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Research paper

Bridging the gap: Discrepancies in energy efficiency and smart readiness of buildings

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ABSTRACT

This study addresses the critical gap between traditional energy performance assessments and the Smart Readiness Indicator, a tool introduced in the European Union to evaluate a building's ability to incorporate smart technologies for improved energy management. This divergence is important as it can lead to misinterpretations of a building's efficiency and adaptability, affecting stakeholders' decisions and policy implementation. Using a comparative analysis of two pilot buildings in Bucharest, Romania, and Nicosia, Cyprus, this research highlights significant differences between energy performance ratings and SRI scores, with findings indicating a discrepancy of up to 18 % in perceived efficiency. Through this analysis, the study not only reveals the limitations of current assessment practices but also provides actionable recommendations to better align energy metrics with the Smart Readiness Indicator, ultimately contributing to a more integrated approach to sustainable building evaluations. The novelty of this work lies in its focus on bridging these assessment gaps, offering insights that go beyond existing literature by proposing enhanced policy measures for the integration of smart readiness into standard building performance evaluations.

1. Introduction

The Smart Readiness Indicator (SRI) emerged from the 2018 revision of the European Directive on the Energy Performance of Buildings (EPBD) (European_Parliament, 2018), later ratified into EU regulation in 2020 (European_Parliament, 2020a, 2020b). Although not mandatory for Member States, Europe aims to promote its widespread use, especially in large new buildings. The SRI focuses on enhancing energy efficiency through precise energy demand information and efficient network management. It encompasses elements like energy efficiency, comparative assessment, and flexibility, pivotal in smart buildings. The methodology considers various functionalities including energy performance maintenance, responsiveness to occupant needs, and energy flexibility. Implementing Regulation (EU) 2020/2156 outlines the assessment process, proposing a scoring system based on impact criteria like energy efficiency and comfort. However, a noticeable gap exists between traditional energy performance assessments and SRI scores, which can lead to a misinterpretation of a building's overall efficiency and adaptability. Traditional energy performance evaluation methods typically rely on static metrics, such as energy use intensity (EUI) and primary energy demand, which focus on a building's physical attributes and efficiency under standard conditions. These methods primarily assess energy consumption without considering dynamic interactions with users or adaptive functionalities. In contrast, the SRI evaluates the building's capacity to respond to user needs, environmental conditions, and grid requirements through smart technologies. This integration of 'smart' capabilities represents a shift toward assessing a building's responsiveness and adaptability, thereby filling a gap in conventional evaluations.

The intersection of smart grid technologies, and energy management systems highlights the growing complication and systemic risks that must be navigated as we advance the implementation of the SRI

Abbreviations: BACS, Building Automation and Control Systems; EPBD, Energy Performance of Buildings Directive.; EU, European Union; FL, Functionality Level; PHI, Passive House Institute; PHPP, Passive House Planning Package; SRI, Smart Readiness Indicator; UTCB, Technical University of Civil Engineering Bucharest.

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(Inglesi-Lotz et al., 2023). The connection of green power capacity, renewable energy penetration, and technological readiness highlights the challenges and systemic risks in achieving zero-emission targets within the constraints of current and future global energy systems (Battisti, 2023). The interplay between EU energy policies, the shift from high natural gas dependence, and the need for accelerated clean technology deployment underscores the complexities and challenges in securing Europe's energy supply while reducing vulnerability to external geopolitical forces (Ah-Voun et al., 2024). While various risks and challenges are associated with implementing smart-ready features, there is a need to focus on those specific to the variability in building typologies and climatic conditions across pilot sites. These factors pose challenges in establishing a standardized approach to SRI evaluation, as performance metrics and outcomes may vary significantly by location. Addressing these factors is essential to ensure the broad applicability and accuracy of the SRI framework across diverse building and climate profiles.

This study delves into this critical issue by examining the discrepancies and synergies between energy efficiency metrics and SRI, which assesses a building's capability to integrate and adapt to new technologies and energy systems. To systematically address this divergence, our research focuses on two pilot buildings located in Bucharest, Romania, and Nicosia, Cyprus. The objective is to compare their energy performance and SRI scores to illustrate the practical implications of this gap. The study seeks to highlight how a building might score well on traditional energy assessments yet fall short in terms of smart readiness, or vice versa. By doing so, it aims to provide a dual perspective that not only reflects on current assessment practices but also proposes policy recommendations for improving the integration of smart technologies in building assessments. Through a detailed analysis of these pilot buildings, the study aims to inform policy decisions that better align energy efficiency metrics with the SRI, thus offering a more comprehensive understanding of building performance in the context of sustainable and smart architecture. This introduction sets the stage for a deeper exploration into how these assessments can be harmonized to foster buildings that are both energy-efficient and technologically advanced, ultimately contributing to the broader goals of sustainable development.

The study is organized into a structured approach that ensures a comprehensive analysis. The literature review discusses existing research on the SRI, exploring its adaptability across various building types and climates while identifying key challenges and suggested improvements. The methodology section details the selection and analysis of the two pilot buildings, including the tools and criteria used for assessing their energy performance and SRI scores. This is followed by the results and discussion, where findings from the pilot studies are presented and compared, and implications for existing literature and policies are discussed. Finally, the policy implications section draws conclusions from these findings to propose recommendations that address the identified gaps between energy efficiency and smart readiness in building assessments.

This study is among the first to conduct a comparative analysis of SRI and traditional energy performance metrics across different climates and building types, offering practical insights into their applicability in diverse contexts. By examining real-world pilot buildings, it addresses the critical gap in current literature regarding the integration of smart readiness into conventional energy assessment frameworks. The findings not only contribute new data but also provide actionable policy recommendations that could serve as a foundation for future alignment between smart technology integration and energy performance standards in building assessments.

2. Literature review: navigating the landscape of SRI

Table 1
Summary of Studies Investigating Smart Readiness Indicator (SRI) Applications, Challenges, and Proposed Improvements.

Study	Focus	Key Findings
Comparative study (Fokaides et al., 2020)	Application of SRI in European residential buildings	Adaptation of SRI methodology to different building typologies and climates, cost implications, potential for energy savings
National level study (Canale et al., 2021)	Estimation of SRI implementation in Italian building stock	Initial estimation of SRI implementation potential, indicating a 5 % SRI on the current residential building stock
Campus buildings study (Plienaitis et al., 2023)	SRI implementation at Kaunas University of Technology	Impact of city-level services on building-level smartness, connection between building energy performance and smartness
Energy Centre Building study (Becchio et al., 2021)	Influence of energy management on SRI	Insights into SRI's effectiveness in assessing building performance, sensitivity to energy requirements, potential influence of energy management measures
Study on post-EPBD buildings (Apostolopoulos et al., 2022)	Comparison of older and newer buildings	Newer buildings show potential for cost-effective enhancement of smartness, retrofit scenarios can elevate SRI class and energy efficiency
Climate-specific SRI studies (Janhunen et al., 2019)	Adaptation of SRI to diverse climate zones	Customization of SRI to address climate challenges, ensuring relevance across different climates
Resistance to SRI implementation (Alanne and Sierla, 2022)	Challenges in SRI application in Mediterranean climates	Need for adjustments in weighting factors, limited improvements in SRI value from retrofitting measures
Proposal for quantitative elements in SRI (Ramezani et al., 2021)	Enhancing objectivity of SRI framework	Inclusion of quantitative criteria like Energy Savings, Maintenance, Fault Prediction, Comfort, and Health and Wellbeing
Challenges and future directions (Siddique et al., 2023)	Improvements and future research directions	Data availability, evaluation criteria clarity, integration of emerging technologies, potential of machine learning and AI in SRI improvement
Challenges in SRI calculation and implementation (Vigna et al., 2020)	Inconsistencies and weaknesses in SRI assessment	Methodological weaknesses, subjectivity in building service selection affecting accuracy and reliability of SRI
Intelligent building management systems study (Morkunaite et al., 2022)	Assessment of energy savings from multiple heating system control upgrades	Investigation of energy savings resulting from combined automation upgrades in building heating systems, development of an analytical model for assessing feasibility of control upgrades.

The literature surrounding the SRI encompasses a diverse array of studies, ranging from its practical application in various building contexts to the challenges encountered in its implementation and proposed avenues for improvement. This section presents a comprehensive overview, clustering the literature into categories focused on SRI application and adaptation, as well as challenges and proposed enhancements to the indicator.

Studies focused on SRI application reveal its adaptability across diverse building typologies and climates, emphasizing its potential for energy savings and cost implications (Fokaides et al., 2020). Additionally, research at both national (Canale et al., 2021) and campus

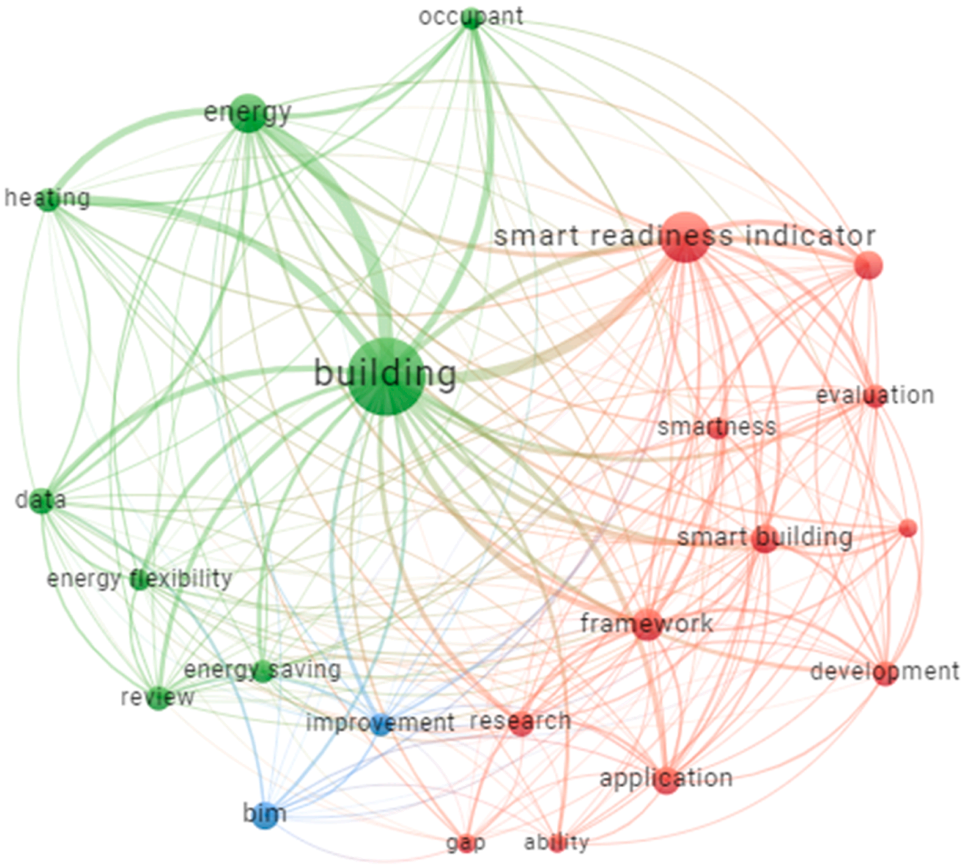


Fig. 1. Bibliometric Chart of Scientific Articles related to SRI - Building smartness research tracker (Smart Readiness Indicator Observatory, 2024).

(Plienaitis et al., 2023) levels underscores the significance of city-level services in influencing building smartness, alongside the correlation between energy performance and SRI scores. Challenges identified in SRI implementation, particularly in Mediterranean climates, include the need for adjustments in weighting factors (Alanne and Sierla, 2022) and limited improvements from retrofitting measures. Proposed improvements aim to enhance the objectivity of the SRI framework by incorporating quantitative elements (Ramezani et al., 2021) and addressing methodological weaknesses, such as inconsistencies in assessment and subjective selection of building services (Vigna et al., 2020). Furthermore, considerations for climate-specific adaptations underscore the necessity of customizing the SRI to address distinct challenges and opportunities across various climatic zones (Janhunen et al., 2019). Future research directions highlight the potential of emerging technologies, like machine learning and artificial intelligence, to enhance the predictive capabilities of the SRI and its adaptability to evolving building technologies (Siddique et al., 2023).

From the literature review, there is a noticeable gap in connecting the smartness of buildings with their energy efficiency. Studies explore SRI applications, revealing its adaptability across building typologies and climates, alongside challenges in its implementation. Proposed improvements aim to enhance the objectivity of the SRI framework by incorporating quantitative elements and addressing methodological weaknesses. However, there remains a significant need to bridge the divide between building intelligence and energy efficiency, as highlighted by the limited focus on this aspect in the current body of literature.

The sparse connection between the SRI and building energy efficiency is also evident by the Building Smartness research tracker of the SRI Observatory (Smart Readiness Indicator Observatory, 2024), within the Smart Square Project (Smart Tools for Smart Buildings: Enhancing the intelligence of buildings in Europe, 2024). This tracker comprehensively analyzes all studies published for the SRI since 2018. Fig. 1, depicting the bibliometric assessment of these studies, further underscores this limited linkage.

3. Methodology

The methodological approach of this study involved the selection and analysis of two low-energy buildings, one located in Bucharest, Romania and the other in Nicosia, Cyprus, to assess their SRI and individual aspects of their energy performance. The choice of these buildings aimed to provide a comparative analysis across different geographic and climatic contexts within Europe. The buildings were chosen based on their adherence to low-energy construction principles and their representation of prevalent building practices in their respective regions. Detailed documentation of each building's technical specifications and energy systems was obtained to facilitate the calculation of their SRI scores.

Using the Smart-Ready-Go! tool, the SRI for each building was calculated, providing a quantitative measure of their smart readiness. This assessment considered various factors, including the integration of smart technologies, energy efficiency measures, and grid interaction capabilities. The calculated SRIs served as a basis for evaluating the buildings' overall readiness to adapt their operations to occupant needs while optimizing energy consumption and interacting with the grid. Furthermore, individual aspects of energy performance, such as heating, cooling, ventilation, lighting, and electricity usage, were analyzed to identify specific strengths and weaknesses in each building's energy systems. This granular analysis provided valuable insights into the effectiveness of implemented energy efficiency measures and the potential for further improvements. The findings from the SRI calculations and energy performance analyses were then synthesized to extract key discussion points and policy implications. The methodological approach

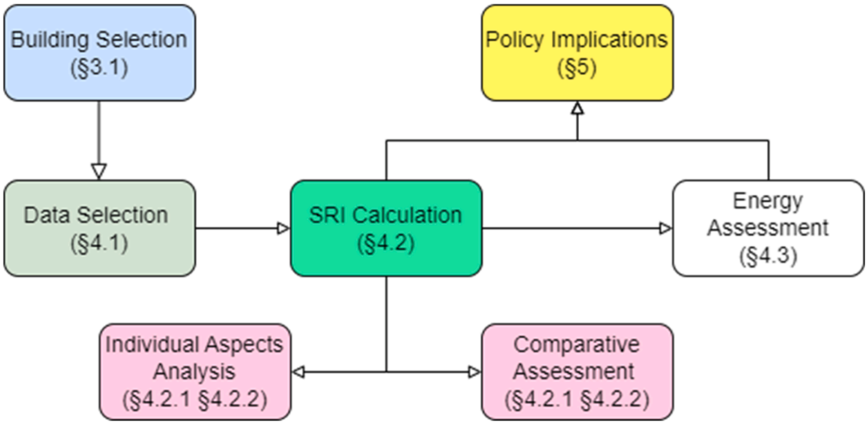


Fig. 2. Study Methodological Approach.

Fig. 3. Exterior view and 3D cross section of pilot building in Bucharest, Romania.

of the study is depicted in Fig. 2.

The study is conducted to highlight the disparity between energy-efficient buildings and their level of smartness, revealing a significant gap in current approaches. By demonstrating this disparity, the study seeks to advocate for the development of a more nuanced approach that considers both energy efficiency and smartness as distinct yet interrelated aspects of building performance.

The selection of pilot buildings in different cities was intended to reflect typi-cal low-energy buildings rather than to com-pare specific climatic conditions. The choice illustrates how SRI scores can vary due to environmental factors, which is acknowledged as a potential area for further research in understanding SRI adaptability across regions.

The two pilot buildings selected for this study demonstrate distinct levels of technological intelligence, which serves as the basis for analyzing the contrast between intelligent readiness and traditional energy performance assessments. The pilot building in Bucharest is equipped with advanced smart systems, including automated lighting and HVAC controls, real-time energy monitoring, and adaptive response mechanisms that adjust energy consumption based on occupancy and external conditions. These features align with the Smart Readiness Indicator's (SRI) criteria for high adaptability and responsiveness to user needs and environmental changes. In contrast, the building in Nicosia lacks such advanced smart features, operating primarily through manual controls and basic automated functions with limited real-time monitoring capabilities. This building's energy performance relies on static efficiency measures without the flexibility to adapt dynamically to varying conditions or user interactions. By comparing building's intelligent features, the study highlights how differences in technological readiness affect overall energy assessment outcomes and the capacity for energy optimization.

Table 2
Technical aspects of Romanian Pilot Building.

Aspect	Specification
Location	Bucharest, Romania
Institution	Technical University of Civil Engineering Bucharest, Faculty of Building Services
Floors	2 (ground floor, first floor)
Height	2.5 m (one level rise)
Intended Use	Exhibition pavilion and residential building
Area (Overall Footprint)	96 m^2
Built Area/Heated Area	170 m^2 / 118 m^2
Total Volume	400 m^3
Building Technical Systems	Air-to-water pump, radiant panels, heat recovery unit (HRU), photovoltaic (PV) system (5.5 kW), electronic water-saving devices, building management system (BMS)
Passive Strategies	Phase change materials (PCMs), high-performance insulation, low-E triple glazed windows
U-Values	Roof 0.121 W/m$^{2\circ}$C;´External Wall 0.129 W/ m$^{2\circ}$C; Floor Above Ground 0.124 W/ m$^{2\circ}$C
Glazing U-Value	0.8 W/ m$^{2\circ}$C
Construction Year	2018
Compliance	Meets recent construction criteria in Romania as per Calculation Methodology MC001 (2022)

3.1. *Description of pilot buildings*

3.1.1. *Pilot building in Bucharest, Romania*

The Romanian pilot building (Fig. 3), nestled within the Faculty of Building Services campus in Bucharest, stands as a beacon of sustainable architecture within the Technical University of Civil Engineering Bucharest (UTCB). Originally conceived as an exhibition pavilion and

Fig. 4. Exterior view of pilot building in Nicosia, Cyprus.

Table 3
Technical aspects of Cyprus Pilot Building.

Aspect	Specification
Location	Tseri, Nicosia, Cyprus
Institution	Energoproject Ltd
Floors	2 (ground floor, first floor)
Height	8 m (two level rise)
Intended Use	Residential unit
Area (Overall Footprint)	149 m^2
Total Volume	≈ 740 m^3
Building Technical Systems	Heat recovery ventilation system, heat pump, solar thermal system, fluorescent and LED lamps, Class A+ appliances, greywater and black water reuse systems, rainwater storage unit, composting unit
Passive Strategies	Heat recovery exchanger ventilation system, achieving an efficiency of 82 % and an outlet air volume of 300 m^3/h. Two-panel closed, forced circulation solar thermal system for partial coverage of domestic hot water requirements.
U-Values	Roof 0.15 W/m^2°C; External walls 0.18 W/m^2°C; Ground floor slab 0.48 W/m^2°C; Window frame 1.3 W/m^2°C; Glazing 0.8 W/m^2°C
Construction Year	2015
Compliance	Meets Passive House standard requirements

residential unit, it now serves as a platform for advocating green building practices and promoting energy efficiency in Romania. Spanning 96 square meters in footprint and boasting a total volume of 400 cubic meters, the building showcases innovative features, aimed at reducing energy consumption and carbon emissions. Active strategies, including an air-to-water pump, radiant panels, and a heat recovery unit, work in tandem with passive techniques like phase change materials (PCMs) to optimize thermal performance and enhance occupant comfort throughout the year. Moreover, the incorporation of high-performance insulation and low-ε triple glazed windows ensures superior thermal efficiency, meeting and even exceeding the latest construction standards mandated by Romanian regulations. Complemented by a 5.5 kW photovoltaic system and advanced building management technology, this sustainable edifice epitomizes a holistic approach to green architecture.

The technical aspects of the Romanian pilot building are given in Table 2

3.1.2. Pilot building in Nicosia, Cyprus

The pilot building in Nicosia, named Tseri Passive House, situated in the suburban area of Nicosia, Cyprus, marks a milestone as the first Passive House constructed in Cyprus (Fig. 4). The Nicosia pilot building has been thoroughly described and analyzed in previous studies (Fokaides et al., 2016; Kylili et al., 2017; Cakyova et al., 2021). Located in Tseri, a suburb south of Nicosia, the two-story, four-bedroom family house boasts a total area of 149 m^2, strategically oriented from east to west to maximize solar exposure during winter months. The building features a reinforced concrete slab foundation and is insulated with glass wool. Organic-based plaster provides external finishing, while triple-glazed windows filled with argon, made of UPVC, ensure superior thermal performance. To mitigate thermal bridges and ensure optimal air tightness, best practices were employed during design and construction. The building is equipped with a heat recovery ventilation system, a heat pump, a solar thermal system, fluorescent and LED lamps, Class A+ appliances, a greywater and black water reuse systems, a rainwater storage unit and a composting unit. The energy design of the Tseri Passive House was carried out using the Passive House Planning Package (PHPP). The design meets the stringent criteria of the Passive House standard, with annual heating requirements limited to 5 kWh/m^{2}a and peak load demand within prescribed limits. The building's air tightness is calculated to be within accepted levels at 0.6 ACh-1. However, the peak cooling load slightly exceeds Passive House standards due to internal and solar heat gains.

3.2. Description of SRI assessment method

In the assessment process for residential buildings, the first step involves identifying relevant services. These services are carefully selected based on the Building Automation and Control Systems (BACS) which are installed. Following this, each selected service undergoes evaluation

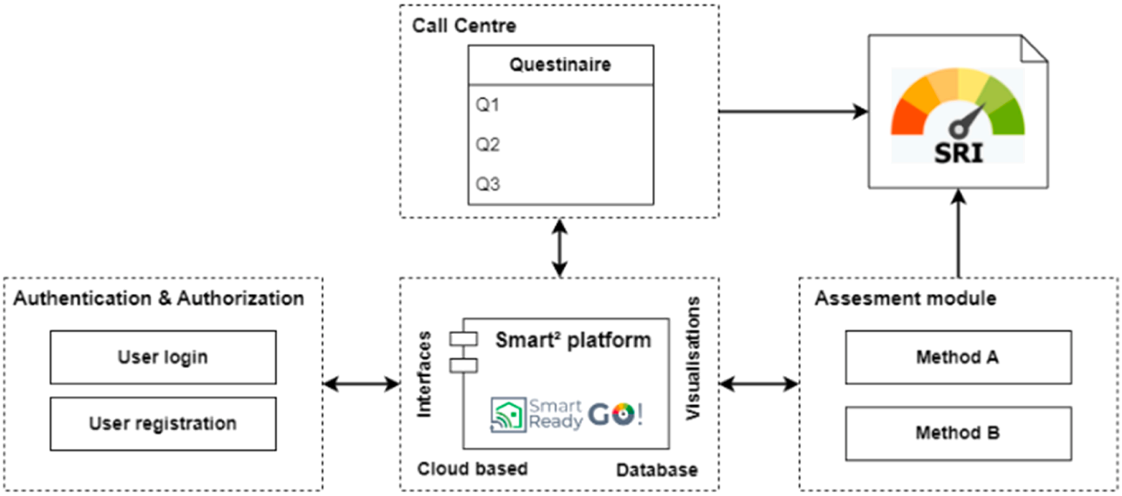


Fig. 5. Architectural structure of Smart-Ready-Go! Tool (Smart-Ready-Go!!, 2024).

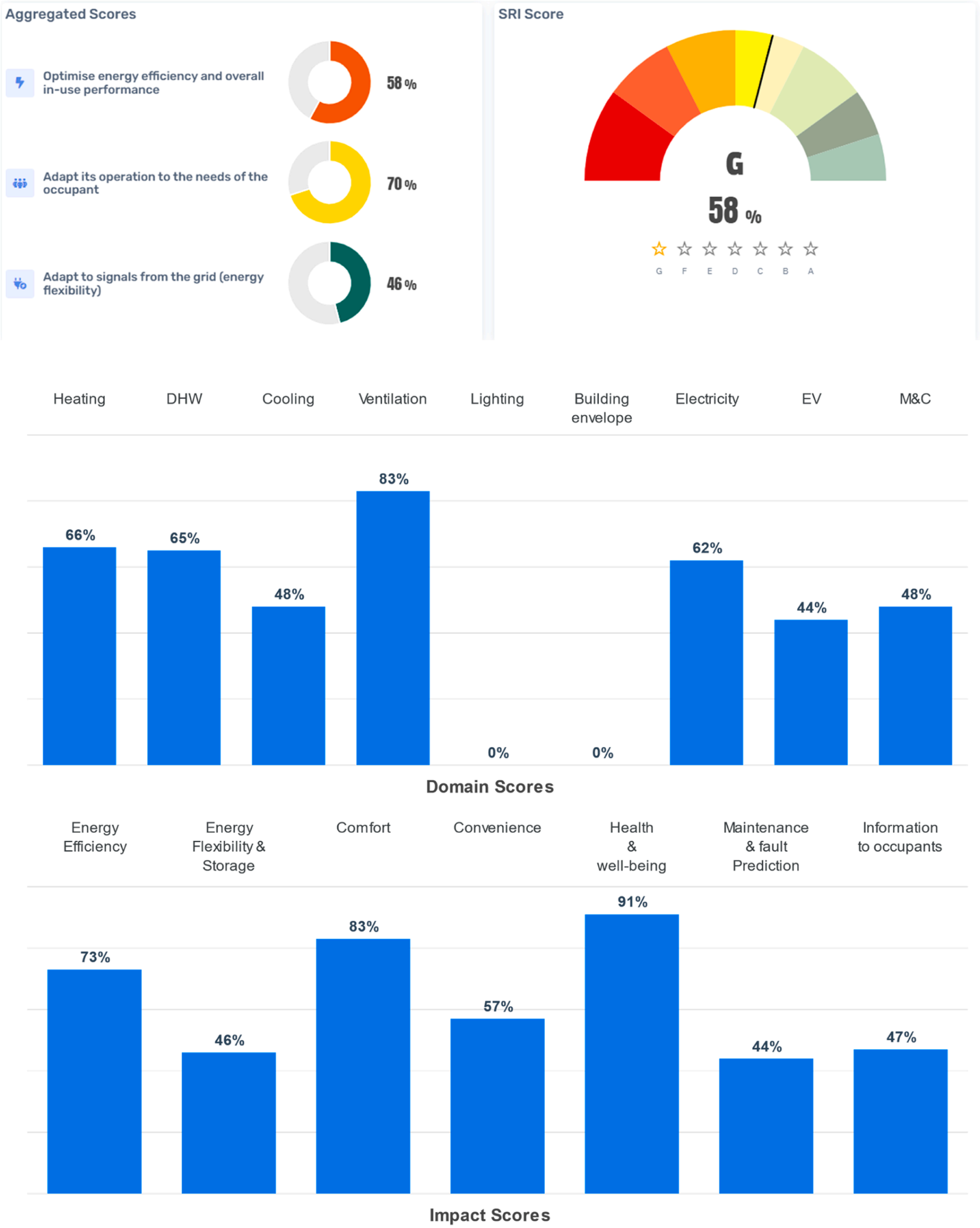


Fig. 6. SRI, Impact and Domain Scores of Bucharest, Romania Pilot.

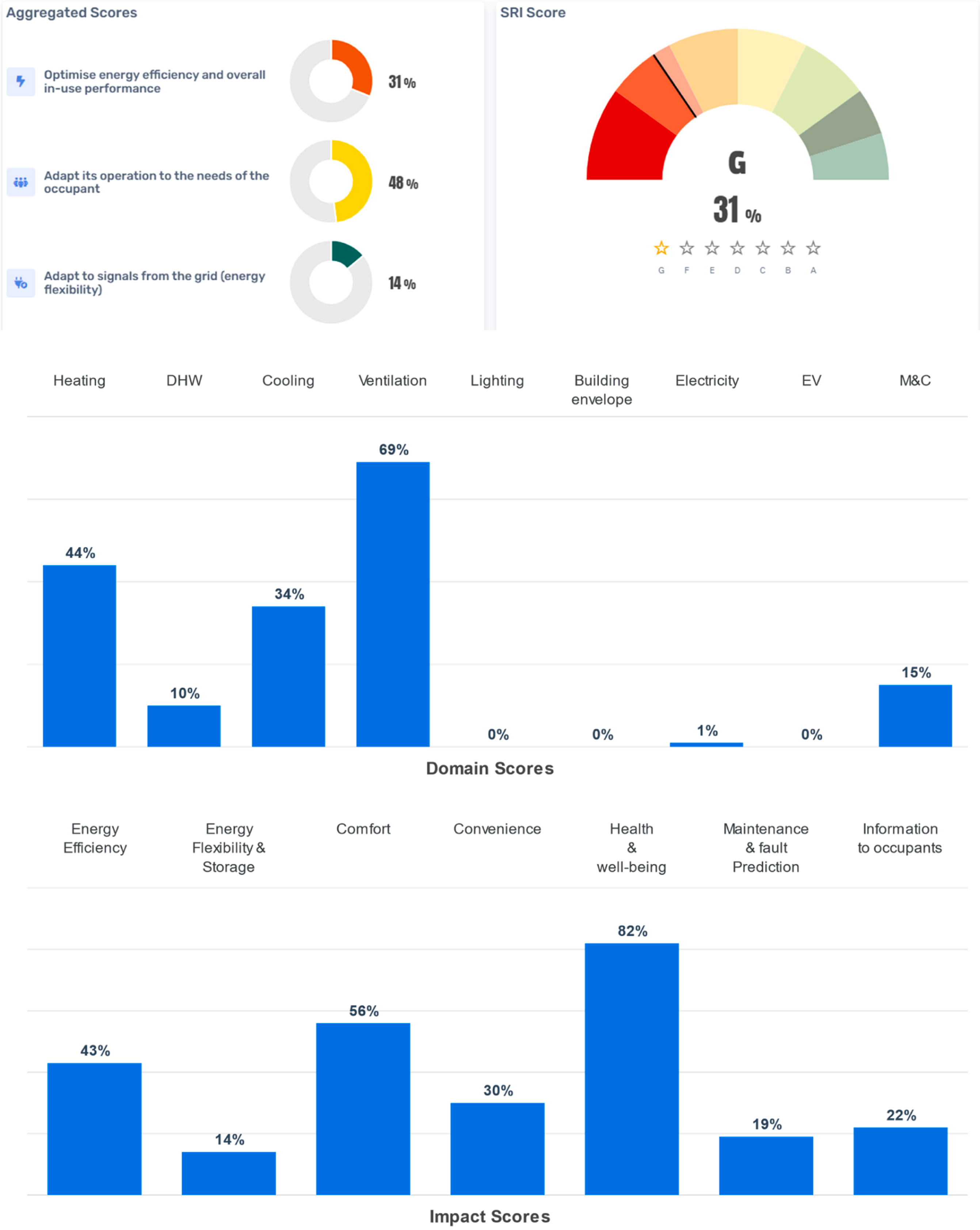


Fig. 7. SRI, Impact and Domain Scores of Nicosia, Cyprus Pilot.

to determine its existing intelligence level and its maximum potential value. Using predefined indications within the methodology, scores are assigned to each service based on its intelligence level, considering various impact criteria. These scores are then accumulated for services within each domain and compared against their maximum values to gauge their performance. Subsequently, percentage averages are calculated for each impact criterion, with the option of applying weighting factors to reflect their respective importance. The percentage values for the three essential functionalities are then weighted, contributing to the determination of the SRI value, which provides an overall assessment of smartness performance.

3.3. SRI assessment tool: smart-ready-go!

The Smart-Ready-Go! tool represents a novel approach to assessing the Smart Readiness Indicator (SRI) for buildings, developed as part of the EU-funded project Smart Square. This tool is designed to simplify and streamline the process of evaluating the smart readiness of buildings across Europe, catering to diverse stakeholders such as building owners, facility managers, and policymakers. The architectural structure of the tool is illustrated in Fig. 5. Its main features are the following:

- At its core, Smart-Ready-Go! is built upon a sophisticated architecture comprising both frontend and backend components. The frontend interface is intuitively designed to facilitate user interaction, featuring input forms for data entry, dashboards for results display, and user guides for effective assessment navigation. This interface ensures accessibility across various user groups, including those with limited digital literacy.
- On the backend, Smart-Ready-Go! employs robust data processing mechanisms to handle information efficiently. Cloud-based services are utilized to ensure scalability, while application programming interfaces (APIs) enable seamless integration with external systems for data retrieval, processing, and user management. One distinctive feature of the tool is its integration with call centers, allowing for data collection from building operators who may not have direct access to digital platforms. Through a structured questionnaire administered during call center interactions, essential building data is swiftly gathered and processed to generate immediate SRI scores.
- The calculation algorithms embedded within Smart-Ready-Go! are meticulously crafted to align with the European Union's SRI framework. These algorithms assess various aspects of building performance, including energy efficiency, system interoperability, and user adaptability. By evaluating predefined criteria, the tool produces transparent and understandable SRI scores, enabling users to identify areas for improvement effectively.
- Extensive validation and testing procedures are conducted to ensure the accuracy, reliability, and user-friendliness of Smart-Ready-Go!. Pilot tests involving a diverse group of buildings across Europe provide valuable feedback for refining the tool's functionality and user interface. Through iterative refinement, Smart-Ready-Go! evolves into a powerful yet accessible tool for assessing the smart readiness of buildings, aligning with the EU's objectives for energy efficiency and digital transformation in the built environment.

The Smart-Ready-Go! tool is freely accessible to all stakeholders as an open-access platform, ensuring inclusivity and democratizing access to smart readiness assessments for buildings across Europe (Smart-Ready-Go!!, 2024).

Table 4
Functionality levels of building services for the two pilot buildings in Bucharest, Romania and Nicosia, Cyprus.

Domain	Relevant Service	Pilot 1 (Bucharest, Romania)	Pilot 2 (Nicosia, Cyprus)
Heating	Heat emission control	Individual room control with communication between controllers and BACS (FL 3)	Individual room control with electronic controller (FL2)
	Heat generator control (heat pumps)	Varibale control of heat generator capacity depending on the load (FL2)	Multi-stage control of heat generator capacity (FL1)
	Storage and shifting of thermal energy	Hot water vessels controlled based on external signals (FL2)	Hot water vessels available (FL1)
	Report information regarding heating system performance	Central reporting with current KPIs and historical data (FL2)	Central reporting with currents KPIs (FL1)
Domestic hot water	Control of DHW storage charging (electric heating)	Automatic control with scheduled charging (FL2)	Automatic control (on/off) (FL0)
	Control of DHW storage charging	Automatic control with scheduled charging (FL2)	Automatic control (on/off) (FL0)
	Report information regarding domestic hot water performance	Information of actual values (FL1)	N/A (FL0)
Cooling	Cooling emission control	Individual room control with communication to BACS (FL3)	Individual room control (FL2)
	Generator control for cooling	Variable control of cooling production (FL2)	Multi-stage control of cooling production (FL1)
	Flexibility and grid interaction	Scheduled operation of cooling system (FL1)	Scheduled operation of cooling system (FL1)
	Report information regarding cooling system performance	Central reporting of current KPIs and historical data (FL2)	Central reporting of current KPIs (FL1)
Controlled ventilation	Supply air flow control at the room level	Local demand control based on air quality sensors (FL4)	Central control based on air quality sensors (FL3)
	Reporting information regarding IAQ	Real time monitoring and historical data (FL2)	Real time autonomous monitoring (FL1)
Lighting	Occupancy control for indoor lighting	Manual on/off (FL0)	Manual on/off (FL0)
Dynamic building envelope	Window solar shading control	N/A	N/A
	Reporting information regarding performance	N/A	N/A
Electricity	Storage of (locally generated) electricity	On site storage of energy (FL4)	N/A (FL0)
	Reporting information regarding electricity consumption	Current generation data available (FL1)	Current generation data available (FL1)
	Reporting information regarding local	Current generation data available (FL1)	N/A (FL0)

(*continued on next page*)

Table 4 (*continued*)

Domain	Relevant Service	Pilot 1 (Bucharest, Romania)	Pilot 2 (Nicosia, Cyprus)
	electricity generation		
	Reporting information regarding energy storage	Current state of charge data available (FL1)	N/A (FL0)
Electric vehicle charging	Charging capacity	>50 % of parking spaces has recharging point (FL4)	N/A
	EV Charging Grid balancing	One way-controlled charging (FL1)	N/A
	EV charging information and connectivity	Reporting information on EV charging status (FL1)	N/A
Monitoring and control	Single platform for automated control & coordination	Single Platform that allows manual control (FL1)	N/A (FL0)
	Smart Grid Integration	Demand side management possible (FL1)	N/A (FL0)
	Central reporting of TBS performance and energy use	Central reporting of real time energy use per energy carrier (FL1)	Central reporting of real time energy use per energy carrier (FL1)

4. Results and discussions

4.1. Assessment of Building Automation and Control Systems (BACS) Functionality Levels (FL)

To document the functionality level of various Building Automation and Control Systems (BACS) within the pilot buildings, a systematic approach was undertaken. Each BACS was evaluated across multiple domains, including heating, domestic hot water, cooling, controlled ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging, and monitoring and control. Relevant services within each domain were assessed based on their functionality level, which ranged from FL0 (basic functionality) to FL4 (advanced functionality), in accordance to the context of the SRI methodology, as outlined in the relevant EU regulations (European_Parliament, 2020a, 2020b). The assessment involved scrutinizing the performance and capabilities of each BACS component, such as heat emission control, generator control, ventilation supply, lighting occupancy control, and more. For instance, in the heating domain, the functionality levels of heat emission control, generator control, storage and shifting of thermal energy, and reporting information regarding heating system performance were thoroughly examined. The results of these evaluations are presented in the following table, showcasing the functionality levels of different BACS services across two pilot buildings located in Bucharest, Romania, and Nicosia, Cyprus. This comprehensive documentation provides valuable insights into the capabilities and effectiveness of BACS in optimizing energy efficiency and building performance.

4.2. Comparative assessment of SRI, impact and domain scores of pilot buildings

Fig. 6 and Fig. 7 depict the SRI scores, the impact scores, and the domain scores of the two pilot buildings in Bucharest, Romania, and Nicosia, Cyprus, providing insights into their smartness performance across various domains and impacts. The comparative assessment of the SRI scores between the pilot buildings in Cyprus and Romania offers valuable insights into their respective smartness performance across various domains.

4.2.1. Comparison of impact scores of pilot buildings

The comparative assessment of domain scores between the Bucharest and Nicosia pilot buildings offers insights into their respective strengths and areas for improvement in key aspects of smartness performance.

4.2.1.1. Optimization of energy efficiency and overall in-use performance. In terms of energy efficiency, the Bucharest pilot building demonstrates a significantly higher score of 73 %, indicating superior efficiency in energy utilization compared to the Nicosia pilot, which scores 43 %. This suggests that the Bucharest building implements more effective energy-saving measures and technologies, leading to reduced energy consumption and improved overall efficiency.

Similarly, in the domain of energy flexibility and storage, the Bucharest pilot outperforms its Nicosia counterpart with a score of 46 % compared to 14 %. This indicates that the Bucharest building has better adaptability and resilience in managing energy demand fluctuations and integrating energy storage solutions, which are crucial for optimizing energy use and grid interaction.

4.2.1.2. Adaptation of operation to the needs of the occupant. Regarding comfort, both buildings achieve relatively high scores, with Bucharest scoring 83 % and Nicosia scoring 56 %. This suggests that both buildings prioritize occupant comfort and well-being through effective HVAC systems, indoor air quality management, and thermal comfort control. However, there is room for improvement in the Nicosia pilot to match the higher comfort standards of the Bucharest building.

In terms of convenience, the Bucharest pilot demonstrates a higher score of 57 % compared to 30 % for Nicosia. This indicates that the Bucharest building offers more user-friendly features and amenities, making it easier for occupants to operate and interact with building systems and services.

In the domain of health, well-being, and accessibility, both pilots achieve relatively high scores, with Bucharest scoring 91 % and Nicosia scoring 82 %. This suggests that both buildings prioritize creating healthy and accessible environments for occupants, with features such as indoor air quality monitoring, accessibility features, and ergonomic design elements.

Maintenance and fault prediction scores are higher for the Bucharest pilot at 44 %, compared to 19 % for Nicosia. This indicates that the Bucharest building implements more robust maintenance practices and predictive maintenance technologies, leading to improved system reliability, reduced downtime, and enhanced occupant satisfaction.

4.2.1.3. Adaptation to signals from the grid (energy flexibility). In the domain of information to occupants, the Bucharest pilot achieves a higher score of 47 % compared to 22 % for Nicosia. This suggests that the Bucharest building provides better communication and transparency to occupants regarding building performance, energy usage, and comfort settings, empowering occupants to make informed decisions and adjust their behavior to optimize energy use.

4.2.2. Comparison of domain scores of pilot buildings

Starting with the Romania pilot, the building showcases higher SRI scores across multiple domains, reflecting a more advanced level of smartness and energy efficiency. The heating domain stands out with an exceptional score of 66 %, indicating highly efficient heating systems and effective control mechanisms. Similarly, the DHW domain achieves a respectable score of 65 %, suggesting efficient water heating practices. Cooling systems perform relatively well with a score of 48 %, indicating efficient cooling energy management. Ventilation systems excel with a perfect score of 83 %, indicating optimal airflow control for indoor air quality and comfort. Moreover, the electricity domain demonstrates improved energy efficiency practices, achieving a score of 62 %. Notably, EV charging infrastructure and M&C systems show promising smartness levels with scores of 44 % and 48 %, respectively, indicating

Table 5
Pilot Building in Bucharest, Romania: Energy Loads Breakdown.

System	Percentual Consumption	Energy consumption [kWh FE/ m^2/year]
Heating	10 %	3.37
Cooling	11 %	3.58
Ventilation	13 %	4.30
Domestic Hot Water	19 %	6.16
Lighting	16 %	5.18
Appliances & Devices	31 %	10.12

ongoing efforts towards integrating advanced technologies for energy optimization.

In contrast, the Cyprus pilot building SRI scores reveal a mixed picture of smartness performance. While certain domains demonstrate commendable efficiency, others exhibit significant room for improvement. In the heating domain, the Cyprus pilot achieves a moderate score of 44 %, indicating efficient energy utilization in heating systems. However, the performance in the domestic hot water (DHW) domain is strikingly low, scoring only 10 %. This suggests a lack of energy-efficient practices in water heating, which could be attributed to outdated systems or inadequate insulation. Similarly, cooling systems in the Cyprus pilot exhibit moderate efficiency, with a score of 34 %, indicating potential for optimization in cooling energy consumption. The ventilation domain performs reasonably well, with a score of 69 %, showcasing efficient airflow management for indoor comfort, which results from the advanced requirements of the Passive House concept for ventilation. Nevertheless, domains such as lighting, dynamic building envelope, electricity, electric vehicle (EV) charging, and monitoring and control (M&C) demonstrate low scores, indicating deficiencies in energy-efficient practices and smart technology integration.

Comparing the two pilot buildings, several notable differences emerge in their smartness performance. The Romania pilot building demonstrates superior energy efficiency across various domains, particularly in heating and cooling, where it outperforms its Cyprus counterpart significantly. This could be attributed to advanced building design and technology integration, along with effective energy management strategies. Conversely, the Cyprus pilot building lags behind in energy efficiency, particularly in DHW and electricity domains, indicating potential inefficiencies in water heating and cooling energy consumption.

4.3. Comparative assessment of energy performance of pilot buildings

4.3.1. Energy assessment of Bucharest, Romania pilot building

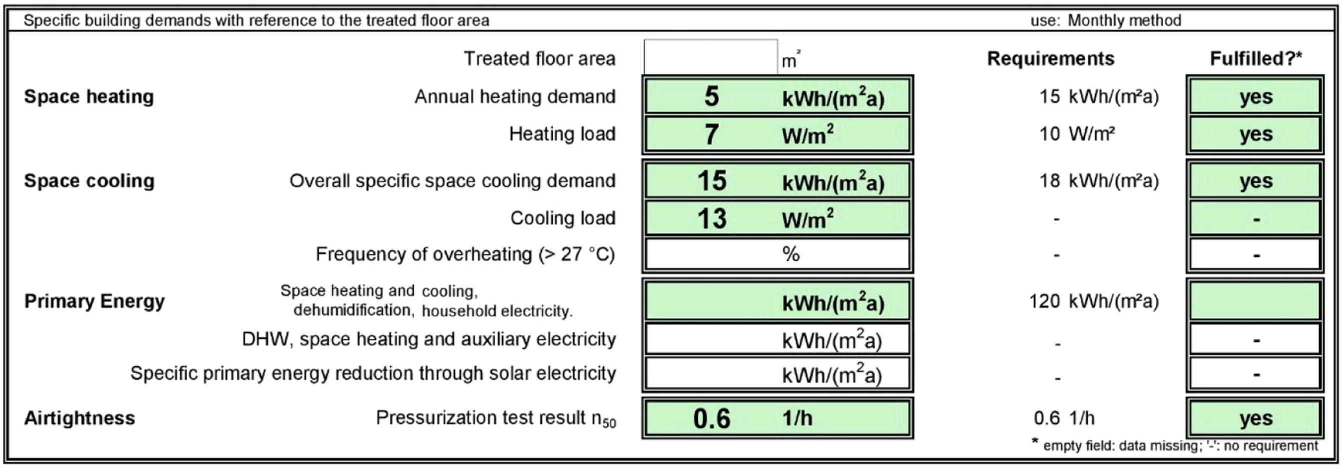
The pilot building in Bucharest integrates solar photovoltaic and thermal panels to generate electricity and provide hot water efficiently. An air-water heat pump with an average COP of 3–4 manages heating, cooling, and hot water needs. The building's ventilation system with heat recovery and a rotary heat exchanger ensures efficient dehumidification and minimal energy wastage. With a building envelope U-value of 0.30 W/m^2K and a roof U-value of 0.121 W/m^2K, the house's thermal losses trough transmission are low (Construction 21 International, 2024). Buffer zones, a ceramic facade, and PCMs regulate indoor temperatures efficiently. The building's design uses low-emissivity windows to capture solar radiation in winter for heating, while reflecting it in summer to minimize overheating. With an air tightness of 0.87 ACH at 50 Pa, the building air leakage is low, reducing energy loss and maximizing heating and cooling efficiency.

The pilot building from Romania achieves a final energy consumption of 32.68 kWh FE/m^2/year, significantly lower than conventional standards applicable in the year in which it was designed. The pilot building's primary energy consumption is 62.09 kWh PE/m^2/year, using a conversion factor of 2.5 for electricity and factoring in 40 % energy coverage from solar panels. This is significantly lower than the 2022 standard of 127.9 kWh PE/m^2/year, securing an A energy efficiency rating in Romania.

4.3.2. Energy assessment of Nicosia, Cyprus pilot building

The energy design of the Nicosia pilot building was crafted using the Passive House Planning Package (PHPP), a spreadsheet tool developed by the Passivhaus Institute. PHPP has been refined through systematic comparisons of dynamic simulations with validated measurements from completed Passive House projects (Passive House Institute (PHI), 2015) Fig. 8 illustrates the specific building demands in relation to the treated floor area, as determined through PHPP analysis.

As anticipated, the space cooling demand surpasses the heating demand. Specifically, the annual heating requirements are capped at 5 kWh/m^2a with a peak load demand of 7 W/m^2—both values comfortably within the Passive House standard limits. Additionally, the building's air tightness was assessed and found to meet accepted levels at 0.6 ACh-1. However, concerning the cooling load, while the overall specific cooling requirement aligns with Passive House regulations at 15 kWh/m^2a, the peak load exceeds stipulated limits. Further scrutiny of the cooling loads, as calculated by PHPP (see Fig. 9), reveals that internal heat loads and solar heat gains collectively contribute to over 50 % of the total cooling demand. This observation can be attributed to the

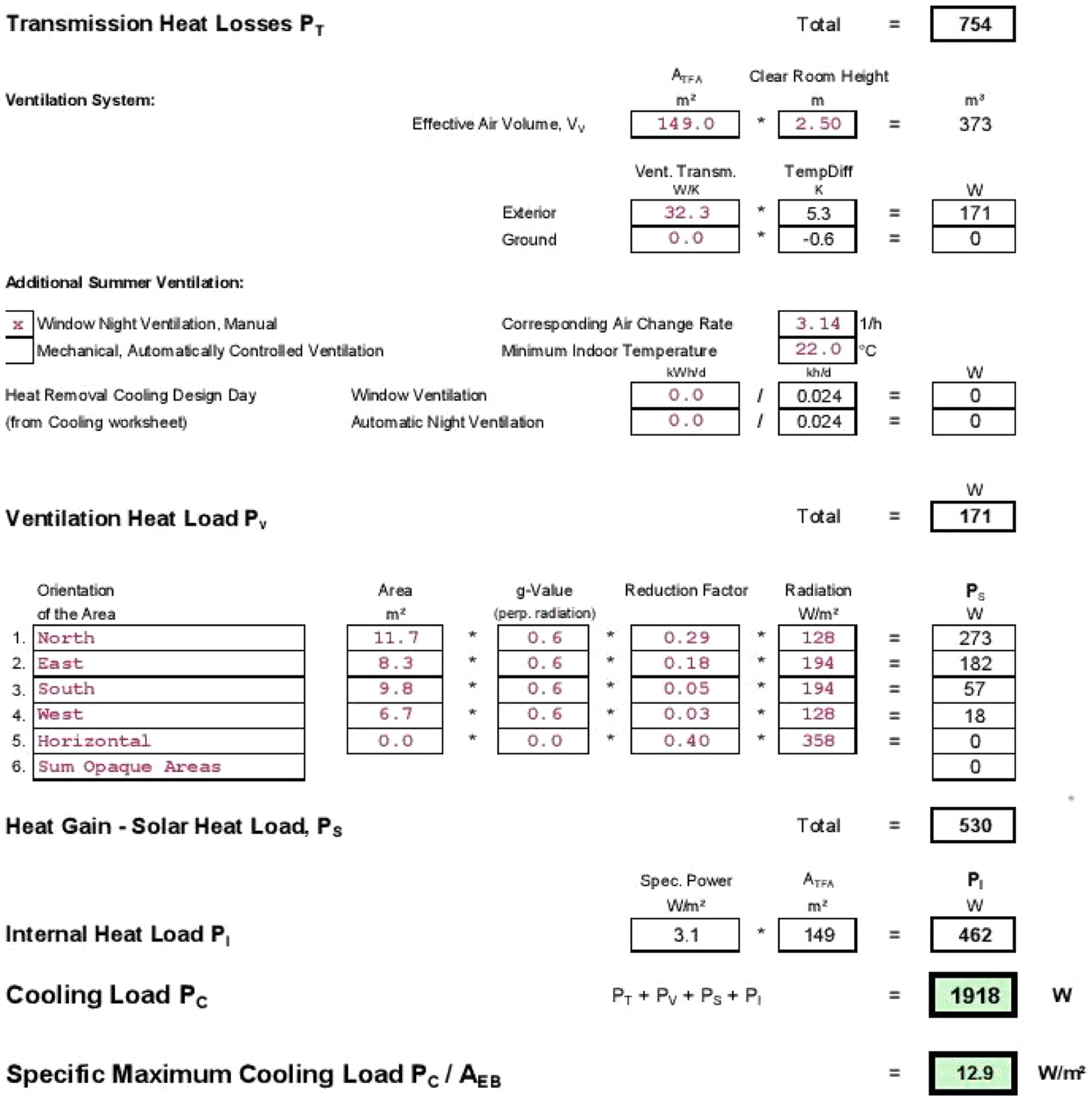


Specific building demands with reference to the treated floor area — use: Monthly method

				Requirements	Fulfilled?*
	Treated floor area		m^2		
Space heating	Annual heating demand	5	kWh/(m^2a)	15 kWh/(m^2a)	yes
	Heating load	7	W/m^2	10 W/m^2	yes
Space cooling	Overall specific space cooling demand	15	kWh/(m^2a)	18 kWh/(m^2a)	yes
	Cooling load	13	W/m^2	-	-
	Frequency of overheating (> 27 °C)		%	-	-
Primary Energy	Space heating and cooling, dehumidification, household electricity.		kWh/(m^2a)	120 kWh/(m^2a)	
	DHW, space heating and auxiliary electricity		kWh/(m^2a)	-	-
	Specific primary energy reduction through solar electricity		kWh/(m^2a)	-	-
Airtightness	Pressurization test result n_{50}	0.6	1/h	0.6 1/h	yes

* empty field: data missing; '-': no requirement

Fig. 8. : Nicosia, Cyprus pilot building specific energy demands derived by PHPP.



Transmission Heat Losses P_T Total = 754

Ventilation System:

	A_{TFA} m²		Clear Room Height m		m³
Effective Air Volume, V_V	149.0	*	2.50	=	373

	Vent. Transm. W/K		TempDiff K		W
Exterior	32.3	*	5.3	=	171
Ground	0.0	*	-0.6	=	0

Additional Summer Ventilation:

☒ Window Night Ventilation, Manual — Corresponding Air Change Rate 3.14 1/h

☐ Mechanical, Automatically Controlled Ventilation — Minimum Indoor Temperature 22.0 °C

		kWh/d		kh/d		W
Heat Removal Cooling Design Day	Window Ventilation	0.0	/	0.024	=	0
(from Cooling worksheet)	Automatic Night Ventilation	0.0	/	0.024	=	0

Ventilation Heat Load P_V Total = W 171

	Orientation of the Area	Area m²		g-Value (perp. radiation)		Reduction Factor		Radiation W/m²		P_S W
1.	North	11.7	*	0.6	*	0.29	*	128	=	273
2.	East	8.3	*	0.6	*	0.18	*	194	=	182
3.	South	9.8	*	0.6	*	0.05	*	194	=	57
4.	West	6.7	*	0.6	*	0.03	*	128	=	18
5.	Horizontal	0.0	*	0.0	*	0.40	*	358	=	0
6.	Sum Opaque Areas									0

Heat Gain - Solar Heat Load, P_S Total = 530

	Spec. Power W/m²		A_{TFA} m²		P_I W
Internal Heat Load P_I	3.1	*	149	=	462

Cooling Load P_C $P_T + P_V + P_S + P_I$ = 1918 W

Specific Maximum Cooling Load P_C / A_{EB} = 12.9 W/m²

Fig. 9. **:** Nicosia, Cyprus pilot building verification of cooling loads derived by PHPP.

substantial solar irradiation typical of subtropical climates, coupled with the moderate solar emissivity levels of the building materials (ε-value).

4.3.3. Comparison of energy performance of pilot buildings

The energy performance of the pilot buildings in Bucharest, Romania, and Nicosia, Cyprus shows a clear focus on integrating sustainable technologies and design to achieve high energy efficiency. The Bucharest building achieves a notably low final energy consumption of 32.68 kWh FE/m^2/year, which is far below the 2022 standard of 127.9 kWh PE/m^2/year in Romania, securing an A energy efficiency rating. This building effectively uses solar energy to cover 40 % of its energy needs, significantly reducing dependency on external energy sources. In contrast, the Nicosia building, designed using the Passive House Planning Package, demonstrates excellent performance in a subtropical climate with high solar irradiation. The structure maintains a strict cap on annual heating requirements at 5 kWh/m^{2}a, indicating superior insulation and building envelope performance. However, it faces challenges with cooling demands due to internal and solar heat gains, resulting in a cooling requirement of 15 kWh/m^{2}a and a peak load that exceeds Passive House standards.

Both buildings exhibit exceptional energy efficiency but with different focal points and challenges. Bucharest's building excels in integrating renewable energy sources and maintaining low energy consumption overall, while Nicosia's building is tailored to manage the intense solar heat typical of its climate, albeit with some challenges in cooling load management. These differences highlight the adaptability of energy-efficient designs to various climatic and environmental conditions.

5. Conclusions and policy implication

5.1. Overview

The policy implications drawn from this study underscore the critical intersection of energy efficiency and smartness in building performance assessment. As the global focus intensifies on sustainable development and carbon mitigation strategies, the imperative to optimize building operations for both energy conservation and smart functionality becomes increasingly apparent. The disparities revealed between energy-efficient buildings and their levels of smartness illuminate significant gaps in current assessment methodologies, signaling a pressing need for more nuanced approaches. By advocating for the refinement of existing standards and certifications to better integrate these dual aspects of building performance, policymakers can pave the way for a more holistic and effective framework for evaluating building sustainability. Furthermore, the urgency for continued research and development efforts aimed at bridging these gaps highlights the importance of fostering innovation and collaboration across disciplines. Ultimately, the policy implications outlined herein emphasize the vital role that informed policymaking and strategic interventions can play in driving the adoption of smart building technologies and practices, thereby advancing the transition towards a more sustainable built environment.

5.1.1. Balancing energy efficiency and smartness in building assessment

The study advocates for the development of a more nuanced approach to building assessment, recognizing energy efficiency and smartness as distinct yet interrelated aspects of building performance. It emphasizes the importance of achieving a balanced integration of these criteria in future standards and certifications. By acknowledging the symbiotic relationship between energy conservation and smart functionality, policymakers can foster the evolution of assessment methodologies to better capture the multifaceted nature of building sustainability. This approach seeks to address the disparities revealed between energy-efficient buildings and their levels of smartness, ultimately promoting more holistic evaluations of building performance. Such advancements in assessment frameworks can drive the adoption of innovative technologies and practices that optimize both energy consumption and operational intelligence, thereby facilitating the transition towards more sustainable built environments.

5.1.2. Enhancing the SRI methodology

There is an urgent need for the ongoing refinement and improvement of the SRI methodology to ensure its effectiveness in accurately capturing and evaluating the smartness of buildings. This refinement is essential for facilitating informed decision-making by stakeholders, including building owners, facility managers, policymakers, and certification bodies. By continuously updating the SRI methodology, researchers and practitioners can address emerging challenges, incorporate new technological advancements, and refine assessment criteria to better align with evolving smart building practices. Such enhancements will enhance the reliability and relevance of SRI assessments, enabling stakeholders to make more informed decisions regarding building design, operation, and certification. Moreover, by ensuring that the SRI methodology remains robust and adaptable, policymakers can promote the widespread adoption of smart building technologies and practices, thereby contributing to the advancement of sustainable and intelligent built environments.

5.1.3. Promoting policy interventions for smart building adoption

There is a critical need for policy interventions and incentives aimed at promoting the widespread adoption of smart building technologies and practices. By implementing supportive policies, governments and regulatory bodies can create an enabling environment for the transition towards more intelligent, energy-efficient building stock. These interventions may include financial incentives, tax breaks, grants, and subsidies to encourage investment in smart building technologies and retrofits. Additionally, regulatory measures such as building codes, standards, and certification requirements can help drive the adoption of smart building practices. By advocating for these policy interventions, stakeholders can accelerate the uptake of smart building solutions, leading to significant energy savings, environmental benefits, and enhanced building performance. Furthermore, by fostering a supportive policy environment, governments can spur innovation, create jobs, and stimulate economic growth in the burgeoning smart building sector.

Table 6
Policy Implications for Addressing the Disparity Between Energy Efficiency and Smartness in Building Assessment.

Policy Implication	Short Description
Balancing Energy Efficiency and Smartness in Building Assessment	Advocate for a nuanced approach to integrate energy efficiency and smartness in building standards for holistic evaluations.
Enhancing the SRI Methodology	Urgency for continuous refinement of the SRI to ensure accurate evaluation of building smartness.
Promoting Policy Interventions for Smart Building Adoption	Advocate for incentives and regulations to accelerate adoption of smart building technologies for energy-efficient construction.
Fostering Interdisciplinary Collaboration in Smart Building Development	Emphasize collaboration among architects, engineers, policymakers, and tech providers to innovate smart building solutions.

5.1.4. Fostering interdisciplinary collaboration in smart building development

It's essential to recognize the necessity for interdisciplinary collaboration and knowledge sharing among various stakeholders in the building industry. Architects, engineers, policymakers, and technology providers must come together to drive innovation and promote best practices in smart building design, construction, and operation. By fostering collaboration, stakeholders can leverage their diverse expertise to develop holistic solutions that integrate energy efficiency, sustainability, and smart technologies seamlessly. This interdisciplinary approach ensures that smart building projects are designed, implemented, and maintained effectively, maximizing their benefits for occupants, communities, and the environment. Moreover, knowledge sharing, and collaboration enable stakeholders to stay abreast of emerging trends, technologies, and regulatory developments, facilitating continuous improvement and adaptation in the rapidly evolving field of smart buildings. By fostering a culture of collaboration, the building industry can overcome silos, break down barriers, and unlock the full potential of smart building technologies to create healthier, more sustainable built environments for all.

In conclusion, the study emphasized the discrepancies between traditional energy performance assessments and the Smart Readiness Indicator (SRI) in the context of sustainable architecture. It highlighted a significant gap that exists in how buildings' energy efficiency and their capability to integrate smart technologies are evaluated and understood, particularly within the European legislative framework.

Key findings from the research on two pilot buildings in Bucharest, Romania, and Nicosia, Cyprus demonstrate that a building can perform well in traditional energy assessments but may lag in smart readiness and vice versa. This disparity suggests that current assessment methods may not fully account for a building's overall performance and potential in terms of energy management and technological integration. The conclusions drawn from these findings strongly advocate for a reevaluation and alignment of energy efficiency metrics with SRI scores. This would involve refining policy frameworks to better integrate smart technologies into building assessments, which in turn would provide a more comprehensive understanding of a building's performance. The study's implications extend to policy-making, suggesting the need for policies that encourage the adoption of both energy-efficient and smart technologies in buildings to meet broader sustainable development goals. This calls for a nuanced approach that balances technical, economic, and environmental aspects of building performance, promoting a future where buildings are not only energy efficient but are also adaptable and responsive to the needs of occupants and the wider energy grid. Such a holistic approach would significantly contribute to the sustainability and resilience of urban environments.

CRediT authorship contribution statement

Cristiana Croitoru: Validation, Formal analysis. **Manolis Souliotis:** Writing – original draft, Visualization. **Florin Bode:** Visualization, Methodology, Investigation. **Răzvan Calotă:** Software, Investigation, Formal analysis. **Paris A Fokaides:** Writing – review & editing, Supervision, Resources, Conceptualization.

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.

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Data availability

Data will be made available on request.

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