[1.] Ştefan ŢĂLU, [2.] Mihai ŢĂLU, [3.] Laura–Catinca LEŢIA

ADOPTION OF IoT–BASED ENERGY MONITORING IN RETROFITTED RESIDENTIAL BUILDINGS: THE ROMANIAN CONTEXT

[1.] The Technical University of Cluj–Napoca, The Directorate of Research, Development and Innovation Management (DMCDI), Cluj–Napoca, ROMANIA.
[2.] University of Craiova, Faculty of Mechanics, Department of Applied Mechanics and Civil Engineering, Craiova, ROMANIA.
[3.] Technical University of Cluj–Napoca, Faculty of Building Services Engineering, Structures Department, Cluj–Napoca, ROMANIA

Abstract: The integration of Internet of Things (IoT) technologies into residential buildings offers significant potential for energy efficiency and sustainability. This study investigates the awareness, adoption, and challenges associated with IoT–based energy monitoring systems in retrofitted residential buildings within Romania. Through semi–structured interviews with 50 professionals in the civil engineering and energy consultancy sectors, the research identifies key factors influencing the implementation of these technologies. Findings reveal moderate awareness levels, with cost and lack of expertise being primary barriers. The study underscores the need for targeted policies and training programs to facilitate the widespread adoption of IoT solutions in Romania's residential sector.
Keywords: civil engineering, energy efficiency, energy monitoring, IoT, residential buildings, retrofitting, smart building technologies

1. INTRODUCTION

Buildings are among the most significant consumers of energy globally, a status primarily driven by their fundamental role in accommodating human activities and the nature of their structural and thermal requirements. The building sector in Europe accounts for roughly 40% of total energy consumption, with about 75% of buildings deemed energy inefficient, emphasizing the need for widespread retrofitting and sustainable upgrades [1].

In Romania, the household and tertiary sectors – including residential, commercial, and institutional buildings – account for approximately 45% of the national total energy consumption [2]. This striking proportion underscores the built environment's pivotal role in shaping national energy profiles and environmental impact.

Given the escalating concerns regarding climate change, resource scarcity, and the rising costs of energy, improving the energy performance of existing buildings has emerged as a cornerstone of national energy strategies. In this regard, the energy renovation of buildings – defined as the process of improving the building envelope, integrating energy–efficient technologies, and incorporating renewable energy sources – constitutes not only a technical imperative but also a strategic socio–economic investment. It is widely recognized that substantial reductions in energy consumption in the building sector are realistically achievable through a phased combination of energy efficiency measures and the widespread deployment of on–site renewable energy solutions. The associated benefits extend beyond energy savings and emission reductions to encompass broader societal, environmental, and economic gains. Economically, energy renovation activities stimulate job creation and catalyze innovation in the construction and energy services sectors. Furthermore, energy–efficient buildings tend to enjoy increased property values, thereby enhancing the financial assets of homeowners and contributing to the housing market's stability [2].

From a societal perspective, improved energy performance in residential buildings offers critical benefits in the realm of social equity and public health. Environmental benefits further justify the prioritization of building energy retrofits. The building sector is a primary contributor to carbon dioxide emissions, making it a focal point for climate mitigation efforts. Studies suggest that the environmental benefits associated with reduced emissions, though difficult to quantify precisely, can amount to approximately 10% of total energy cost savings, thus reinforcing the ecological rationale for building renovations. On a systemic level, energy renovations contribute to the stability and resilience of energy systems by reducing peak demand and enabling energy self–generation. These improvements reduce the strain on electricity and heating infrastructures and contribute to enhanced energy security, especially during periods of high demand or price volatility [2].

The scale of opportunity within Romania is significant. The country's total building floor area exceeds 493 million square meters, of which 86% pertains to residential structures [2]. Private ownership dominates (84%), presenting a significant variable in policy implementation and financial incentive uptake. The age distribution of Romania's residential buildings further illustrates the imperative for large–scale renovation. A considerable portion of the existing stock was constructed between 1961 and 1980, a period during which energy performance requirements were either minimal or nonexistent. These buildings were not designed with thermal efficiency in mind, and as a result, they suffer from poor insulation, inefficient heating systems, and elevated energy demands. Furthermore, heating alone accounts for approximately 55% of the energy consumption in apartments and up to 80% in single–family homes, highlighting a critical domain for intervention. Climatic variations across Romania's geographical regions exacerbate this dynamic, with colder zones exerting greater pressure on household energy consumption.

Within this context, the adoption of Internet of Things (IoT)–based energy monitoring systems in residential buildings, particularly in retrofitted structures, represents a promising technological frontier [3–5]. These systems enable real–time tracking and management of energy use, facilitating behavioral changes and system optimizations that can significantly enhance energy efficiency outcomes [6–9]. However, the extent of adoption of such systems in Romania remains insufficiently explored, with factors such as cost, technical complexity, user awareness, and infrastructural compatibility significantly influencing their uptake.

Over the last decades, the Architecture, Engineering, and Construction (AEC) sector has progressively integrated digital technologies to enhance the planning, renovation, operation, and energy management of buildings [10]. In the context of Romania's retrofitted residential building stock, these advancements, particularly the emergence of IoT–based systems, are increasingly being leveraged to monitor energy consumption, optimize performance, and support long–term sustainability objectives.

This study thus seeks to explore the adoption patterns, benefits, and challenges of implementing IoT–based energy monitoring technologies in retrofitted residential buildings in the Romanian context. Through qualitative research involving industry professionals, this paper aims to illuminate current trends, identify barriers to wider implementation, and offer actionable insights to policymakers, engineers, and stakeholders in the built environment.

2. THE INTEGRATION OF IOT IN ENERGY MONITORING SYSTEMS IN RETROFITTED RESIDENTIAL BUILDING TECHNOLOGIES

In the contemporary built environment, the integration of IoT technologies into residential buildings – particularly retrofitted ones – represents a significant advancement toward energy–efficient and sustainable urban living. IoT has evolved from a conceptual network of connected devices into a fully operational ecosystem that underpins the transformation of traditional buildings into intelligent, adaptive, and resource–optimized environments [11–13]. Through the deployment of diverse devices, sensors, and systems, this ecosystem facilitates the continuous collection, exchange, and analysis of data, thereby enabling real–time energy monitoring and decision–making processes tailored to dynamic user behavior and environmental conditions [14–16].

The integration of IoT in energy monitoring within retrofitted residential buildings is not merely additive but transformative. It allows for the coordination of building systems – such as lighting, Heating, Ventilation, and Air Conditioning (HVAC), and electrical distribution – under a unified digital infrastructure [17, 18]. This synergy supports the automation of functions, predictive control mechanisms, and efficient resource distribution, contributing not only to reductions in energy consumption but also to enhanced comfort, safety, and environmental stewardship.

Hierarchical structure of IoT–based intelligent systems in buildings

Smart building systems typically operate through a tri–level hierarchical architecture that ensures modularity and operational coherence (Figure 1).

- Data infrastructure level: This foundational tier includes the vast array of sensors and devices embedded within the building, which continuously collect raw data on parameters such as temperature, occupancy, humidity, lighting levels, and energy usage.
- System infrastructure level: Acting as the core intelligence, this level processes and analyzes incoming data, leveraging advanced algorithms and data analytics tools to draw meaningful inferences. It facilitates decision–making for functions such as energy load balancing and anomaly detection.
- Service level: This top layer provides end–user services tailored to stakeholders – residents, building managers, utilities, and policymakers – thereby supporting operational decisions and strategic planning.

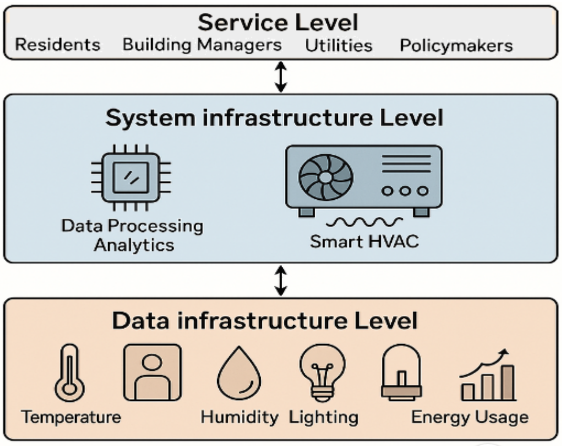

Figure 1. Diagram of a smart building system operating through a tri–level hierarchical architecture.

A vital subsystem in this framework is the HVAC system, which consumes a significant portion of energy in residential buildings. Smart HVAC systems, enhanced with IoT capabilities, ensure that thermal comfort is maintained with minimal energy input by adjusting to occupancy and external climatic variations in real–time [17, 18].

IoT architecture and data flow model

The underlying architecture of IoT in smart buildings is structured to deliver ambient intelligence via four critical stages (Figure 2) [19–22]:

- Sensing/Perception stage: Physical parameters are measured using a variety of embedded sensors. These devices capture a wide spectrum of variables, including – but not limited to – temperature, humidity, energy consumption, light intensity, occupancy, air quality, and structural vibrations. The collected data serves as the empirical basis for subsequent analysis, enabling the digital representation of physical processes.
- Communication/Network stage: The sensed data is transmitted through a diverse range of communication technologies – both wired (e.g., Ethernet, Modbus) and wireless (e.g., Zigbee, LoRaWAN, Wi–Fi, NB–IoT) – tailored to specific requirements such as bandwidth, energy efficiency, and spatial distribution. The choice of protocol is influenced by contextual variables such as building layout, interference levels, and power constraints, ensuring optimal data flow from edge devices to higher–tier processing platforms.
- Data Processing and Analysis stage: Data is aggregated, filtered, and analyzed either locally at the edge or within centralized cloud systems. Advanced analytics – often powered by machine learning, artificial intelligence, and statistical modeling – are applied to extract actionable insights. This stage supports functionalities such as predictive maintenance, energy optimization, and adaptive control strategies.
- Cloud/Storage stage: This stage encompasses both short– and long–term data management. Centralized cloud platforms offer scalable infrastructure for the persistent storage of large

volumes of heterogeneous data. These systems enable the integration of real–time streams with historical datasets, thereby facilitating comprehensive longitudinal analyses. Cloud–based frameworks support advanced computational tasks, including deep learning, cross–domain data fusion, and high–fidelity simulation—enhancing the system's capacity for predictive modeling, decision support, and strategic planning in smart building environments.

This process enables stakeholders to extract actionable insights, automate building operations, and align energy consumption with predefined efficiency and sustainability targets.

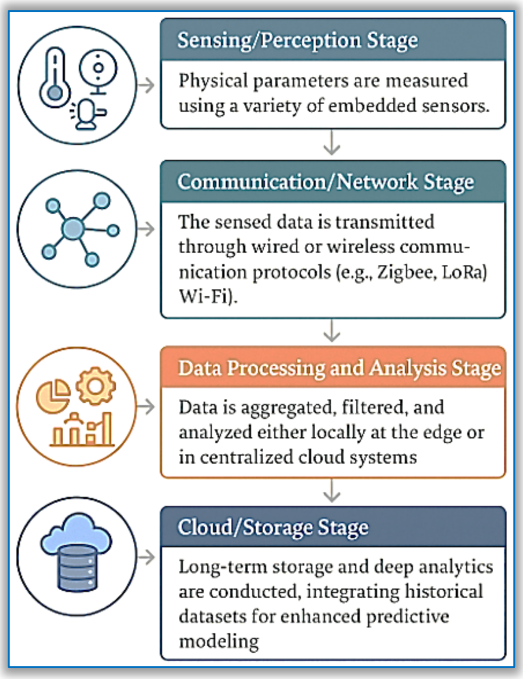

Figure 2. Diagram with IoT architecture and data flow model

Key applications of IoT in retrofitted residential buildings

The incorporation of IoT in retrofitted residential settings yields a comprehensive range of applications that substantively enhance both operational efficiency and user experience.

Figure 3 illustrates how retrofitted residential buildings benefit from key IoT applications:

- Energy management: Real–time monitoring of energy usage through smart meters and sub–meters facilitates demand–side management. Predictive algorithms can forecast energy needs and adapt HVAC cycles, minimizing waste and peak load demands.
- Occupant comfort and safety: Smart thermostats, lighting controls, and air quality sensors ensure that indoor environmental conditions align with occupant preferences. Safety is improved through gas leak detectors, smoke alarms, and automated emergency response systems.
- Facility management and maintenance: Continuous performance tracking of appliances and systems enables predictive maintenance, reducing unexpected failures and extending equipment lifespan. IoT also supports remote diagnostics and system updates.
- Security and access control: Integrated systems combine surveillance cameras, motion detectors, and biometric or smart card access points to enhance residential security. Real–time alerts and activity logs enable rapid response to security breaches.
- Space utilization optimization: Occupancy sensors and usage analytics can guide space planning and multifunctional area adaptation, especially in high–density or multi–family buildings.
- Environmental monitoring and sustainability: IoT platforms assess indoor air quality, CO_2 levels, and environmental pollutants. Data–driven insights support the implementation of green practices and inform retrofit decisions.

Figure 3. Diagram with key applications of IoT in retrofitted residential buildings

- Predictive analytics and decision support: Advanced analytics, powered by machine learning and AI, identify patterns in energy consumption, predict future trends, and suggest interventions for improved energy performance and cost savings.

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

Relevance to the Romanian residential sector

Given that over 60% of Romania's residential buildings were constructed before modern thermal performance standards were implemented, the retrofitting of these buildings offers a significant opportunity for energy savings. IoT–based monitoring and control systems are particularly well–suited to address the inefficiencies of this aging building stock by enabling tailored retrofitting strategies, validating energy performance improvements, and offering transparency to stakeholders on the return on investment in renovation initiatives.

3. RESEARCH METHODOLOGY

A qualitative research methodology was adopted to gain comprehensive insights into the integration of IoT–based energy monitoring systems in retrofitted residential buildings. Semi–structured interviews were conducted between February 1st and April 30th, 2025, targeting a purposive sample of 50 professionals from the civil engineering and energy consultancy sectors across Romania. The participants included chief executive officers (CEOs), project managers, and technical experts, selected for their direct involvement in building renovation and smart energy system implementation. Of the total respondents, 68% were male (n = 34) and 32% were female (n = 16), a distribution that mirrors the ongoing gender disparity traditionally observed within the Romanian construction and engineering domains. Participants were selected through random sampling to ensure a diverse representation of experiences and perspectives. 80% of the respondents held academic qualifications in civil engineering, architecture, or construction–related disciplines, while the remaining 20% were specialists in energy efficiency and smart technology integration. Educationally, the sample was well–qualified, with 80% of participants holding a bachelor's degree and 20% possessing postgraduate qualifications (master's or doctoral level), indicating a technically proficient group. Regarding professional tenure, 70% of respondents had fewer than eight years of field experience, reflecting a workforce largely composed of early– to mid–career professionals with recent exposure to digital construction trends and IoT–based innovations. Meanwhile, 20% had between eight and fifteen years of experience, and 8% had over fifteen years, thereby ensuring a balanced representation across career stages. Interviews were conducted either in person or via video conferencing platforms, each lasting approximately 45 minutes. The interview protocol included questions on participants' familiarity with IoT technologies, experiences with implementation, perceived benefits and challenges, and client receptiveness. Transcripts were analyzed using thematic analysis to identify recurring patterns and themes. Quantitative data from interview responses were processed using SPSS software ver. 22.0.
The following questions focusing on smart buildings were addressed to the participants:

- Theme 1: Perception of IoT integration in retrofitted buildings

Q1) a) How would you characterize the role of IoT in improving energy performance in retrofitted residential buildings? b) In your experience, how has the perception of IoT among construction stakeholders evolved over the last five years? c) Do you believe that IoT is currently underutilized in Romania's building retrofit sector? Why or why not?

- Theme 2: Practical experience with IoT–based energy monitoring

Q2) a) Can you describe a project where IoT technologies were integrated specifically for energy monitoring in a retrofitting context? b) What technical or logistical barriers have you encountered in deploying IoT systems during retrofits? c) How do you assess the effectiveness of installed IoT devices in achieving the intended energy efficiency outcomes?

- Theme 3: Decision–making in technology selection

Q3) a) What criteria do you consider most important when selecting IoT solutions for retrofitted buildings (e.g., cost, compatibility, scalability)? b) Are there specific brands or technologies that have become standard in your practice for energy monitoring? Why? c) How do project stakeholders (owners, consultants, contractors) influence the final selection of IoT solutions?

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

— Theme 4: Interoperability and integration challenges

Q4) a) How do you ensure that newly integrated IoT systems are compatible with legacy building systems during retrofitting? b) What integration protocols or platforms have you found most effective for connecting diverse IoT devices? c) Have you faced any data synchronization or latency issues in multi–device environments?

— Theme 5: User engagement and building occupant interaction

Q5) a) To what extent are residents involved or educated in the use of IoT–enabled energy monitoring systems after retrofitting? b) Have occupant behaviors changed in response to access to real–time energy data? Can you provide examples? c) What feedback mechanisms are typically employed to improve user interaction with smart systems post–installation?

— Theme 6: Data analytics, privacy, and long–term system management

Q6) a) How is the data generated by IoT energy monitoring systems managed, stored, and protected? b) What role does data analytics play in ongoing performance optimization of retrofitted buildings? c) What are your primary concerns regarding data privacy and cybersecurity in IoT–based retrofitted systems?

— Theme 7: Future perspectives and industry readiness

Q7) a) What developments do you foresee in the next five years regarding IoT applications in residential retrofitting in Romania? b) Do you consider the Romanian construction industry adequately prepared – technologically and legislatively – for large–scale IoT adoption? c) What policy changes or financial incentives would best support IoT integration in energy retrofits?

4. RESULTS AND DISCUSSIONS

The analysis of participant responses revealed varying degrees of understanding across the different themes related to IoT integration in retrofitted buildings.

- The following sections present the results for each interview question, highlighting the knowledge levels and the overall trends observed in the responses (Table 1).

Table 1. The analysis of participant responses across all seven interview questions

Question No.	Very High Understanding (%)	High Understanding (%)	Adequate Understanding (%)	Limited Understanding (%)	Average Certainty Level (%)
Q1	38	26	28	8	88
Q2	42	32	22	4	91 (inferred)
Q3	48	24	22	6	89 (inferred)
Q4	38	32	22	8	87 (inferred)
Q5	36	42	16	6	85 (inferred)
Q6	46	32	18	4	90 (inferred)
Q7	56	22	16	6	92 (inferred)

— Regarding Question 1, which explored the role of IoT in enhancing energy performance in retrofitted buildings, 38% of participants demonstrated a very high level of understanding, while 26% reported a high level of understanding. A further 28% of participants stated they had an adequate understanding, and 8% acknowledged having a limited understanding of the subject. These results indicate a generally strong awareness of IoT's role in improving energy efficiency, though a small group of participants appeared to have less familiarity with this aspect of smart building technologies. The average certainty level among participants was 88%, suggesting that most respondents felt confident in their understanding of the topic.

— Question 2, which addressed participants' practical experience with IoT–based energy monitoring, showed that 42% of respondents had a very high level of understanding, and 32% indicated a high level of understanding. Another 22% expressed an adequate understanding, and 4% admitted to having limited knowledge. These findings suggest that a significant portion of participants have a good grasp of the practical applications of IoT for energy monitoring, although some participants still faced challenges in fully understanding the operational aspects of these systems.

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

- The responses to Question 3, which focused on the decision–making process in selecting IoT technologies for retrofitted buildings, revealed that 48% of participants demonstrated a very high level of understanding, while 24% had a high level of knowledge. A further 22% expressed an adequate understanding, and 6% admitted to having limited familiarity with the topic. These results highlight that the majority of participants are well–versed in the factors influencing technology selection, such as cost, scalability, and compatibility. However, a small group of participants appears to have a less comprehensive understanding of the criteria for choosing appropriate IoT solutions.
- Question 4, which explored the challenges of integrating IoT systems with legacy building infrastructure, revealed that 38% of respondents reported a very high level of understanding, and 32% had a high level of understanding. Another 22% of participants stated they had an adequate understanding, while 8% felt their knowledge was limited. These results suggest that most participants are familiar with the challenges of ensuring compatibility between new IoT technologies and existing building systems, but some still experience difficulties in addressing integration issues.
- In response to Question 5, which examined user engagement with IoT–based energy monitoring systems, 36% of participants indicated a very high level of understanding, while 42% expressed a high level of understanding. A further 16% reported an adequate understanding, and 6% admitted to having limited knowledge. These results demonstrate a solid understanding among participants regarding how building occupants interact with smart systems and the potential for user behavior to influence energy efficiency outcomes. However, a small proportion of respondents still appear to lack in–depth knowledge of user engagement strategies.
- The analysis of responses to Question 6, which addressed data management, analytics, privacy concerns, and long–term system maintenance, revealed that 46% of participants exhibited a very high level of understanding, and 32% had a high level of understanding. Another 18% expressed an adequate understanding, and 4% admitted to having limited knowledge. These findings suggest that most respondents are aware of the importance of managing data securely and using analytics for optimizing the performance of retrofitted buildings. However, there is still a small group of participants who are less familiar with the complexities of data privacy and long–term system management.
- For Question 7, which focused on the future perspectives and market dynamics in the smart building sector, 56% of participants reported a very high level of understanding, and 22% expressed a high level of understanding. A further 16% stated they had an adequate understanding, and 6% admitted to having limited knowledge. These results suggest that most participants are well–informed about the future trends and opportunities within the smart building industry, indicating a strong awareness of the evolving market. However, a small portion of respondents still have room for improvement in understanding the long–term outlook for IoT in the built environment.
  - To further analyze the consistency and depth of knowledge exhibited by participants across the seven thematic areas, a composite understanding index was developed (Table 2). This approach transforms qualitative response categories into a simplified quantitative score, enabling clearer comparisons across themes. Each level of understanding – very high, high, adequate, and limited – was assigned a corresponding score (3, 2, 1, and 0 respectively). By aggregating these scores based on the percentage of responses in each category, a composite score (on a scale of 0 to 3) was calculated for each theme.

The resulting scores highlight key trends in participant knowledge. As shown in Table 2, the highest–scoring theme was Q7, which focused on future perspectives and industry readiness, with a score of 2.28. This suggests that participants felt most confident discussing the long–term trajectory and potential of IoT applications in retrofitted buildings. Similarly, themes related to technical implementation – such as Q3 (technology selection) and Q6 (data analytics and privacy) – also received high scores, indicating strong familiarity with operational decision–making and data–related considerations. In contrast, lower scores were observed for Q1 (perception of IoT in energy performance) and Q4 (interoperability challenges), both scoring 1.94. This indicates areas where conceptual clarity and systems integration knowledge may still require development within the professional community. Overall, this simplified scoring index provides a practical lens for evaluating professional readiness and highlights where targeted knowledge enhancement could support more effective IoT integration in the Romanian retrofit sector.

Table 2. Composite understanding scores by theme

Question (theme)	Composite understanding score (0–3 scale)	Interpretation
Q1	1.94	Solid understanding
Q2	2.12	Strong practical engagement
Q3	2.14	Technically informed decision–making
Q4	1.94	Moderate technical knowledge
Q5	2.04	Good awareness of user behavior
Q6	2.20	High competence in technical depth
Q7	2.28	Very strong industry foresight

- To complement the thematic analysis, an additional layer of interpretation was introduced to examine how participants' professional background characteristics – including years of field experience, educational attainment, and professional role – correlated with their expressed understanding across the seven thematic areas. This analysis sought to reveal whether certain background attributes were associated with higher thematic comprehension, thereby contributing to a more nuanced profile of expertise within Romania's construction and energy efficiency sectors (Table 3).

Table 3. Summary of understanding distribution according to professional background

Background characteristic	Dominant areas of theme understanding	Interpretation
≥ 8 Years of Experience	Q2, Q4, Q6	Strong operational expertise shaped by prolonged field exposure
Postgraduate education	Q1, Q7	Enhanced conceptual and strategic foresight driven by advanced academic training
Technical expert	Q4, Q6	Specialization in system integration and cybersecurity
CEO/project manager	Q3, Q7	Emphasis on decision–making and industry adaptation strategies

Analysis of the data indicated that participants with over eight years of professional experience demonstrated markedly higher levels of understanding, particularly in themes Q2, Q4, and Q6. Educational background also played a pivotal role in shaping thematic knowledge distribution. Participants possessing postgraduate degrees consistently exhibited elevated comprehension in conceptual and forward–looking themes, particularly Q1 and Q7. These findings imply that advanced academic training fosters strategic thinking and a deeper conceptualization of technological trajectories in the building retrofit sector. Professional role within the organization further influenced knowledge specialization. Technical experts, typically responsible for system design and integration, showed superior understanding in Q4 and Q6, highlighting their proficiency in addressing challenges related to system interoperability and data protection. In contrast, chief executive officers and project managers scored significantly higher in Q3 and Q7, indicating their strategic involvement in decision–making processes and future readiness assessments. These results collectively indicate that background factors such as experience, education, and role not only influence individual thematic strengths but also shape the broader capacity for informed decision–making and successful implementation of IoT systems in retrofitted residential environments.

- To supplement the thematic and correlation analyses, a cluster analysis was conducted using the aggregated response scores across the seven interview themes (Q1–Q7). The goal was to identify distinct participant profiles based on patterns of understanding and certainty levels. Using a K–means clustering method (with k=3), three main clusters were revealed, as summarized in Table 4.

Table 4. Summary of clusters based on participant knowledge profiles

Cluster	Description	% of participants	Dominant traits
C1	Holistic high–performers	34	Consistently high/very high understanding across all themes
C2	Technically focused specialists	42	High scores on Q2, Q3, Q4, Q6; lower on Q5 and Q7
C3	Emerging practitioners	24	Adequate to limited understanding, especially in Q1, Q5, Q7

- Cluster 1 represents a technically mature group, typically comprising professionals with postgraduate degrees and over 8 years of experience. These participants demonstrated comprehensive insight into both the technical and strategic aspects of IoT adoption.
- Cluster 2 consisted of participants with strong technical grounding – especially in areas like system integration and data analytics – but with lower engagement in user–centric or forward–looking themes. This suggests a need for targeted training in policy awareness and stakeholder communication.
- Cluster 3 reflects a younger, less experienced segment, often early–career professionals or those newly involved in smart building projects. Their responses suggest potential but highlight knowledge gaps, particularly regarding IoT's broader implications for energy policy and occupant interaction.

This clustering offers actionable insights for workforce development and training strategies. For instance, cluster–specific educational modules or mentorship programs could enhance holistic IoT knowledge and foster system–wide optimization. The presence of such distinct knowledge groups also reinforces the need for interdisciplinary collaboration in IoT–based retrofit projects.

5. BEST PRACTICES IN THE ROMANIAN CONTEXT

This section synthesizes the emerging best practices that can serve as replicable models.

- Legacy system compatibility: One of the most cited obstacles was the technical difficulty of integrating IoT devices with existing building infrastructure. Many older Romanian residential buildings lack standardized systems or digital readiness, which complicates sensor installation, data flow, and centralized control. Professionals noted the need for flexible middleware and standardized communication protocols.
- Limited technical expertise: While operational familiarity with IoT is growing, participants acknowledged a persistent gap in deeper system design knowledge and data analytics. This challenge is compounded by a shortage of interdisciplinary training programs that bridge civil engineering, IT, and building automation.
- Fragmented vendor ecosystem: The Romanian market often lacks coherent integration across hardware and software vendors. Respondents mentioned cases of partial system deployments failing due to incompatible platforms or lack of support across different stages of implementation.
- Budget constraints and ROI uncertainty: Especially in residential retrofits, there is often hesitation to invest in IoT systems without clear, short–term return on investment. Stakeholders sometimes prioritize immediate cost reductions over long–term sustainability and operational efficiency gains.
- Data privacy and cybersecurity concerns: While not always a priority during early implementation, respondents expressed growing concerns over data protection, especially as smart devices collect increasing amounts of occupant and energy data.

6. FUTURE RESEARCH DIRECTION

Building on the findings of this study, several directions emerge for future research in the field of IoT–based retrofitting:

- Longitudinal case studies – Investigating how IoT implementations evolve over time in retrofitted buildings could uncover insights into system degradation, user adaptation, and ROI trends.

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

- Behavioral and usability studies – Exploring occupant engagement more deeply through user–centered research can help optimize the design of interfaces, feedback loops, and automation systems.
- Interoperability frameworks for legacy systems – There is a need for technical studies focused on middleware, open protocols, and standards that facilitate integration with Romania's aging building stock.
- Privacy and data governance models – Given the increasing reliance on real–time building data, future work should explore privacy–preserving analytics, secure edge computing, and policy–ready frameworks for data governance.
- Comparative regional studies – Expanding this research to include other Eastern European contexts could help identify shared barriers and successful strategies across similar socio–economic and regulatory environments.
- AI–Enhanced energy management – Investigating the role of predictive analytics, anomaly detection, and adaptive control in optimizing energy usage within retrofitted buildings could push the boundaries of efficiency and automation.

By addressing these areas, future research can contribute to a more resilient, intelligent, and user–responsive built environment – ensuring that IoT's promise in Romania's construction sector is fully realized.

7. CONCLUSION

This study provides valuable insights into the current state of IoT adoption in retrofitted residential buildings in Romania, based on thematic analysis of responses from industry professionals. The findings indicate encouraging levels of engagement and awareness, particularly in domains like practical experience, technology selection, and market perspectives. However, disparities remain – most notably in theoretical understanding of energy performance, integration challenges with legacy systems, and occupant engagement strategies. Professionals demonstrated robust operational knowledge (74%) and strong familiarity with data analytics and long–term system management (78%). The correlation between informed decision–making and technical expertise suggests a growing maturity in the field. Yet, areas such as energy efficiency theory, user–centric design, and legacy system compatibility remain partially underdeveloped. These gaps highlight the need for enhanced training, more integrative system design approaches, and continued cross–disciplinary collaboration. The overall optimism regarding the smart building sector's future suggests Romania is on a promising path. For this momentum to translate into broader, more effective adoption, targeted policy interventions, educational programs, and industry incentives must be aligned with the practical realities and specific needs of local construction professionals.

References

[1] R. Vadruccio, C. Siragusa, A. Tumino, "Increasing energy efficiency in smart building through Internet of Things retrofitting intervention", Procedia Computer Science, vol. 219, pp. 263–270, 2023
[2] Ministry of Regional Development, Public Administration and European Funds, Romania, Strategy for mobilising investments in the renovation of residential and commercial buildings existing at national level, both public and private – Version 2/2017 – October 2017. Available from https://energy.ec.europa.eu/system/files/2018–07/ltrsenromania_0.pdf.
[3] V. Tanasiev, G.C. Pătru, D. Rosner, G. Sava, H. Necula, and A. Badea, "Enhancing environmental and energy monitoring of residential buildings through IoT", Automation in Construction, vol. 126, 103662, 2021
[4] Y.L. Cheng, M.H. Lim, and K.H. Hui, "Impact of internet of things paradigm towards energy consumption prediction: A systematic literature review", Sustainable Cities and Society, vol. 78, 103624, 2022
[5] B. Mobaraki, F. Lozano–Galant, R.P. Soriano, and F.J. Castilla Pascual, "Application of low–cost sensors for building monitoring: a systematic literature review", Buildings, vol. 11, issue 8, article 336, 2021
[6] D. Ibaseta, A. García, M. Álvarez, B. Garzón, F. Díez, P. Coca, C. Del Pero, J. Molleda, "Monitoring and control of energy consumption in buildings using WoT: A novel approach for smart retrofit", Sustainable Cities and Society, vol. 65, 102637, 2021
[7] A.S. Shah, H. Nasir, M. Fayaz, A. Lajis, and A. Shah, "A review on energy consumption optimization techniques in IoT based smart building environments," Inf., vol. 10, no. 3, 2019

[8] D. Minoli, K. Sohraby and B. Occhiogrosso, "IoT considerations, requirements, and architectures for smart buildings—energy optimization and next–generation building management systems," in IEEE Internet of Things Journal, vol. 4, no. 1, pp. 269–283, 2017
[9] M. Arun, G. Gopan, S. Vembu, D.U. Ozsahin, H. Ahmad, F.A. Maged, "Internet of things and deep learning–enhanced monitoring for energy efficiency in older buildings, Case Studies in Thermal Engineering", vol. 61, 104867, 2024
[10] F. Lygerakis, N. Kampelis, and D. Kolokotsa, "Knowledge Graphs' Ontologies and Applications for Energy Efficiency in Buildings: A Review". Energies. vol. 15, issue 20, article 7520, 2022
[11] N.H. Motlagh, A. Khatibi, and A. Aslani, "Toward sustainable energy–independent buildings using internet of things," Energies, vol. 13, no. 22, pp. 1–17, 2020
[12] D. Xie D, Q. Xie, "Internet of things–based study on online monitoring system of building equipment energy saving optimization control using building information modeling", Science Progress, vol. 107, issue 2, 2024
[13] Ş. Ţălu, M. Ţălu, and L.C. Leţia, "The Internet of Things in civil engineering: a review of challenges and solutions in the Romanian context". Acta Technica Corviniensis – Bulletin of Engineering, Hunedoara, Romania, Tome XVI, Fascicule 4, pp. 109–116, 2023.
[14] Ş. Ţălu, M. Ţălu, and L.C. Leţia, "Incorporating Internet of Things (IoT) and Big Data Analytics in the development of smart buildings in the Romanian context". Acta Technica Corviniensis – Bulletin of Engineering, Hunedoara, Romania, Tome XVII, Fascicule 3, pp. 83–89, 2024.
[15] D. Nazarov, A. Nazarov, and Ş. Ţălu, "BIM–technologies for a smart city". AIP Conference Proceedings, vol. 2657, 020050, pp. 1–4, 2022. Eds.: Zakharova G. and Semenov A. IV International Scientific and Practical Conference "New Information Technologies In the Architecture and Construction" (NITAC 2021), Ekaterinburg, Russia, November 2–3, 2021.
[16] A.M. Khorasgani, G.A. Eskandar, and M. Maleki, "Smart buildings construction and maintenance by means of Internet of Things (IoT): a review", American Journal of Engineering Research (AJER), vol. 12, issue 6, pp. 43–51, 2023.
[17] M.D. Rashon, R.C. Tesiero, Y.T. Acquaah, and Balakrishna Gokaraju, "Review of HVAC systems history and future applications", Energies, vol. 16, no. 17: 6109, 2023.
[18] L. Guanjing, A. Casillas, M. Sheng, and J. Granderson, "Performance evaluation of an occupancy–based HVAC control system in an office building", Energies, 16, no. 20: 7088, 2023.
[19] M. Jia, A. Komeily, Y. Wang, and R.S. Srinivasan, "Adopting Internet of Things for the development of smart buildings: A review of enabling technologies and applications", Automation in Construction, vol. 101, pp. 111–126, 2019.
[20] A. Nazarov, D. Nazarov, and Ş. Ţălu, "Information security of the Internet of Things". In: Proceedings of the International Scientific and Practical Conference on Computer and Information Security – INFSEC, SCITEPRESS – Science and Technology Publications, Lda, vol. 1, pp. 136–139, 2021. Eds.: Nazarov D. and Nazarov A. International Scientific and Practical Conference on Computer and Information Security (INFSEC 2021) Yekaterinburg, Russia, April 5th–6th, 2021.
[21] R. Dallaev, T. Pisarenko, Ş. Ţălu, D. Sobola, J. Majzner, and N. Papež, "Current applications and challenges of the Internet of Things". New Trends In Computer Sciences, vol. 1, issue 1, pp. 51–61, 2023.
[22] G. Marques, J. Saini, M. Dutta (Eds.) IoT Enabled Computer–Aided Systems for Smart Buildings. EAI/Springer Innovations in Communication and Computing. 2023, Springer, Cham.

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665