies / platforms	Advantages	Limitations	Example studies
Standalone digital applications	Locally installed or offline games running on a single device, or screen-based digital games not dependent on continuous real-time data connection.	Desktop software, mobile apps, simulation tools, classroom digital games	High control, stable performance, no continuous internet required	Limited scalability, device dependency, limited real-world data integration	[8,47,49,50,52,68]
Web-based platforms	Browser-based games, online dashboards, or cloud-hosted platforms accessible via the internet.	HTML5 games, online simulations, web dashboards, cloud-based interfaces	High accessibility, easy distribution, scalable	Requires internet access, may have performance or engagement constraints	[53,55,59,64,69,70]
Hybrid / multi-platform systems	Integration of multiple delivery modes or linkage with real-world systems, including monitored data, dashboards, sensors, or smart devices.	IoT-connected games, smart-meter dashboards, smart thermostats, cloud platforms, blended learning setups	Rich interaction, real-time feedback, adaptive or context-aware potential	Complex implementation, higher technical requirements, privacy and data-integration issues	[45,48,51,54,60,71]
Immersive / 3D environments	Fully or partially immersive systems, or interactive 3D environments using extended-reality or game-engine technologies.	VR headsets, AR mobile apps, MR systems, Unity3D environments, 3D simulations, head-mounted displays	High engagement, realistic interaction, experiential learning, spatial understanding	High cost, hardware requirements, accessibility barriers, limited use in the reviewed studies	[50,51,63,67,72]



	2008	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Standalone (n =37)	0	1	2	0	4	3	0	4	4	2	5	2	0	2	1	6	1
Web-Based (n = 28)	1	3	3	1	2	0	1	3	3	4	1	1	1	0	2	2	0
Hybrid / IoT (n = 4)	0	0	1	0	0	0	0	1	0	1	1	0	0	0	0	0	0

Fig. 7. Temporal distribution of delivery methods used in the 69 included studies. Standalone = locally installed or offline applications; web-based = browser-accessible or cloud-hosted platforms; hybrid/IoT = systems connected to sensors, dashboards, real-time data, or Internet of Things infrastructure.

3.6. *Energy-related applications*

This section addresses RQ1 by identifying energy-related applications. The selected studies addressed a range of energy-related applications within the built environment. These were categorized into heating, ventilation, and air conditioning, appliances, whole-building energy performance, lighting, renewable energy systems, and other application areas, based on the primary focus of each study. Across the selected literature, the heating, ventilation, and air conditioning systems and appliance-related applications were among the most commonly addressed domains, alongside studies focusing on whole-building energy performance and lighting systems. These application areas were consistently represented across the studies and were often considered in combination within individual implementations, particularly in studies that examined multiple end-use systems or overall household energy consumption [45,48,53]. In contrast, renewable energy applications were less frequently addressed, with only a limited number of studies focusing on domains such as photovoltaic systems or energy generation scenarios [8]. Several studies also adopted integrated approaches, incorporating multiple energy-related applications within a single framework, particularly in cases involving whole-building analysis or combined energy-use scenarios [60]. Collectively, multiple energy application areas were frequently considered within individual studies, resulting in overlapping across categories. The distribution reflects the range of domains in which serious games have been applied within the built environment.

3.7. *User profiles and sample sizes*

This section addresses RQ2 by examining the target users and sample characteristics of the reviewed studies. Across the selected studies, user profiles were predominantly non-professional, with only a limited number of studies targeting expert users. As summarized in Table 6, non-professional participants accounted for most of the literature (81.2%), followed by mixed or multi-stakeholder groups (15.9%), while studies focusing exclusively on professional users were rare (2.9%). This distribution indicates that serious games in the energy and built environment domain are primarily designed for awareness raising and behavioral engagement rather than for supporting expert-level decision-making. School-aged learners and mixed-user configurations also represented a notable portion of the sample, whereas employees, occupants, and energy professionals were comparatively underrepresented.

Table 6
Detailed user profile categories and sample size summary.

User profile category	No. of studies	% of studies	Typical users included	Studies with reported N	Median N	Range
Household residents	20	29.0%	Homeowners, tenants, families, social housing residents, low-income residents, household occupants	16	82.0	4–3603
University students	14	20.3%	Undergraduate students, graduate students, dormitory residents, architecture/engineering students	14	46.5	10–10,000
Mixed / multi-stakeholder	11	15.9%	Students, staff, visitors, policymakers, practitioners, local stakeholders, households, managers	6	245.0	50–10,000
School students and educators	10	14.5%	Children, primary/secondary school students, teachers, educators, parents	10	67.0	13–6000
General adults / community users	7	10.1%	Adult residents, community participants, public users, app users	7	91.0	10–349
Employees / occupants	5	7.2%	Corporate employees, public-sector employees, research staff, building occupants	4	127.5	18–230
Energy / building professionals	2	2.9%	Energy engineers, consultants, policy professionals, academics	2	19.0	19–19

Note: N refers to the number of participants reported in each study. Percentages are calculated based on the total number of selected studies (n = 69). Some studies reported mixed or multi-stakeholder samples; therefore, interpretation should consider possible overlaps between user categories.

This pattern suggests a strong reliance on accessible populations (i.e., students) which may limit the generalizability of findings to real-world contexts where energy decisions are made by a broader range of stakeholders. The distribution of sample sizes across these user categories is presented in Table 6. There is substantial variability in reported sample sizes, with several categories exhibiting highly skewed distributions and extreme outliers. For instance, student- and school-based studies occasionally involved large-scale deployments, whereas professional-user studies remained consistently small. Consequently, median values provide a more reliable representation of central tendency than mean values in this context. The observed dispersion highlights inconsistencies in study design and scale, which should be considered when interpreting and comparing results across the selected studies.

This indicates that most serious game applications in this area have been developed for public-facing learning, awareness, and engagement purposes rather than for specialist professional training. The relatively high share of student-based samples also suggests that many studies were conducted in educational settings where recruitment is easier and interventions can be embedded into existing teaching activities. However, this raises an important methodological issue, as student participants may not accurately represent real-world household decision-makers or professional energy actors. In addition, sample sizes were highly uneven across the reviewed studies, with some categories including both small exploratory pilots and large-scale implementations. This heterogeneity should be considered when interpreting the overall evidence base, as it limits direct comparability across studies.

3.8. User–building interactions

This section addresses RQ2 by examining how users interact with building-related systems within serious game environments. The identified interactions were classified into five main types: manual input, simulation-based interaction, feedback-driven interaction, real-time or data-driven interaction, and adaptive or intelligent interaction. Manual input interactions refer to cases where users select actions or adjust predefined options, such as operational settings or energy-saving strategies, within controlled interfaces. Simulation-based interactions occur in modeled or virtual environments, where users manipulate variables and observe outcomes, commonly supporting scenario-based decision-making (e.g., [45,48]). Feedback-driven interactions provide system-generated responses, such as energy indicators, performance metrics, or progress feedback, helping users understand the consequences of their decisions and supporting iterative learning [53]. Real-time or data-driven interactions involve external or live data sources, such as sensor data or monitored building performance, allowing game responses to reflect actual or changing conditions. However, these were observed in only a limited number of studies, suggesting that most applications remained within predefined or simulated environments (e.g., [60]). Adaptive or intelligent interactions, where scenarios, feedback, or difficulty change based on user behavior or performance, were also rare and mostly limited to simple rule-based adjustments rather than fully adaptive or AI-driven systems (Fig. 8).

3.9. Technological features

This section addresses RQ2 by identifying the technological features used to support interaction, feedback, and system integration. The selected studies used a diverse range of technological features to design, implement, and deliver serious games within the built environment. These features were categorized into 3D visualization and simulation, gamification mechanics, data and sensor integration, feedback and analytics, user interface and user experience design, immersive technologies, artificial intelligence and adaptive systems, and online or cloud-based technologies, based on their primary function within the game environment. The categorization of these technological features is illustrated in Fig. 9.

Across the selected literature, 3D visualization and simulation technologies were among the most commonly implemented features, enabling users to explore building environments and interact with simulated scenarios. These were frequently used to represent indoor spaces, environmental conditions, and system behavior within controlled virtual settings.

Gamification mechanics were also widely incorporated, particularly accomplishment-based elements such as challenges, quests, missions, points, scores, feedback, dashboards, levels, progression, badges, and achievements. These elements were used to structure user engagement, provide performance feedback, and support progression within the game environment (e.g., [53]). In addition, many studies integrated data and sensor-based features, allowing games to incorporate real-time or context-based information related to energy consumption and environmental conditions (e.g., [60]).

Several studies also implemented feedback and analytics features, providing users with information on their actions, performance, and outcomes. These features were commonly used to support interaction and track progress within the game environment. In parallel, user interface and user experience design elements played a key role in enabling interaction, with studies emphasizing intuitive navigation, visual clarity, and accessibility.

More advanced technological features were less frequently observed. These included immersive technologies, such as virtual and augmented reality, which were used to enhance user presence and interaction within simulated environments. Similarly, artificial intelligence and

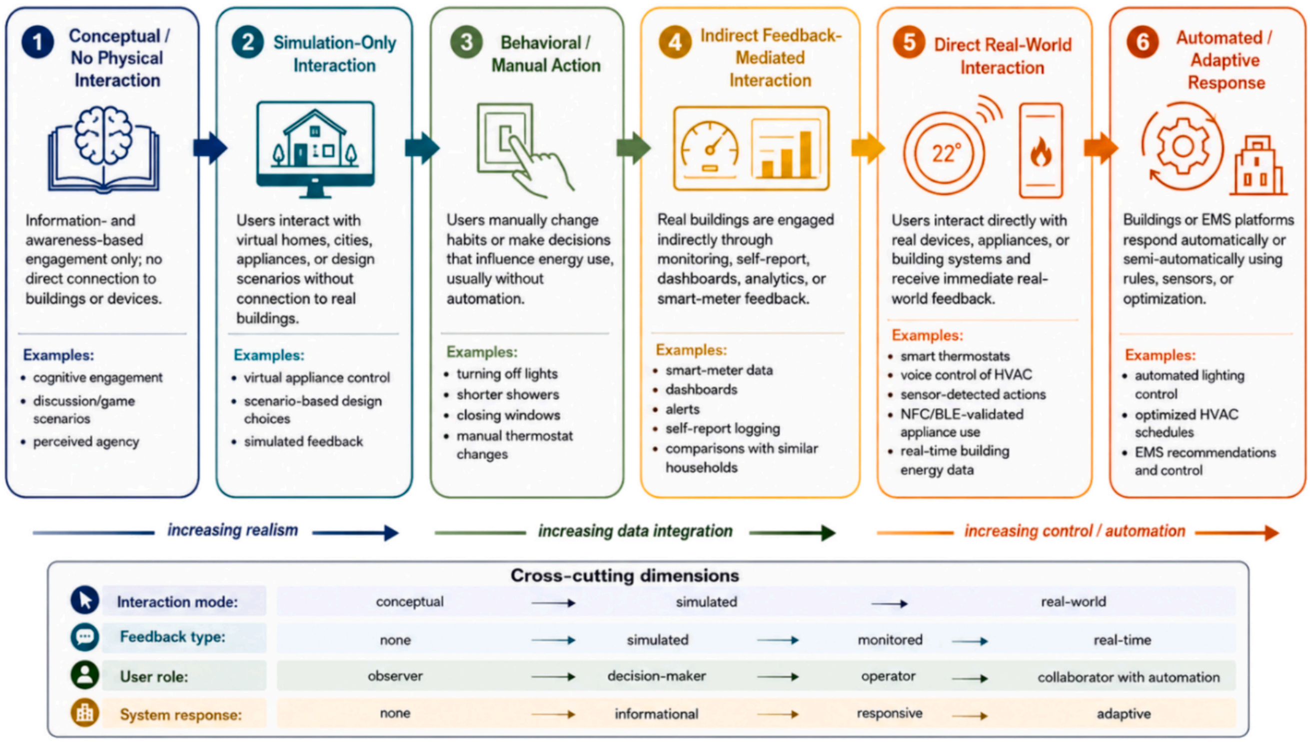


Fig. 8. Categorization and qualitative synthesis of user-building interactions identified in the selected studies. Most studies cluster around simulation, behavioral change, and feedback-based automated or adaptive building responses.

adaptive systems were applied in some studies to personalize user experiences or adjust system responses dynamically. Finally, several studies employed online and cloud-based technologies, enabling web-based deployment, data storage, and multi-user interaction across platforms.

3.10. Reported outcomes

This section addresses RQ3 by summarizing the outcomes reported in the selected studies. The outcomes were grouped into five non-mutually exclusive categories: energy-related performance, learning, behavioral, psychological and user-experience, and system or interaction outcomes. Energy-related performance outcomes were reported in 40 studies (58.0%), followed by learning outcomes in 38 studies (55.1%), behavioral outcomes in 37 studies (53.6%), psychological and user-experience outcomes in 31 studies (44.9%), and system or interaction outcomes in 8 studies (11.6%) (Table 7). Energy-related performance outcomes included measured or simulated electricity and gas consumption, energy savings, thermostat settings, appliance load shifting, demand response, and energy-efficiency decisions. Some studies reported measurable improvements, including 3.46% electricity and 7.48% gas savings among active EnerGAware users [45], a 16.31% short-term electricity reduction during a residence energy competition [53], and approximately 8% short-term electricity savings in an app-based intervention [10]. However, these effects were often short-term or not sustained, indicating that evidence of lasting real-world energy impact remains limited.

Learning outcomes were frequently reported in educational and simulation-based studies, including improvements in energy awareness, knowledge acquisition, energy-efficiency understanding, and systems-level learning [50,52]. Behavioral outcomes included energy-saving practices, behavioral intentions, adoption intentions, in-game decisions, and willingness to adjust household systems [8,64]. However, many behavioral findings were based on self-reported intentions or simulated choices rather than verified real-world behavior. Psychological and user-experience outcomes included engagement, motivation, attitudes, usability, satisfaction, acceptance, and perceived behavioral control. These outcomes were generally positive, especially in studies using feedback, competition, or interactive simulations, although some longer deployments reported declining engagement over time. System and interaction outcomes were less common and mainly focused on task performance, interaction quality, platform use, and usability-related system performance.

3.11. Evaluation approaches

This section addresses RQ3 by examining how the reviewed studies evaluated effectiveness, usability, and impact. The selected studies employed a range of evaluation approaches to assess the effectiveness, usability, and impact of serious games in energy-related applications. These approaches were categorized into questionnaires and surveys, pre–posttests and knowledge assessments, behavioral and performance-based measures, observation and logging methods, qualitative approaches, comparative or control group designs, and physiological measures, based on the primary method used to collect and analyze data. The categorization of evaluation approaches is illustrated in Fig. 10.

Across the selected studies, questionnaires and surveys were the most commonly applied evaluation approaches, frequently used to capture user perceptions, satisfaction, engagement, and self-reported outcomes [51,73]. In addition, pre–posttests and knowledge assessments were widely employed to evaluate learning gains and knowledge acquisition resulting from game-based interventions [45,53,64]. Several studies also utilized behavioral and performance-based measures, drawing on in-game data such as scores, completion rates, decision-making patterns, and time spent on tasks to assess user performance and interaction. Similarly, observation and logging methods were used to collect objective data on user actions and system interactions, often through system logs or interaction tracking.

Several studies adopted qualitative approaches, including interviews, focus groups, and open-ended feedback, to gain deeper

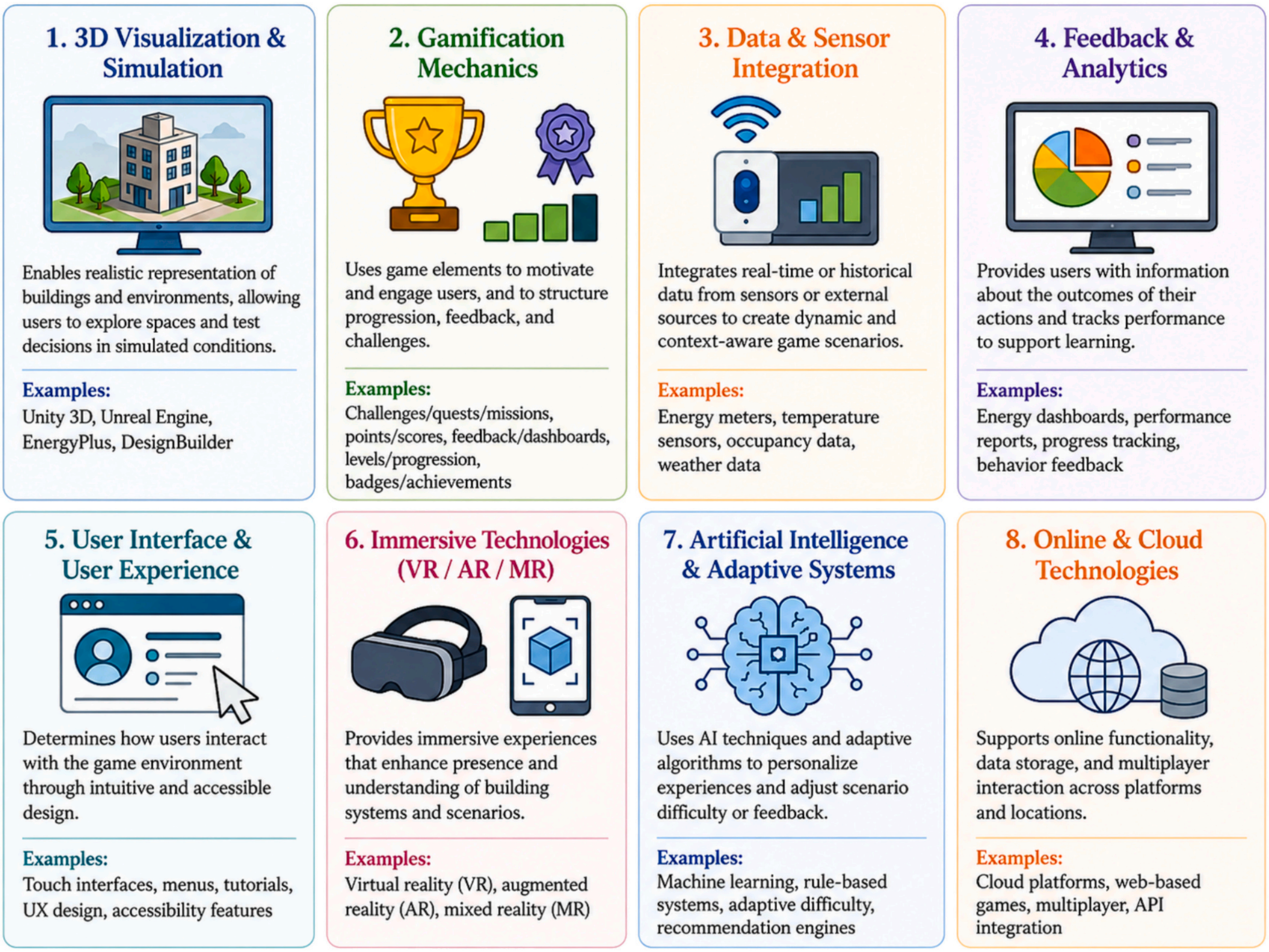


Fig. 9. Categorization of technological features used in serious games for the environment built across the selected studies.

insights into user experiences and perceptions [55,75]. In some cases, comparative or control group designs were implemented to examine the effectiveness of serious games relative to traditional learning methods or alternative interventions [46,57]. More advanced evaluation approaches were less frequently reported. These included physiological measures, including heart rate, eye tracking, or galvanic skin response, used to assess user engagement and emotional responses [54].

3.12. Reported challenges

This section addresses RQ4 by identifying the main challenges reported across the selected studies. The selected studies identified a range of challenges associated with the design, implementation, and evaluation of serious games for energy-related applications. These challenges were categorized into technical challenges, user-related challenges, design and usability challenges, implementation and deployment challenges, and evaluation-related challenges, based on the nature of the reported limitations. As summarized in Table 8, the most frequently reported challenges were technical and user-related challenges, followed by issues related to design and usability.

A smaller number of studies reported challenges associated with implementation and evaluation processes. Technical challenges included limitations related to system performance, integration with external data sources, and the complexity of developing interactive environments [45,47,51]. These issues were particularly evident in studies involving data-driven platforms or system integration. User-related challenges were commonly associated with participant engagement, variability in user knowledge, and differences in user behavior [10,44,64]. These challenges were reported across both general user groups and mixed populations. Design and usability challenges included issues related to interface complexity, clarity of instructions, and balancing game elements with educational content, often identified through user feedback or usability assessments [65,66]. Implementation and deployment challenges were reported in studies involving real-world applications, including constraints related to infrastructure, scalability, and accessibility [56,58]. Evaluation-related challenges included limitations in study design, small sample sizes, reliance on self-reported data, and difficulties in measuring long-term outcomes [10,47]. Multiple challenges were often reported within the same study, resulting in overlaps across categories.

3.13. Learning theories and conceptual frameworks

This section addresses RQ4 by examining the theoretical foundations used to guide serious game design and evaluation. The reviewed studies employed a range of learning theories and conceptual frameworks to inform the design and evaluation of serious games. These were categorized into behavioral theories, motivational theories, experiential and constructivist approaches, gamification frameworks, and cognitive learning theories, based on their primary focus. As shown in Table 9, behavioral theories were the most commonly applied, reflecting a strong emphasis on behavior change, decision-making, and social influence

Table 7
Reported outcome categories across the selected studies.

Outcome category	Commonly analyzed outcomes	Summary of reported results	Example studies
Energy-related performance outcomes	Electricity/gas consumption, energy savings, demand response, thermostat setpoints, appliance load, peak shifting, simulated or measured energy performance	Some studies reported measurable reductions or improved energy-related decisions, but effects varied substantially. For example, reported savings included 3.46% electricity and 7.48% gas in EnerGAware, 16.31% short-term electricity reduction in a residence competition, and approximately 8% short-term electricity savings in an app-based intervention. However, several effects were not statistically significant or were not sustained over time.	[10,45,53,60,67]
Learning outcomes	Energy awareness, knowledge acquisition, understanding of energy efficiency, systems understanding, sustainability knowledge	Learning outcomes were frequently positive, especially in educational or simulation-based settings. Several studies reported improved knowledge, awareness, or conceptual understanding, although many relied on short-term pre–posttests or self-reported learning.	[50–52,64]
Behavioral outcomes	Energy-saving actions, behavioral intention, adoption intention, in-game choices, thermostat or appliance adjustment, conservation practices	Behavioral outcomes were commonly assessed through self-reports, intentions, or gameplay decisions. Some studies showed increased intention or willingness to act, but fewer verified whether behaviors persisted in real-world settings.	[8,10,73]
Psychological and user-experience outcomes	Motivation, engagement, attitudes, perceived behavioral control, satisfaction, usability, acceptance, enjoyment	Most studies reported positive engagement, motivation, usability, or acceptance. However, engagement often declined over time in longer deployments, suggesting that initial interest does not necessarily translate into sustained participation.	[48,51,63,64]
System and interaction outcomes	Task performance, interaction quality, platform use, completion, usability-related system performance, decision accuracy	Fewer studies evaluated system-level or interaction outcomes directly. These outcomes were usually reported in studies using simulations, dashboards, logs, or interactive platforms, and were mainly used to assess functionality or user interaction rather than energy impact.	[59,65,67,74]

within energy-related contexts. This was followed by motivational theories, which were used to support user engagement and participation, and experiential approaches, which focused on learning through interaction and experience within game environments. Gamification frameworks were also widely adopted to structure game elements and user engagement mechanisms, while cognitive learning theories were comparatively less frequently reported. In addition, a small number of studies did not explicitly state any underlying theoretical foundation.

3.14. Reported future directions

This section addresses RQ4 by synthesizing the future research directions proposed in the selected studies. The selected studies identified a set of future research directions that can be grouped into technological advancements, user-centered design improvements, methodological enhancements, application expansion, and integration with real-world systems. These categories represent the main areas of development highlighted across the selected studies, which presents a structured overview of the reported directions and their interrelationships. The future directions related to technological advancements focus on the integration of emerging technologies, including artificial intelligence, adaptive systems, and immersive environments, as well as improvements in simulation realism and system responsiveness. In parallel, user-centered design improvements emphasize enhancing user engagement, usability, and accessibility, alongside the incorporation of personalization and adaptive learning mechanisms to better accommodate diverse user groups.

The prior studies also highlight the need for methodological enhancements, particularly using longitudinal study designs, larger and more diverse participant samples, and the adoption of objective and performance-based evaluation measures. In addition, several studies point toward application expansion, including extending serious games to new energy domains, broader building contexts, and cross-disciplinary applications. Lastly, a key area of development involves integration with real-world systems, where future work aims to connect serious games with real-time data, sensor networks, and smart building technologies. This includes linking simulation environments with practical decision-making contexts and supporting implementation within real-world energy systems.

4. Discussion

The findings suggest that serious games for energy-related

Fig. 10. Overview of evaluation approaches used in serious games for energy-related applications in the built environment, illustrating key categories and their role within a typical evaluation workflow.

applications in the built environment are not developing as a fully integrated intervention field, but rather as a set of loosely connected educational, behavioral, and technological experiments. The strongest pattern across the selected studies is the dominance of residential and educational contexts, with limited attention to professional, industrial, and operational environments. This is evident in studies targeting household residents, social housing tenants, students, and school communities, where the primary emphasis is often awareness, engagement, or household-level energy conservation [45,49,51,53]. While these settings are useful for recruitment and controlled testing, they only partially represent the context in which energy-related decisions are made in practice. Building managers, designers, energy consultants, facility operators, and policymakers remain underrepresented, despite their central role in shaping actual building performance.

This imbalance has important implications for design and evaluation. Because many studies are conducted with accessible non-professional users, the resulting games often prioritize simplified learning tasks, visible rewards, and short-term engagement. For example, accomplishment-oriented mechanics such as challenges, quests, missions, points, scores, feedback, dashboards, levels, progression, badges, and achievements are common across the reviewed literature, reflecting a broader tendency in gamification research to rely on measurable and easily implemented design elements [85,86]. However, recent work on motivation and pro-environmental behavior suggests that the effectiveness of such elements depends less on whether they are intrinsically or extrinsically oriented, and more on whether they support autonomy, competence, relatedness, internalization, and personally meaningful goals [87,88]. Therefore, achievement-based mechanics should not be treated as inherently weak or ineffective. Rather, their long-term value depends on how they are embedded within broader behavior-change designs that connect game feedback, energy-saving actions, social context, and users' own reasons for acting.

A second issue is the mismatch between the ambitions of the reviewed studies and the strength of their evidence. Several games aim to promote behavior change, household energy conservation, or energy-related decision-making, yet many evaluations rely on short-term surveys, pre–post knowledge tests, or self-reported intentions. Studies such as EnerGAware and EnergyCat provide stronger examples because they attempt to connect gameplay with household energy behavior or monitored consumption data [45,46]. Similarly, Wemyss et al. [10] demonstrate the value of examining whether intervention effects persist beyond initial engagement. However, such longitudinal and behavior-focused evidence remains limited. This creates a gap between reported educational or motivational benefits and the level of evidence needed to verify real-world energy impact.

This gap reflects a limitation of the current empirical evidence base rather than a methodological limitation of the present review.

Technological findings reinforce the same limitation. Most serious games remain standalone or web-based systems, usually operating through predefined scenarios rather than real building conditions. Simulation-based games can be valuable for helping users understand complex trade-offs, as seen in studies on residential rebound effects, building sustainability, and energy simulation education [50,61,68]. Simulation-based approaches may be insufficient on their own to demonstrate real energy-performance impact unless they are supported by real-world data, longitudinal evaluation, or operational validation. More recent work, including Kim et al. [48] and Kim et al. [60], shows the potential of linking games with smart thermostats, eco-feedback, real-time data, and community-level energy mechanisms. These examples indicate a possible direction for the field, but they remain exceptions rather than the norm.

The reviewed studies also show that social influence is one of the most promising but unevenly implemented design pathways. Social comparison, peer engagement, competition, and cooperation appear in several household and student-focused interventions [44]. This aligns with broader evidence that social norms and peer comparison can influence energy conservation behavior [89]. However, social mechanics are not automatically effective. Competitive ranking may increase

Table 8
Classification of reported challenges.

Challenge category	Description	Typical issues	Example studies
Technical challenges	Challenges related to system development, performance, data integration, and technical reliability.	Integration with sensors or external data sources, platform stability, real-time data handling, technical complexity, interoperability, and system performance.	[45,47,48,51,54]
User-related challenges	Challenges associated with user variability, participation, motivation, and sustained engagement.	Differences in prior knowledge, motivation, household routines, digital literacy, user fatigue, attrition, and declining engagement over time.	[10,44,46,53,64]
Design and usability challenges	Challenges related to interface design, gameplay clarity, usability, and balancing educational and game elements.	Interface complexity, unclear instructions, excessive cognitive load, weak usability, limited accessibility, and difficulty balancing learning content with engaging gameplay.	[45,52,65,66,76]
Implementation and deployment challenges	Challenges related to applying serious games in real-world settings and scaling them beyond controlled studies.	Infrastructure requirements, recruitment, deployment cost, access to real users, institutional constraints, scalability, and integration into operational or educational settings.	[48,51,56,58,59]
Evaluation-related challenges	Challenges associated with research design, outcome measurement, and validation of impact.	Small sample sizes, short study durations, reliance on self-reported data, lack of control groups, limited longitudinal evidence, and difficulty measuring real-world energy impact.	[10,45–47,64]

Note: Challenge categories are not mutually exclusive because several studies reported more than one limitation or implementation barrier. The table reports representative studies for each category; the full study-level coding is provided in the Supplementary Materials.

engagement for some users but reduce autonomy or discourage others, especially when users differ in baseline knowledge, motivation, or household constraints. Therefore, future serious games should treat social influence as a design variable requiring careful testing, not as a universal solution.

4.1. Relationship between game elements and user types

To further examine how gamification strategies vary across application contexts, the identified game elements were analyzed in relation to dominant user types and mapped through the Octalysis core drives. As shown in Fig. 11, different user groups appear to be associated with different motivational emphases: student-focused applications are most strongly associated with Core Drive 2, household-oriented applications with Core Drive 5, and professional-oriented systems with Core Drive 3. This pattern suggests that game design in the built environment is not universal; rather, motivational strategies vary according to the intended users, learning context, and type of energy-related decision-making involved.

The dominance of accomplishment-based mechanics in student-focused applications aligns with Goal-Setting Theory, which emphasizes structured tasks, measurable progress, and feedback [90]. In the reviewed studies, this drive was represented by elements such as challenges, quests, missions, points, scores, feedback, dashboards, levels, progression, badges, achievements, goals, commitments, and pledges. These elements are well suited to educational settings because they provide clear learning targets, visible progress, and performance-based reinforcement. However, this pattern also indicates a potential methodological bias. Since many gamification studies rely on student samples, the dominance of Core Drive 2-driven designs may partly reflect research convenience rather than evidence that accomplishment-based mechanics are the most effective approach for real-world energy behavior change. Supporting this concern, previous gamification studies have shown that reward- and achievement-based systems can generate short-term engagement without necessarily producing sustained behavioral outcomes [85,91].

In contrast, household-oriented applications showed stronger alignment with Core Drive 5. This drive was reflected through elements such as competition, contests, leaderboards, rankings, collaboration, teamwork, cooperation, social comparison, peer pressure, social norms, negotiation, and multiplayer interaction. These mechanisms are consistent with Social Learning Theory and Self-Determination Theory, particularly where users observe, compare, or coordinate their behavior with others [89,92]. In household energy contexts, social comparison and peer feedback can make otherwise invisible energy practices more visible and socially meaningful. However, their effectiveness depends heavily on design. Cooperative and community-oriented approaches may strengthen relatedness and collective engagement, whereas competitive ranking systems may reduce autonomy or discourage users who perform poorly. Therefore, social gamification should not be treated as inherently effective; it requires careful calibration to the user group and behavioral context.

Professional-oriented applications were more strongly associated with Core Drive 3, including simulation, strategic decision-making, resource management, budgeting, exploration, interactive navigation, creative tasks, and customization. These elements align with constructivist and experiential learning theories, which emphasize learning through interaction, experimentation, and decision-making [93]. Such approaches are particularly relevant in professional built-environment contexts, where users often need to understand complex trade-offs between energy performance, cost, comfort, design choices, and operational constraints. Simulations, scenario-based decision-making, and interactive exploration can support deeper systems thinking than simple achievement-based mechanics. However, despite this strong theoretical alignment, many reviewed studies provided limited empirical validation beyond short-term knowledge or engagement outcomes. More rigorous evidence is needed to determine whether empowerment-based mechanics improve professional judgement, design decisions, or long-term practice.

A further observation from Fig. 11 is the relatively limited role of Core Drive 1, Core Drive 4, Core Drive 6, Core Drive 7, and Core Drive 8 across user groups. Core Drive 1 was represented by narrative, storytelling, scenario-based tasks, and role-play or identity-based design, while Core Drive 4 included avatars, mascots, virtual pets, virtual assets, homes, islands, trees, virtual currency, coins, and money. These drivers may be important for deeper personal relevance, identity formation, and long-term engagement, yet they were less prominent than accomplishment- and social-influence-based mechanics. Core Drive 6, Core Drive 7,

Table 9
Learning theories and conceptual frameworks reported across the selected studies.

Category	Description	Examples of theories/frameworks	Example studies
Behavioral theories	Frameworks focus on behavior change, decision-making, social influence, habit formation, or persuasive intervention mechanisms.	Theory of Planned Behavior, Value-Belief-Norm theory, Fogg Behavior Model, social norms theory, persuasive technology, behavior-change principles.	[8,10,44,48,53,64,73]
Motivational theories	Frameworks focusing on intrinsic/extrinsic motivation, engagement, autonomy, competence, relatedness, or motivational design.	Self-Determination Theory, ARCS motivational model, intrinsic motivation theory, flow theory, IMMS.	[50,52,53,63,74,77,78]
Experiential and constructivist approaches	Frameworks emphasize learning through interaction, simulation, inquiry, role-play, exploration, and reflection.	Experiential learning, constructivism, inquiry-based learning, situated learning, simulation-based learning.	[49–51,56,58,79]
Gamification and serious game frameworks	Frameworks used to structure game design, mechanics, motivational affordances, or serious game development.	Octalysis, MDA framework, Four-Dimensional Framework, serious game design principles, gamification design frameworks.	[47,55,65,76,80,81]
Cognitive learning theories	Frameworks focusing on knowledge acquisition, cognitive processing, conceptual change, or structured learning objectives.	Bloom's Taxonomy, cognitive load theory, conceptual change theory, multimedia learning theory, information processing.	[50,69,76,77,82]
Not explicitly reported	Studies that did not clearly state a formal theory or framework, although some used implicit design principles such as feedback, awareness raising, or user engagement.	N/A	[54,62,83,84]

Note: Some studies employed more than one theory or framework; therefore, categories are not mutually exclusive. The table reports representative aligned studies for each category, while the full study-level coding is provided in the Supplementary Materials.

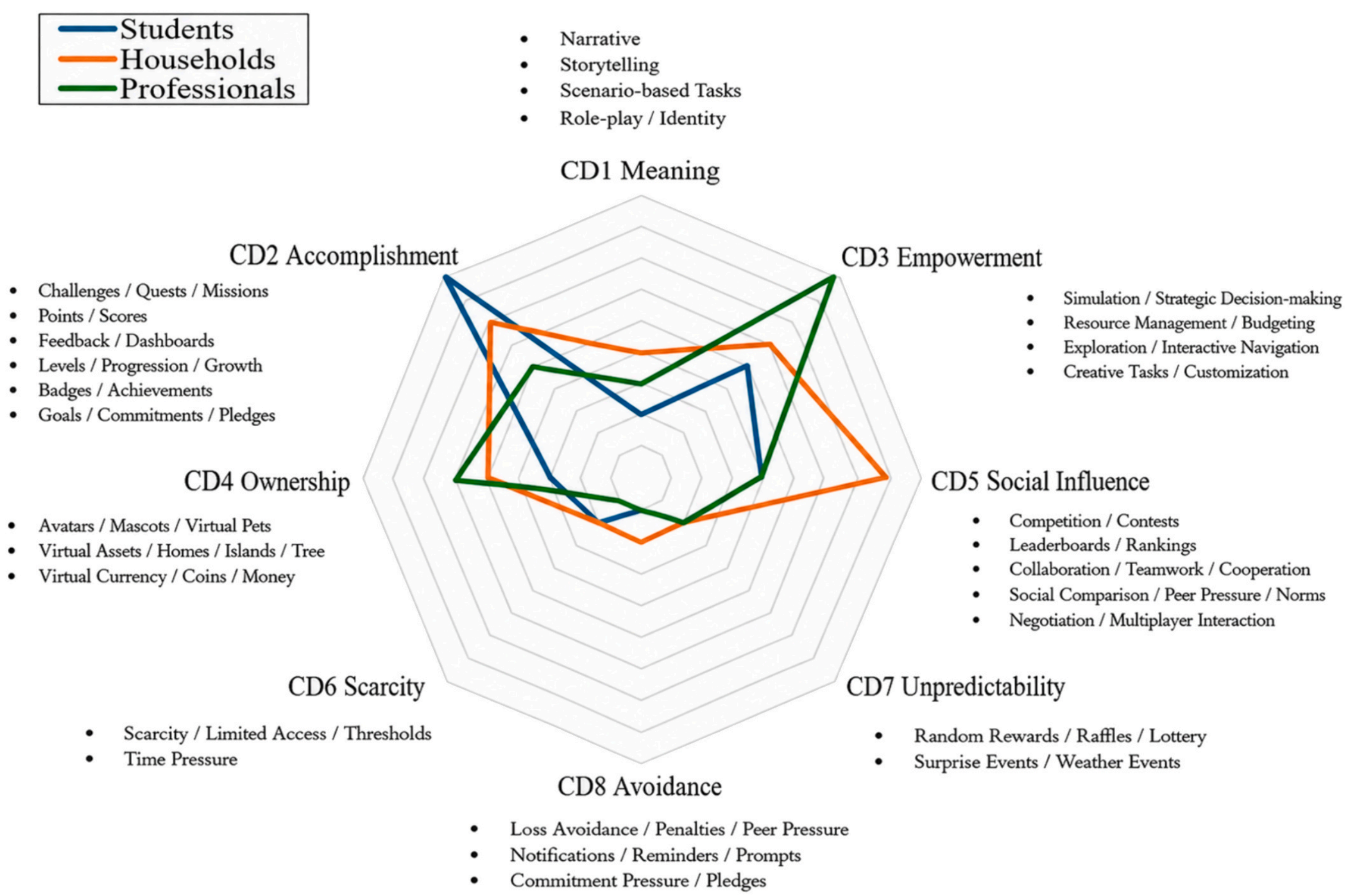


Fig. 11. Relationship between Octalysis core drives and dominant user types across the reviewed studies. Values represent normalized relative intensities on a 0–10 scale derived from qualitative synthesis, not direct frequency counts.

and Core Drive 8 were also comparatively weak, appearing through elements such as limited access, thresholds, time pressure, random rewards, raffles, surprise events, weather events, penalties, reminders, prompts, and commitment pressure. Their limited use suggests that urgency, uncertainty, scarcity, and avoidance-based mechanisms remain underdeveloped in energy-related serious games and gamified interventions.

The findings indicate a mismatch between dominant design practices and the motivational complexity required for real-world built-environment applications. Current studies appear to prioritize easily measurable mechanics, such as points, badges, levels, leaderboards, and feedback, while deeper motivational constructs related to meaning, ownership, identity, creativity, and long-term behavioral internalization remain less developed [86,94]. This is a critical limitation because energy behavior is shaped not only by knowledge or short-term motivation, but also by household routines, social norms, professional judgement, environmental constraints, and sustained engagement over time.

Future studies should empirically test the effectiveness of different game design strategies across user groups, particularly through comparative and longitudinal designs. Greater attention should be given to meaning, ownership, and identity-based design, while empowerment-based approaches should be tested more rigorously in professional and decision-support contexts. In addition, integrating serious games with real-world energy data, such as smart meters, sensors, IoT systems, and building-performance feedback, could improve the ecological validity of behavioral outcomes. Finally, future research should adopt stronger theory-driven approaches by explicitly linking game mechanics to learning, motivation, and behavior-change constructs, and by validating their effects on decision-making, practice, and long-term energy outcomes.

4.2. Linking game elements, core drives, and learning theories

To further interpret the relationship between the identified game elements and the reported learning theories, a mapping was developed using the Octalysis framework as an intermediate analytical layer. This mapping links individual game elements to their corresponding Octalysis core drives and then to the learning theories identified across the reviewed studies. As illustrated in Fig. 12, the mapping shows how specific motivational mechanisms align with broader theoretical learning constructs.

Fig. 12 highlights the dominance of accomplishment- and social-driven mechanisms and their links to Goal-Setting Theory, Self-Determination Theory, and Social Learning Theory. The strongest concentration appears in Core Drive 2, which includes challenges, quests, missions, points, scores, feedback, dashboards, levels, progression, badges, achievements, goals, commitments, and pledges. These elements align strongly with Goal-Setting Theory because they translate abstract energy-related objectives into measurable targets, visible progress, and performance-based feedback (e.g., [85]). In energy-related applications, such mechanics can help users track progress, complete structured tasks, and receive reinforcement for desired actions. However, the dominance of Core Drive 2 also indicates a potential over-reliance on achievement-based design. If these mechanics are used mainly as rewards or performance markers, they may support short-term engagement without necessarily producing durable behavioral change or deeper internalization [91].

Core Drive 5 was also strongly represented. This drive included competition, contests, leaderboards, rankings, collaboration, teamwork, cooperation, social comparison, peer pressure, social norms, negotiation, and multiplayer interaction. These elements align with Self-Determination Theory through the need for relatedness and with Social Learning Theory through peer observation, comparison, and social feedback [89,92]. In energy-related and built-environment applications, social mechanisms can make individual energy practices more visible and socially meaningful. However, their impact depends strongly on implementation. Cooperative and community-based mechanisms may support collective engagement, whereas competitive rankings may discourage users who perform poorly or feel pressured. Therefore, social influence should not be treated as automatically beneficial; it requires careful design and empirical testing.

A clear theoretical alignment was also observed for Core Drive 3, which included simulation, strategic decision-making, resource management, budgeting, exploration, interactive navigation, creative tasks, and customization. These elements support constructivist and experiential learning because they allow users to test decisions, explore trade-offs, manipulate variables, and reflect on outcomes [93,95]. This is particularly relevant in energy and built-environment contexts, where users must understand relationships between comfort, cost, efficiency, behavior, and system performance [58]. Compared with simple points or badges, empowerment-based mechanics can support deeper systems thinking. However, many studies still provide limited empirical validation beyond short-term knowledge gain, meaning that the claimed experiential benefits are often stronger theoretically than empirically.

Core Drive 1 and Core Drive 4 were present but less dominant than Core Drive 2 and Core Drive 5. Core Drive 1 included narrative,

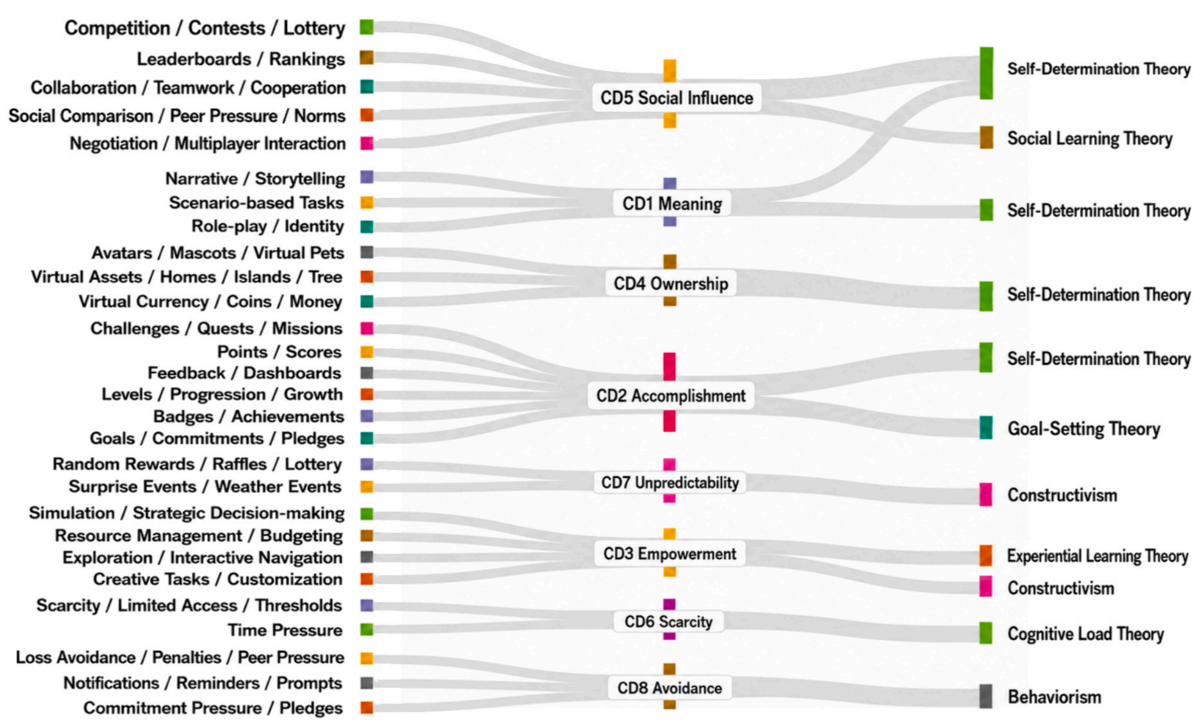


Fig. 12. Mapping of consolidated game-element groups to Octalysis core drives and associated learning theories. The mapping reflects the dominant motivational function of each element group and its theoretical alignment, rather than a fixed one-to-one classification.

storytelling, scenario-based tasks, and role-play or identity-based design, while Core Drive 4 included avatars, mascots, virtual pets, virtual assets, homes, islands, trees, virtual currency, coins, and money. These drivers are theoretically important because they can support personal relevance, autonomy, identity formation, and emotional investment in the game environment [94]. However, in the reviewed studies, these elements were often secondary to more easily measurable mechanics such as points, challenges, feedback, and leaderboards. This suggests that deeper motivational constructs remain underdeveloped in energy-related serious games and gamified interventions [86].

Core Drive 6: Scarcity and Impatience, Core Drive 7: Unpredictability and Curiosity, and Core Drive 8: Loss and Avoidance. Core Drive 6 was represented by scarcity, limited access, thresholds, and time pressure; Core Drive 7 by random rewards, raffles, lotteries, surprise events, and weather events; and Core Drive 8 by loss avoidance, penalties, peer-pressure-related avoidance, notifications, reminders, prompts, commitment pressure, and pledges. Their limited use may reflect a cautious approach to pressure-based, uncertainty-based, or loss-based mechanics, which can create urgency but may also increase stress or reduce autonomy if poorly designed. Nevertheless, these mechanisms may have value when used carefully to simulate real-world constraints, risks, and consequences in energy decision-making [96,97].

The mapping shows that serious games and gamified interventions in the built environment are mainly designed around accomplishment, feedback, and social engagement, with moderate use of meaning- and empowerment-based approaches and weaker use of ownership, scarcity, unpredictability, and avoidance. Although many game elements can be linked to established learning theories, the reviewed studies often stop at descriptive or conceptual alignment. Few studies explicitly test whether these theoretical relationships lead to sustained behavioral, educational, or energy-related outcomes.

Future research should move beyond descriptive mapping and empirically compare different motivational strategies. For example, studies could compare competition with cooperation, achievement-based feedback with meaning-based narratives, or simulation-based learning with simple dashboard feedback. Longitudinal designs are particularly needed to determine whether these mechanics produce lasting behavior change rather than short-term engagement. In addition, integrating serious games with objective data sources, such as smart meters, IoT systems, building sensors, and in-game analytics, would improve the validity of outcome measurement. Finally, future studies should adopt stronger theory-driven designs by explicitly linking game mechanics to learning, motivation, and behavior-change constructs, and by validating their effects on decision-making, practice, and long-term energy outcomes.

Fig. 13 depicts the synthesis-based future research roadmap for serious games in energy-related applications in the built environment. The roadmap translates the main limitations identified in the review into structured directions, including technological advancement, user-centered design, methodological improvement, application expansion, and real-world system integration. It highlights the need to move from controlled, short-term studies toward scalable, data-driven, and context-aware serious games capable of supporting real-world decision-making and long-term behavioral change.

4.3. A taxonomy of serious games for energy-related applications

Based on the synthesis of findings across all research questions (RQ1–RQ4), a taxonomy is proposed to systematically classify serious games for energy-related applications in the built environment. The taxonomy integrates key dimensions identified in the review, including application context, user profiles, learning objectives, game design, interaction mechanisms, technological features, and evaluation approaches. Unlike existing generic taxonomies of serious games, this framework is specifically tailored to the energy domain and reflects the structural patterns and limitations identified in the literature (Fig. 14).

Fig. 13. Synthesis of the future roadmap for energy-related serious games in the built environment.

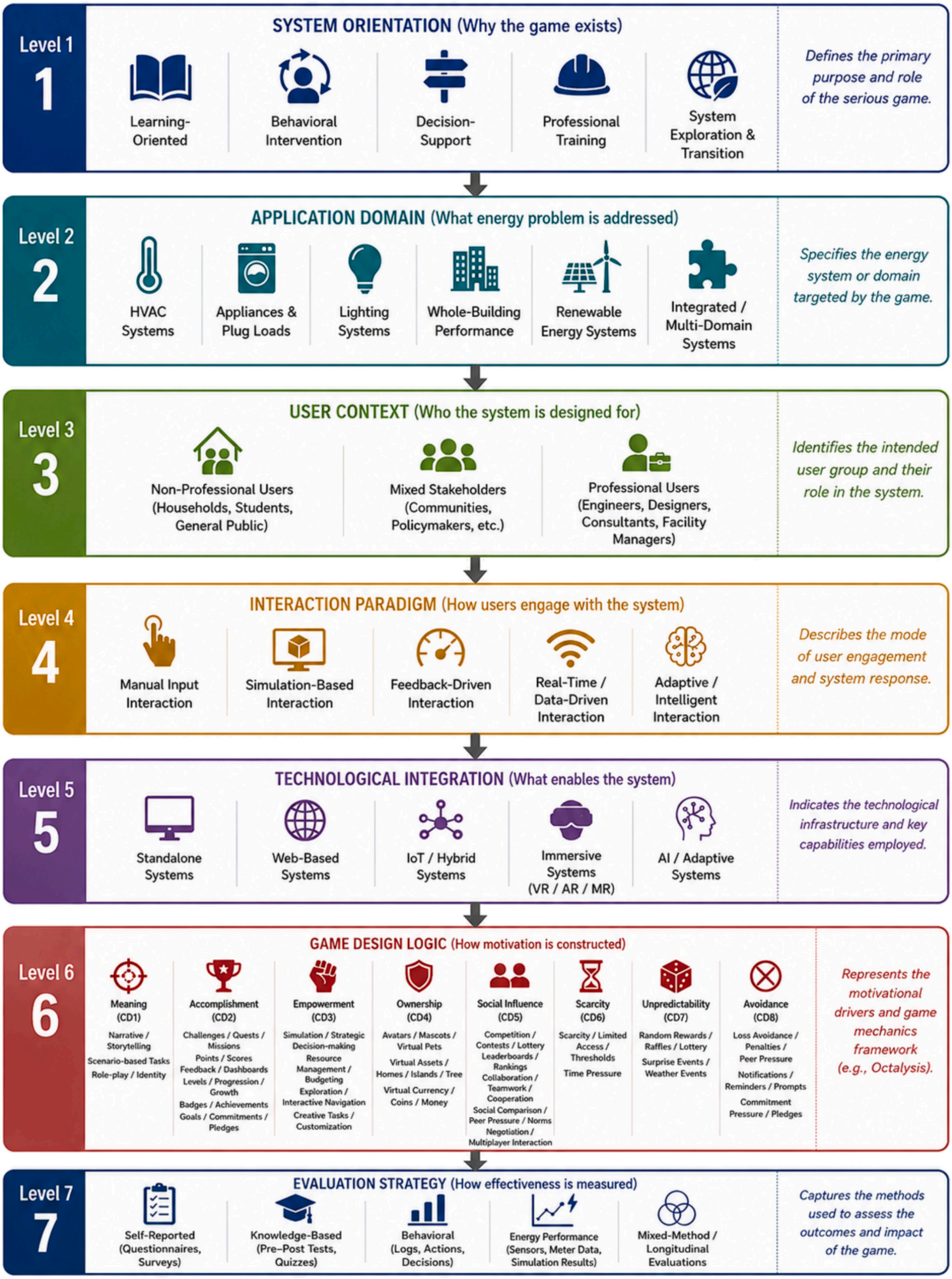


Fig. 14. Hierarchical taxonomy of serious games for energy-related applications in the built environment.

The taxonomy categories should not be interpreted as strictly mutually exclusive. In several studies, serious games addressed multiple objectives, user groups, interaction types, or evaluation outcomes. Therefore, the taxonomy is intended as a flexible classification framework in which categories may overlap, while each study can still be interpreted according to its dominant purpose, primary user group, main interaction mode, and principal evaluation strategy.

The proposed taxonomy provides a structured synthesis of serious games for energy-related applications in the built environment. Unlike prior studies that treat design, technology, and outcomes as separate dimensions, this taxonomy uses a hierarchical structure in which system purpose acts as the main organising principle. At the highest level, games are differentiated according to their core orientation, including knowledge-focused systems, behavior-change interventions, decision-support tools, and professional training applications. This distinction is important because system purpose influences the required interaction complexity, technological integration, and expected outcomes. For example, decision-support and professional training games often require simulation-based or data-driven interactions, while awareness-oriented games are usually delivered through simpler standalone formats.

At the intermediate level, the taxonomy shows how user context, interaction types, and technological configurations are connected. The dominance of non-professional users is reflected in the frequent use of simulation-based and feedback-driven interactions delivered through standalone or web-based platforms. In contrast, real-time data integration and adaptive systems remain limited and are mainly associated with emerging hybrid or IoT-enabled applications. This highlights a gap between the complexity of real-world energy systems and the simplified interaction models commonly used in current serious games.

At the design level, the taxonomy integrates the Octalysis Framework and shows that serious games for energy-related applications are primarily shaped by accomplishment- and social-influence-based motivational mechanisms. Core Drive 2 is the dominant category, represented by elements such as challenges, quests, missions, points, scores, feedback, dashboards, levels, progression, badges, achievements, goals, commitments, and pledges. Core Drive 5: Social Influence and Relatedness is also strongly represented through competition, contests, leaderboards, rankings, collaboration, teamwork, cooperation, social comparison, peer pressure, social norms, negotiation, and multiplayer interaction. This indicates that many existing games prioritize measurable progress, performance feedback, and peer-based engagement.

The taxonomy also shows that meaning- and empowerment-based mechanisms occupy a moderate position within the literature. Core Drive 1: Epic Meaning and Calling is represented through narrative, storytelling, scenario-based tasks, and role-play or identity-based design, while Core Drive 3 is represented through simulation, strategic decision-making, resource management, budgeting, exploration, interactive navigation, creative tasks, and customisation. These drivers are particularly relevant for energy-related applications because they can support contextual learning, systems thinking, and decision-making under realistic constraints. However, they are less dominant than accomplishment-based mechanics, suggesting that many studies still favour simpler and more measurable design features over deeper motivational and experiential structures.

Core Drive 4 appears as a secondary but meaningful design category, including avatars, mascots, virtual pets, virtual assets, homes, islands, trees, virtual currency, coins, and money. These elements can support personal investment and attachment to the game environment, but they are not as consistently used as achievement- and social-influence-based mechanics. The least represented drivers are Core Drive 6: Scarcity and Impatience, Core Drive 7: Unpredictability and Curiosity, and Core Drive 8: Loss and Avoidance. These include mechanisms such as limited access, thresholds, time pressure, random rewards, surprise events, weather events, penalties, reminders, prompts, and commitment pressure. Their limited use suggests that urgency, uncertainty, and loss-based mechanisms remain underdeveloped in serious games for energy-related applications.

The evaluation level reveals a major methodological limitation. Many studies rely on short-term or self-reported measures, regardless of the complexity of the game or its intended outcomes. This creates a persistent gap between claimed behavioral benefits and empirical validation. The taxonomy therefore highlights a mismatch between dominant design practices and the requirements of real-world energy behavior change.

This taxonomy offers a unifying framework for comparing studies and identifying underexplored configurations, including professional-oriented, data-driven systems with longitudinal evaluation. Future studies could use the taxonomy as a design and evaluation framework by comparing different combinations of system purpose, user group, interaction mode, technological integration, motivational design, and evaluation strategy. Longitudinal validation using smart-meter data, sensor logs, in-game analytics, or observed behavioral measures would help determine whether these configurations produce sustained real-world energy outcomes.

4.4. Implications for practice, teaching, and future research

The findings have implications beyond future research. For practice, the proposed taxonomy can help designers, building professionals, energy consultants, and policymakers identify which types of serious games are appropriate for different energy-related objectives. For example, awareness-oriented games may be suitable for household education, while simulation-based and data-driven games may be more appropriate for retrofit decision-making, demand-response training, or smart-building operation. The review also suggests that practical applications should move beyond generic engagement mechanics and incorporate real-world building data, user-specific feedback, and longer-term behavioral tracking where possible.

For teaching, the findings can support the design of structured learning activities in architecture, building science, sustainability, and energy-efficiency education. Educators can use taxonomy to align learning objectives, game elements, interaction modes, and assessment methods. For instance, students could use simulation-based serious games to explore trade-offs between comfort, cost, energy use, and carbon emissions, while professional training courses could use role-based scenarios to support decision-making in building design, retrofitting, or facility management.

Fig. 15 proposes a staged scale-up pathway from teaching and awareness pilots to behavior-change simulations, data-integrated prototypes, real-building living labs, and scalable adaptive interventions. It highlights the need for co-design, professional applications, smart-building and IoT integration, longitudinal evaluation, and deployment-oriented research.

The proposed future research roadmap illustrates how energy-related serious games in the built environment can progress from small-scale educational applications toward scalable, data-integrated, and impact-oriented interventions. The current evidence base shows that most studies are still concentrated in teaching, awareness, and behavior-change contexts, often using standalone or web-based games with students, households, or other non-professional users. Therefore, the first stage of the future focuses on strengthening serious games as teaching and awareness tools for energy literacy. The next stage extends this into behavior-change simulations, where users can explore energy decisions, comfort trade-offs, and household or building scenarios in a controlled environment. The roadmap then proposes a shift toward data-integrated prototypes that connect serious games with smart meters, sensors, dashboards, and real-time feedback. This transition is important because the review shows that real-world data integration and adaptive functionality remain limited in existing studies. The fourth stage moves serious games into living labs, where interventions can be tested with real users in homes, campuses, offices, and operational buildings. Finally, the roadmap highlights scalable adaptive interventions as the

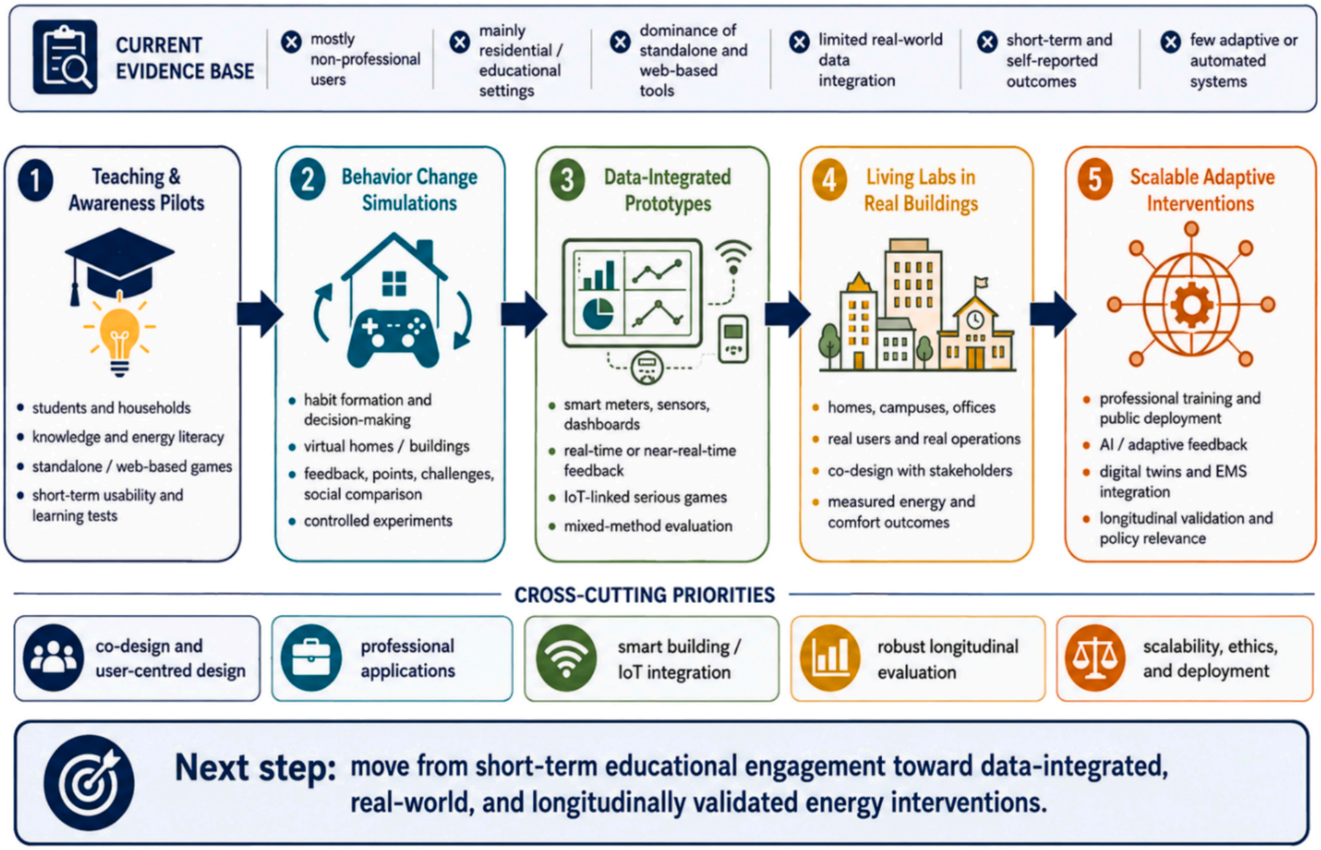


Fig. 15. Proposed future research plan for scaling energy-related serious games from educational pilots to data-integrated, real-world, and adaptive built-environment interventions.

long-term goal, involving AI-supported feedback, digital twins, energy management systems, professional training, and longitudinal validation. Overall, the figure proposes that future research should move beyond short-term educational engagement and toward real-world, data-driven, and longitudinally evaluated applications that can demonstrate measurable energy, comfort, behavioral, and decision-making outcomes. This direction directly responds to the gaps identified in the review, including the dominance of non-professional users, limited professional applications, weak real-world integration, short evaluation periods, and scarce evidence of measurable energy impact.

5. Conclusion

This study systematically reviewed serious games for energy-related applications in the built environment. The results show a clear pattern: most studies rely on short-term, achievement-based approaches, often tested with non-professional users in controlled settings. These designs may improve knowledge and engagement; however, current evidence remains insufficient to confirm their sustained impact on long-term behavior change or real-world energy performance. One of the main contributions of this study is the proposed hierarchical taxonomy, which brings together previously separate dimensions into a single structured framework. By placing system purpose at the top and linking it to design, interaction, and evaluation choices, the taxonomy helps explain how different elements of serious games are connected. It also makes it easier to compare studies and identify gaps, especially in areas such as professional applications, data-driven systems, and long-term evaluation. Within the Octalysis mapping, Core Drive 2 and Core Drive 5 were the dominant motivational categories, while Core Drive 1 and Core Drive 3 occupied a moderate position, Core Drive 4 appeared as a secondary design layer, and Core Drive 6, Core Drive 7, and Core Drive 8 were comparatively weak.

Several issues stand out across the literature. Many studies depend heavily on student or household samples, which limits how well the findings apply to real-world contexts. Game design is mostly focused on achievement and social features, with less attention given to deeper motivational aspects. Most systems are still screen-based, with limited use of real-time data, adaptive features, or integration with actual building systems. At the same time, evaluation methods are often short-term and based on self-reports, which makes it difficult to confirm real impact. Current evidence suggests that serious games in this area have primarily been evaluated as educational tools, while their role as practical interventions for energy systems remains underexplored. Moving forward, research needs to shift toward more realistic and applied approaches. This includes connecting games to real-world data, designing systems that adapt to users, and using longer-term and more objective evaluation methods. Addressing these points is necessary if serious games are to move beyond controlled experiments and contribute meaningfully to energy efficiency and sustainability in practice.

This review has several limitations. First, only peer-reviewed journal articles, conference papers, and book chapters reporting original research were included, which may have excluded relevant grey literature, technical reports, theses, and non-English studies. Second, although a predefined extraction framework was used and unclear classifications were discussed with the supervisory team, formal inter-rater reliability testing and independent double coding were not conducted. This limits the reproducibility of the coding and means that the findings should be interpreted as a structured qualitative synthesis rather than as a fully independently replicated coding exercise. Third, the included studies were highly heterogeneous in design, sample size, intervention type, evaluation method, and outcome reporting, which prevented meta-analysis and limited direct comparison of effect sizes across studies.

CRediT authorship contribution statement

Abdollah Baghaei Daemei: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Nima Izadyar:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Ehsanolah Assareh:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Heide Karen Lukosch:** Supervision, Investigation, Conceptualization. **Matthaios Santamouris:** Writing – review & editing, Writing – original draft, Supervision. **Mona Abd Al Salam:** Visualization, Methodology, Conceptualization. **Amirhosein Ghaffarianhoseini:** Writing – original draft, Visualization, Resources. **Ali GhaffarianHoseini:** Writing – original draft, Visualization, Resources.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly and Microsoft 365 Copilot in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

The full dataset of the selected studies is provided as an Excel file, including detailed extraction of study characteristics (e.g., context, users, learning objectives, game elements, interaction types, technologies, and evaluation methods).

The Octalysis game elements mapping is also provided as an Excel file, including the summary, mapping, and coding process. Supplementary data to this article can be found online at doi:https://doi.org/10.1016/j.erss.2026.104826.

Data availability

Data will be made available on request.

References

[1] H. Haberl, et al., Built structures influence patterns of energy demand and CO2 emissions across countries, Nat. Commun. 14 (1) (2023) 3898.
[2] A. Baghaei Daemei, A. Jamali, Experimental and simulation study on thermal effects and energy efficiency of a green wall in the humid condition of Rasht, J. Energy Manag. Technol. 6 (1) (2022) 15–21.
[3] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energ. Buildings 40 (3) (2008) 394–398.
[4] R. Aeinehvand, et al., Proposing alternative solutions to enhance natural ventilation rates in residential buildings in the Cfa climate zone of Rasht, Sustainability 13 (2) (2021) 679.
[5] J. Henriques, J. Catarino, Motivating towards energy efficiency in small and medium enterprises, J. Clean. Prod. 139 (2016) 42–50.
[6] E. Rasheed, et al., Integrating internet of things (IoT) approach to post-occupancy evaluation (POE): an experimental at-the-moment occupant comfort control system, Buildings 14 (7) (2024) 2095.
[7] A.B. Daemei, et al., An experimental analysis and deep learning model to assess the cooling performance of green walls in humid climates, Front. Energy Res. Volume 12–2024 (2024).
[8] D.B. Agusdinata, et al., Effectiveness of conservation messages to reduce households' GHG emissions: a serious-gaming experiment, J. Environ. Manag. 351 (2024) 119948.
[9] A. Hashemi Araghi, et al., Zero-carbon building materials in New Zealand context: a systematic literature review, Discov. Appl. Sci. 7 (6) (2025) 544.
[10] D. Wemyss, et al., Does it last? Long-term impacts of an app-based behavior change intervention on household electricity savings in Switzerland, Energy Res. Soc. Sci. 47 (2019) 16–27.
[11] J. Breuer, G. Bente, Why so serious? On the relation of serious games and learning, Eludamos J. Comput. Game Cult. 4 (2010) 7–24.
[12] D. Johnson, et al., Gamification and serious games within the domain of domestic energy consumption: a systematic review, Renew. Sust. Energ. Rev. 73 (2017) 249–264.
[13] M. Boissier, et al., Designing serious games to understand the challenges of the anthropocene, Proc. Des. Soc. 3 (2023) 1397–1406.
[14] R. Damaševičius, R. Maskeliūnas, T. Blažauskas, Serious games and gamification in healthcare: a meta-review, Information 14 (2) (2023) 105.
[15] M. Xu, et al., Game-based learning in medical education, Front. Public Health (2023). Volume 11–2023.
[16] I. Doumas, et al., Serious games for upper limb rehabilitation after stroke: a meta-analysis, J. Neuroeng. Rehabil. 18 (1) (2021) 100.
[17] P. Rego, P.M. Moreira, L.P. Reis, Serious games for rehabilitation: A survey and a classification towards a taxonomy, in: In 5th Iberian Conference on Information Systems and Technologies, IEEE, 2010.
[18] A. Solinska-Nowak, et al., An overview of serious games for disaster risk management – prospects and limitations for informing actions to arrest increasing risk, Int. J. Dis. Risk Reduct. 31 (2018) 1013–1029.
[19] B.Z. Demiray, et al., FloodGame: an interactive 3D serious game on flood mitigation for disaster awareness and education, Environ. Model. Softw. 188 (2025) 106418.
[20] A.B. Daemei, Z. Feng, D. Paes, A serious game for mould prevention education: a comparative study with video-based learning, J. Comput. Assist. Learn. 42 (2) (2026) e70227.
[21] T. Relvas, et al., A serious game for raising air pollution perception in children, J. Comput. Educ. 12 (1) (2025) 133–163.
[22] K. Madani, T.W. Pierce, A. Mirchi, Serious games on environmental management, Sustain. Cities Soc. 29 (2017) 1–11.
[23] C.K.W. Tan, H. Nurul-Asna, Serious games for environmental education, Intgr. Conserv. 2 (1) (2023) 19–42.
[24] N. Abdurahmanovic, Enhancing energy efficiency through user engagement and behaviour change: a review on gamification approaches and serious games in energy systems, Energy 334 (2025) 137496.
[25] A. Baghaei Daemei, Prototyping an AI-powered tool for energy efficiency in New Zealand homes, ABC2: J. Archit. Build. Constr. Cities 2025 (01) (2025) 20–37.
[26] X. Wu, S. Liu, A. Shukla, Serious games as an engaging medium on building energy consumption: a review of trends, categories and approaches, Sustainability 12 (2020) 8508.
[27] E. Delemere, P. Liston, Exploring the use of Behavioural techniques in serious games for energy efficiency: a systematic review and content analysis, Behav. Soc. Issues 31 (1) (2022) 451–479.
[28] E. Delemere, P. Liston, Engaging Serious Games for Energy Efficiency, Springer Nature Switzerland, Cham, 2022.
[29] K.S. Khan, et al., Five steps to conducting a systematic review, J. R. Soc. Med. 96 (3) (2003) 118–121.
[30] R.P. De Lope, N. Medina-Medina, A comprehensive taxonomy for serious games, J. Educ. Comput. Res. 55 (5) (2017) 629–672.
[31] P.A. Rego, P. Moreira, L. Reis, Serious Games for Rehabilitation: A Survey and a Classification Towards a Taxonomy, 2010, pp. 1–6.
[32] A. Baghaei Daemei, et al., Gamification for air quality education: a systematic literature review, Build. Environ. 270 (2025) 112526.
[33] D. Scorgie, et al., Virtual reality for safety training: a systematic literature review and meta-analysis, Saf. Sci. 171 (2024) 106372.
[34] A. Elnosh, M. Calais, D. Parlevliet, A systematic literature review of digital twin research for photovoltaic systems: trends, challenges, and opportunities, Renew. Sust. Energ. Rev. 226 (2026) 116326.
[35] S. Mariyam, et al., Converting waste into sustainable aviation fuel (SAF): a systematic literature review, Renew. Sust. Energ. Rev. 226 (2026) 116380.
[36] C. Wohlin, Guidelines for snowballing in systematic literature studies and a replication in software engineering, in: Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering, Association for Computing Machinery, London, England, United Kingdom, 2014 p. Article 38.
[37] C. Wohlin, et al., Successful combination of database search and snowballing for identification of primary studies in systematic literature studies, Inf. Softw. Technol. 147 (2022) 106908.
[38] Y.-k. Chou, Actionable Gamification: Beyond Points, Badges, and Leaderboards, 2015.
[39] C.-M. Chen, L. Ming-Chaun, C.-P. Kuo, A game-based learning system based on octalysis gamification framework to promote employees' Japanese learning, Comput. Educ. 205 (2023) 104899.
[40] Karać, J. and M. Stabauer, Gamification in E-Commerce. 2017. 41–54.
[41] A. Baghaei Daemei, et al., Prototyping a serious game to enhance indoor air quality awareness among the general public in New Zealand, E3S Web Conf. 689 (2026) 05010.
[42] A. Baghaei Daemei, Z. Feng, D. Paes, Developing a serious game for indoor air quality and mold prevention education in residential buildings, Smart Sustain. Built Environ. (2025) 1–36.
[43] Y.-k. Chou, Actionable Gamification: Beyond Points, Badges, and Leaderboards, Octalysis Media, 2015.

[44] D. Geelen, et al., Exploring the use of a game to stimulate energy saving in households, J. Des. Res. 10 (2012) 102–120.
[45] M. Casals, et al., Assessing the effectiveness of gamification in reducing domestic energy consumption: lessons learned from the EnerGAware project, Energ. Buildings 210 (2020) 109753.
[46] R. Hafner, et al., Results and insight gained from applying the EnergyCat energy-saving serious game in UK social housing, Int. J. Serious Games 7 (2020) 27–48.
[47] J.D. Fijnheer, H. Oostendorp, R. Veltkamp, Household energy conservation intervention: a game versus dashboard comparison, Int. J. Serious Games 6 (2019) 23–36.
[48] H. Kim, et al., MySmartE – an eco-feedback and gaming platform to promote energy conserving thermostat-adjustment behaviors in multi-unit residential buildings, Build. Environ. 221 (2022) 109252.
[49] U. Dorji, P. Panjaburee, N. Srisawasdi, Effects of Gender Differences and Learning Performance within Residence Energy Saving Game-Based Inquiry Playing, 2014.
[50] H. Dib, N. Adamo-Villani, Serious sustainability challenge game to promote teaching and learning of building sustainability, J. Comput. Civ. Eng. 28 (5) (2014) A4014007.
[51] G. Mylonas, et al., An educational IoT lab kit and tools for energy awareness in European schools, Int. J. Child-Comp. Interact. 20 (2019) 43–53.
[52] J.C. Yang, K. Huang, T.-C. Liu, A digital game-based learning system for energy education: an energy conservation pet, Turk. Online J. Educ. Technol. 11 (2012) 27–37.
[53] M. Senbel, V.D. Ngo, E. Blair, Social mobilization of climate change: university students conserving energy through multiple pathways for peer engagement, J. Environ. Psychol. 38 (2014) 84–93.
[54] N. Dimitriou, et al., ChArGED: implementing a framework for improving energy efficiency in public buildings through IoTenabled energy disaggregation and serious games. In 2018 IEEE international conference on pervasive computing and communications workshops (PerCom workshops), IEEE, 2018.
[55] G.E. Lee, et al., Makahiki: an open source game engine for energy education and conservation. In foundations of digital games, in: Raleigh North Carolina: Proceedings of the International Conference on the Foundations of Digital Games, 2012.
[56] C. Cooremans, et al., Play the Game: Learning about Energy Efficiency Can Be Fun–Seriously! In Proceedings of the Eceee Summer Study 2019, 2019.
[57] E. Knol, P. de Vries, EnerCities - A serious game to stimulate sustainability and energy conservation: Preliminary Results, eLearning Papers 25 (2011) 1–10.
[58] G. Bekebrede, E. Van Bueren, I. Wenzler, Towards a joint local energy transition process in urban districts: the GO2Zero simulation game, Sustainability 10 (8) (2018) 2602.
[59] P. Makris, et al., SOCIALENERGY: a gaming and social network platform for evolving energy markets' operation and educating virtual energy, Communities (2018) 1–6.
[60] H. Kim, et al., Social energy games for smart and connected residential communities: mechanism design, Energ. Buildings 346 (2025) 116187.
[61] C.F. Reinhart, et al., Learning by playing – teaching energy simulation as a game, J. Build. Perform. Simul. 5 (6) (2012) 359–368.
[62] P. Patlakas, R. Raslan, A computer game to help people understand the energy performance of buildings, Proc. Instit. Civil Eng. Eng. Sustain. 170 (6) (2017) 308–321.
[63] J. Gao, et al., Willingness Analysis of Demand-Side Flexible Energy Regulation Using Gamified Simulation, 2025.
[64] V. Rai, A.L. Beck, Play and learn: serious games in breaking informational barriers in residential solar energy adoption in the United States, Energy Res. Soc. Sci. 27 (2017) 70–77.
[65] M. Avila, et al., Energy management system based on a gamified application for households, Energies 14 (12) (2021) 3445.
[66] A. Alturkistani, M. Alrige, GreenKSA: a theory-based gamified application to foster pro-environmental behavior in Saudi Arabia, Sustainability 18 (2) (2026) 692.
[67] J. Wu, et al., Using interactive gamified simulation to explore how economic incentives affect appliance flexible regulation potential, Energy 338 (2025) 138931.
[68] O. Garay Garcia, et al., Assessing the Residential Energy Rebound Effect by Means of a Serious Game, Springer International Publishing, Cham, 2018.
[69] S.M. Barna, J.P. Deason, E. Shittu, Solar energy prosumer decision-making: developing a simulation framework for enabling cognitive learning in energy management. In IISE annual conference, in: Proceedings, Institute of Industrial and Systems Engineers (IISE), 2020.
[70] B. Reeves, et al., Increasing energy efficiency with entertainment media: an experimental and field test of the influence of a social game on performance of energy behaviors, Environ. Behav. 47 (1) (2015) 102–115.
[71] T.G. Papaioannou, et al., An IoT-based gamified approach for reducing occupants' energy wastage in public buildings, Sensors 18 (2) (2018) 537.
[72] R. Stone, et al., Exploiting gaming technologies to visualise dynamic thermal qualities of a domestic dwelling: Pilot study of an interactive virtual apartment. in, in: Behave Energy Conference, 2014.
[73] M. Casals, et al., A serious game enhancing social tenants' behavioral change towards energy efficiency, in: In 2017 global internet of things summit (giots), IEEE, 2017.
[74] N.S. Yaduvanshi, T. Payne, J.Y. Park, Net-zero home race: a board game to engage and educate students for sustainable building retrofits, J. Archit. Eng. 31 (4) (2025) 04025038.
[75] C. Pisithpunth, et al., THE GROWTH: An Environmental Game Focusing on Overpopulation Issues, Springer International Publishing, Cham, 2014.
[76] D.S. Özgen Turan, Y. Afacan, E. Surer, Effects of biophilic design on sustainable behaviors: introducing the use of serious game as a measure of sustainable behavior, Archnet-IJAR Int. J. Archit. Res. 20 (1) (2024) 55–74.
[77] F.-H. Tsai, K.-C. Yu, H.-S. Hsiao, Exploring the factors influencing learning effectiveness in digital game- based learning, Educ. Technol. Soc. 15 (2012).
[78] Y.-K. Juan, T.-W. Chao, Game-based learning for green building education, Sustainability 7 (5) (2015) 5592–5608.
[79] P. Panjaburee, U. Dorji, N. Srisawasdi, Investigating Factors Affecting Conceptual Learning Progression when Playing Digital Game-based Inquiry Learning for Energy Education. Proceedings of the 22nd International Conference on Computers in Education, ICCE 2014, 2014, pp. 588–597.
[80] J. Sousa, et al., Gamification as a way to involve young adults in energy efficiency and sufficiency—A case study, in: in ECEEE Summer Study Proceedings, 2019.
[81] H. Kimura, T. Nakajima, Designing persuasive applications to motivate sustainable behavior in collectivist cultures, PsychNology J. 9 (2011) 7–28.
[82] M. Soekarjo, H.V. Oostendorp, Measuring effectiveness of persuasive games using an informative control condition, Int. J. Serious Games 2 (2) (2015).
[83] Rasku, J., M. Mäenpää, and S. Alanko, Your Very Own Polar Bear: Drawing Attention to Household Energy Efficiency Through Gamification. 2024. 1–6.
[84] Odom, W., J. Pierce, and D. Roedl, Social Incentive & Eco-Visualization Displays: Toward Persuading Greater Change in Dormitory Communities. 2008.
[85] J. Hamari, J. Koivisto, H. Sarsa, Does Gamification Work? — A Literature Review of Empirical Studies on Gamification, 2014.
[86] K. Seaborn, D.I. Fels, Gamification in theory and action: a survey, Int. J. Human-Comp. Stud. 74 (2015) 14–31.
[87] D. Baxter, L.G. Pelletier, The roles of motivation and goals on sustainable behaviour in a resource dilemma: a self-determination theory perspective, J. Environ. Psychol. 69 (2020) 101437.
[88] R.M. Ryan, E.L. Deci, Intrinsic and extrinsic motivation from a self-determination theory perspective: definitions, theory, practices, and future directions, Contemp. Educ. Psychol. 61 (2020) 101860.
[89] W. Abrahamse, L. Steg, Social influence approaches to encourage resource conservation: a meta-analysis, Glob. Environ. Chang. 23 (6) (2013) 1773–1785.
[90] E. Locke, G. Latham, Building a practically useful theory of goal setting and task motivation: a 35-year odyssey, Am. Psychol. 57 (2002) 705–717.
[91] E.L. Deci, R. Koestner, R.M. Ryan, Extrinsic rewards and intrinsic motivation in education: reconsidered once again, Rev. Educ. Res. 71 (1) (2001) 1–27.
[92] H. Allcott, Social norms and energy conservation, J. Public Econ. 95 (9) (2011) 1082–1095.
[93] D.A. Kolb, R.E. Boyatzis, C. Mainemelis, Experiential learning theory: Previous research and new directions, in: in Perspectives on Thinking, Learning, and Cognitive Styles, Routledge, 2014, pp. 227–247.
[94] R.M. Ryan, E.L. Deci, Intrinsic and extrinsic motivations: classic definitions and new directions, Contemp. Educ. Psychol. 25 (1) (2000) 54–67.
[95] J. Gee, What video games have to teach us about learning and literacy, Comput. Entertain. 1 (2003) 20.
[96] J. Sweller, Cognitive load during problem solving: effects on learning, Cogn. Sci. 12 (2) (1988) 257–285.
[97] R. Ryan, C. Rigby, A. Przybylski, The motivational pull of video games: a self-determination theory approach, Motiv. Emot. 30 (2006) 344–360.