

Research paper

Exposing the limits in the residential building energy performance certification model



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ABSTRACT

This study examines the energy performance of residential buildings in Cyprus, focusing on the accuracy of the iSBEM-Cy Energy Performance Certification (EPC) system. Cyprus presents a unique context due to its Mediterranean climate and aging building stock, constructed mostly between 1980 and 2000 without energy efficiency regulations. This research investigates the discrepancies between simulated and actual energy consumption in typical Cypriot homes. Previous studies have highlighted the limitations of current EPC models, often showing significant variances between predicted and real-world energy usage. Using a comparative analysis, this study collects data from 15 residential units, examining heating, cooling, lighting, and hot water energy use. The results reveal notable differences, particularly in cooling loads, suggesting the need for improved modelling of user behaviour and local climate conditions. This research underscores the importance of accurate EPCs for effective policy-making and sustainable building practices, contributing to enhanced energy efficiency and reduced greenhouse gas emissions in the building sector. Future endeavours should prioritize integrating granular behavioural and climate-specific data to refine energy certification models further.

1. Introduction

In recent decades, global efforts to establish regulations to reduce energy consumption and increase energy efficiency in buildings (Seyfar et al., 2022; Wang and Lin, 2025) and in energy-intensive economic sectors (Ifeyanyi Ibekwe et al., 2024; Buonomano et al., 2022) have gained significant momentum. This priority is especially critical in Europe, where buildings represent 40 % of overall energy usage (Kalogirou, 2015; Karytsas et al., 2019), with final users' energy needs comprising up to 80 % of this demand (Vardopoulos, 2017; Zhang et al., 2022). Furthermore, energy use in buildings plays a major role in driving climate change, contributing to 36 % of the greenhouse gas

emissions linked to energy production (Harputlugil and de Wilde, 2021; Michael et al., 2020; Savvides et al., 2023). This is largely due to the fact that 75 % of existing buildings are classified as energy inefficient (Dixit, 2017; Vardopoulos et al., 2023). Enhancing the energy efficiency of buildings is essential not only for cutting greenhouse gas emissions but also for improving occupant comfort and lowering operating costs (Buonomano et al., 2024; Vassiliades et al., 2023).

A variety of technologies and energy sources have played a role in shaping the current energy landscape (Barone et al., 2022; Muhumuza et al., 2019), with political and economic considerations heavily influencing the selection of these sources (Mazzei and Palombo, 1999; Taylor et al., 2024). The implementation of the dual substitution policy has effectively facilitated the shift toward greener solutions, with

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Nomenclature

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|------|---|
| EAC | Electricity Authority Cyprus |
| EPBD | Energy Performance of Buildings Directive |
| EPC | Energy Performance Certification |
| DT | Digital Twin |
| HVAC | Heating, ventilation and air-conditioning |
| nZEB | Nearly zero-energy building |
| RLM | Recommendation List of Measures |
| SHGC | Solar Heat Gain Coefficient |
| VT | Visual Transmittance |

socioeconomic factors proving to be key influences (Wang et al., 2019; Bai et al., 2023). Traditionally, electricity is mainly produced through fossil fuel-based power generation methods. However, to modernize energy infrastructure and facilitate renewable-based energy production, novel regulations have recently been introduced (Genoese et al., 2015; Makhholm, 2015). The opening of the electricity market to competition, coupled with government initiatives, has significantly impacted funding for combined heat and power plants, with financial incentives and fuel support costs being key factors (Sundberg and Henning, 2002; Atanasoae, 2018). Moreover, climate policies such as emissions trading and taxes have affected decisions on power plants investments, thereby enhancing the energy grid flexibility (Nagel et al., 2022; Abrell et al., 2022).

The European Energy Performance of Buildings Directive (EPBD) provides guidelines to improve building energy performance and highlights the path for countries to adopt green energy measures (Maduta et al., 2023; López-Ochoa et al., 2019). This regulation is essential for addressing the design and refurbishment of buildings, along with the selection of appropriate solutions from the available options. The original EPBD required all European countries to issue energy performance certificates for buildings under construction, for sale, or for rent (Motuzienė et al., 2021; Vaquero, 2020). The 2018 update to the EPBD revised previous directives to include long-term renovation strategies, building infrastructure technologies, electric mobility, smart functionality metrics, heating system evaluations, and building automation and control solutions (Sesana et al., 2019; Economidou et al., 2020; Moseley, 2017). Specifically, the revised EPBD aims to enhance energy efficiency in the EU's building sector, crucial for achieving climate neutrality by 2050 (Maduta et al., 2023). Additionally, Zangheri et al. (2022) discuss the cost-optimal methodology, which mandates Member States to assess and update energy performance requirements every five years, showing positive trends towards compliance (Zangheri et al., 2022). However, challenges remain, particularly in aligning national strategies with EU benchmarks and increasing renovation rates to meet zero-emission goals (Maduta et al., 2023; Olasolo-Alonso et al., 2023). Overall, while progress is evident, further efforts are needed to ensure effective implementation of the revised EPBD.

Cyprus, as a European Union member, presents a distinctive case for examining building energy efficiency. This uniqueness stems from its specific climatic conditions and the significant potential for renovating its real estate assets. Most residential buildings in Cyprus were built during the period from 1980 to 2000, a time when energy performance regulations were not yet established (Constantinides et al., 2024). Consequently, these buildings typically exhibit low energy efficiency (Heracleous et al., 2022). The combination of Cyprus's Mediterranean climate, characterized by hot summers and mild winters, and the opportunity to enhance the energy performance of these older buildings, makes it an ideal context for studying the impacts and benefits of implementing modern energy efficiency measures (Vardopoulos et al., 2024).

In Cyprus, the building sector represents more than 30 % of the

nation's overall energy consumption, posing a considerable challenge for the government to reduce energy usage in existing structures (Vardopoulos et al., 2024; Agathokleous and Kalogirou, 2021). This high consumption is primarily due to the inefficiencies of older buildings that were constructed without modern energy-saving measures. To address this issue, the Cypriot government has adopted the Simplified Building Energy Model (iSBEM-Cy) (Dimitriou et al., 2020), which serves as a crucial tool for energy performance certification (EPC) of both residential and non-residential buildings. iSBEM-Cy evaluates buildings' energy use and ensures they meet current regulations, playing a vital role in the country's efforts to enhance energy efficiency and sustainability (Italos et al., 2022; Barone et al., 2023).

Previous research has highlighted notable issues and inconsistencies within building energy performance certification processes (Few et al., 2023). Various studies have demonstrated that current energy models often lack reliability, leading to discrepancies between predicted and actual energy consumption (Gouveia et al., 2020; Monfils et al., 2016; Iribar et al., 2021). Inconsistencies in software predictions further complicate the accuracy of these assessments. Additionally, there is a recognized need for improved energy management techniques to ensure more accurate evaluations. These findings underscore the important role of user behaviour in influencing energy performance (Laaroussi et al., 2020), suggesting that any effective EPC system must account for how occupants interact with their living environments (Mahdavi and Berger, 2019). Addressing these challenges is essential for developing more accurate and reliable building energy assessments.

The aim of this study is to assess the precision and reliability of the iSBEM EPC system in Cyprus. By conducting an in-depth comparative analysis, this research aims to determine the accuracy of the iSBEM EPC. By focusing on this specific system, the study addresses a significant research gap concerning the precision of the software and its performance in everyday applications. This investigation is crucial for determining whether iSBEM can provide accurate and reliable assessments of building energy performance, thereby enforcing improvements in energy certification processes and enhancing overall building energy efficiency.

This research has significant implications for legislators, specialists, and interested parties by rigorously assessing the accuracy and effectiveness of the iSBEM-Cy system. The findings from this study can be instrumental in guiding policy-making decisions, ensuring they are based on reliable data and accurate assessments of building energy performance. Moreover, the findings can help refine and improve existing energy efficiency regulations, making them more effective in promoting sustainable practices. It contributes to the advancement of more reliable and eco-friendly building energy certification methods, thereby supporting broader initiatives to improve energy efficiency and environmental sustainability within the building sector.

The research is meticulously organized into six distinct sections to provide a comprehensive analysis. It begins with an introduction that sets the stage for the study, followed by a detailed literature review on EPC, highlighting existing knowledge and gaps. The methodology section outlines the data collection process and the criteria for selecting a representative sample of buildings. The results section presents the findings, focusing on discrepancies between measured and simulated energy consumption. The discussion section delves into the implications of these findings, emphasizing the importance of considering various factors affecting energy performance. Finally, the conclusions underscore the necessity for ongoing improvements in energy performance models to enhance their accuracy and reliability.

2. Literature review

The European Union is actively pursuing building decarbonization through policies like the EPBD and Energy Efficiency Directive (EED) (Beltrán-Velamazán et al., 2023). These directives require Member States to develop long-term renovation strategies and implement nearly

zero-energy buildings (NZEBs) (D'Agostino et al., 2017). The revised EPBD introduces zero-emission buildings (ZEBs) as the future standard from 2030, emphasizing energy efficiency and renewable energy (Maduta et al., 2022). While progress is evident, challenges persist in increasing renovation rates and achieving zero-emission buildings (Maduta et al., 2023). The EU is strengthening requirements for building decarbonization through the recast EPBD, which includes mandatory assessment frameworks and more unified national targets (Beltrán-Velamazán et al., 2023). These efforts aim to reduce greenhouse gas emissions, enhance energy resilience, and improve quality of life while moving towards a climate-neutral continent by 2050 (Maduta et al., 2023, 2022), and they are not only reshaping renovation practices across Europe, but are also creating the necessary conditions for the integration of advanced digital tools into building energy assessment and management workflows.

In this evolving regulatory and technological context, digital twins (DTs) are emerging as powerful tools for enhancing building energy performance assessment and management. These virtual replicas enable real-time monitoring, predictive maintenance, and data-driven decision-making (Arsecularatne et al., 2024). DTs can accurately predict energy performance at early design stages, with validation showing less than 3.5 % difference between predicted and actual values (Rutkowski et al., 2024). They also facilitate operational energy performance classification using smart sensors and real-time measurements (Spudys et al., 2023). DTs offer numerous benefits across the energy sector, including improved asset performance, increased efficiency, and reduced environmental impact (Ghenai et al., 2022). However, challenges such as interoperability issues, data quality concerns, and the need for standardized frameworks must be addressed (Arsecularatne et al., 2024). As DT technology continues to evolve, integrating machine learning and artificial intelligence will further enhance energy system efficiency and support the transition to clean energy (Ghenai et al., 2022). As such, DTs may serve as a key enabler in bridging the gap between regulatory ambitions and real-world energy performance, especially when integrated with existing certification frameworks.

Within this landscape of evolving performance standards and emerging digital infrastructures, Energy Performance Certificates (EPCs) continue to play a pivotal role in evaluating and comparing building energy efficiency across the EU. EPCs evaluate building energy efficiency, classifying properties from A (most efficient) to G (least efficient) (Kaya et al., 2021). There are three main types of building energy performance indices: Asset Ratings, based on modelled energy use under uniform conditions; Operational Ratings, derived from measured energy consumption; and the Operation and Maintenance (O&M) Index, which compares actual energy use to simulated performance (Goldstein and Eley, 2014). Some frameworks, like the EU H2020 OrbEEt project, aim to extend standard EPC practices by incorporating dynamic business and behavioural information (Tsatsakis et al., 2017). While EPCs provide useful comparisons between buildings, they may not always reflect real energy consumption or environmental impact. Integrating EPCs with green building rating systems can lead to more informed retrofit decisions, balancing energy performance and environmental considerations (Pagliaro et al., 2015).

EPCs provide valuable insights into building energy performance and suggest cost-effective improvements. Studies using EPC data have focused on enhancing building energy efficiency and urban planning. Research in València, Spain, revealed poor energy performance in peripheral districts, highlighting the need for targeted retrofitting measures (Manso-Burgos et al., 2023). Analysis of EPCs from nine European countries showed varied information framing, emphasizing the importance of effective communication to influence renovation decisions (Taranu and Verbeeck, 2018). In Portugal, a large-scale EPC analysis identified windows and roofs as the most energy-inefficient elements, with roof retrofitting offering the highest potential for energy savings (Gouveia and Palma, 2019). However, EPCs may not always reflect real energy consumption or environmental impact. Integrating EPCs with

green building rating systems could lead to more balanced retrofit decisions, considering both energy performance and environmental impact (Pagliaro et al., 2015).

EPCs under the EPBD show significant variation across EU member states in assessment methods and implementation (Maduta et al., 2023; Semple and Jenkins, 2020). This lack of uniformity complicates cross-country comparisons and may lead to inconsistent conclusions about building energy performance (Semple and Jenkins, 2020; Ferrantelli and Kurnitski, 2022). Different EPC classification methods can result in widely varying renovation rates, costs, and energy savings estimates (Ferrantelli and Kurnitski, 2022). Despite progress towards energy-efficient buildings, challenges persist in increasing renovation rates and achieving zero-emission buildings (Maduta et al., 2023). To address these issues, end-users express interest in innovative EPC features that could enhance reliability, compliance, and market acceptance (Zuhaib et al., 2022). Harmonizing EPC methodologies and aligning with user needs could improve the effectiveness of EPCs in driving deep renovations and reducing environmental impact across the EU (Maduta et al., 2023; Zuhaib et al., 2022).

EPCs play a crucial role in improving building energy efficiency, but face challenges in implementation and effectiveness. The Recommendation List of Measures (RLM) within EPCs lacks consistency and sufficient information, discouraging renovations (Gonzalez-Caceres et al., 2020). Despite their importance, EPCs have varying impacts on renovation decisions across EU countries and age groups (Charalambides et al., 2019). To address barriers to energy renovations, innovative financing instruments are emerging, including on-bill financing, energy efficiency mortgages, and one-stop shops (Bertoldi et al., 2021). The EU has progressively developed energy efficiency policies for buildings over the past 50 years, evolving from early responses to the 1973 Oil Embargo to more comprehensive approaches like the Energy Performance of Buildings Directive (Economidou et al., 2020). While progress has been made, challenges remain in fully exploiting the potential for energy savings in buildings across the EU.

Implementing EPC in Mediterranean buildings faces unique challenges due to diverse climatic conditions (Ribeiro Hoffmann et al., 2024) and architectural styles (Vassiliades et al., 2024a). Studies reveal significant discrepancies between calculated and actual energy consumption, particularly in cooling demands (Vardopoulos et al., 2024). The Mediterranean climate's high temperatures (Barone et al., 2024), lead to increased air conditioning usage (Arnautakis and Katsaprakakis, 2021), especially in cities with arid climates (Vardopoulos, 2018). Many buildings in this region remain uninsulated and poorly ranked in energy performance (Katsaprakakis et al., 2020). However, there is substantial potential for energy savings, with proposed upgrades potentially reducing consumption by up to 65 % (Katsaprakakis et al., 2020). Implementing nearly zero energy building (nZEB) concepts (Georgiou et al., 2024), including self-consumption schemes (Kotarela et al., 2020), and renewable energy integration (Koukou et al., 2022), offers promising solutions for Mediterranean buildings, although the incorporation of energy storage systems requires supportive policies to improve economic viability (Pyrgou and Santamouris, 2022; Tsangas et al., 2023).

Research indicates that EPCs face challenges in accurately reflecting actual energy consumption and effectively promoting renovations (Mugarra et al., 2025; Li et al., 2019; Jenkins et al., 2021). The standardized approach of EPCs often overestimates energy use due to the exclusion of occupant behaviour (Monfils et al., 2016). This discrepancy between theoretical and real consumption limits EPC impact on purchase and renovation decisions (Taranu and Verbeeck, 2018). Quality control issues are prevalent, with studies showing high rates of inconsistencies in EPCs (Iribar et al., 2021). To improve EPC effectiveness, researchers suggest integrating behavioural parameters into calculations (Monfils et al., 2016), enhancing information framing using behavioural insights (Taranu and Verbeeck, 2018), and implementing more comprehensive assessment methods. These could include simplified measurements, laser scanning, and envelope testing, along with

calibration using actual consumption data and tailored renovation recommendations (Gonzalez-Caceres et al., 2022). Such improvements aim to increase EPC accuracy, user trust, and ultimately, their impact on renovation decisions.

Research on zero-energy consumption residences demonstrates significant potential for reducing energy use in buildings across Europe. Studies show that combining heavy building renovations, electric vehicles, and photovoltaic panels can reduce energy consumption by over 90 % at the neighbourhood scale (Nematchoua et al., 2021; Vassiliades et al., 2024b). The EPBD aims to achieve nZEBs in the EU, with a focus on both new constructions and retrofitting existing buildings (D'Agostino et al., 2017). However, implementation varies among Southern European countries, with many not adequately prepared for effective nZEB implementation (Olasolo-Alonso et al., 2023). In the Netherlands, recent sustainable building projects often fall short of NZEB goals, highlighting the need for greater focus on cost-effective solutions and life cycle costs in the early design phase (Zeiler et al., 2016). These findings underscore the importance of European directives in driving energy efficiency improvements in the building sector.

Despite the extensive body of literature on EPCs, there remains a significant research gap in studies examining the accuracy of these certificates against real-world data, particularly considering regional variations and different building types. This study aims to address this gap by comparing measured and calculated energy ratings using the iSBEM-Cy software, which is used for building energy certification in Cyprus. Through assessing iSBEM-Cy's efficacy, this research aims to offer important perspectives on its precision and consistency. Finally, the results will help the Cyprus government make better policy decisions, increase the accuracy of energy performance assessments, and improve the building energy certification process.

3. Methodology

This study builds upon prior research (Vardopoulos et al., 2024), which investigated the level of inconsistencies of the simulated energy consumption by iSBEM-Cy, compared to the actual energy conditions of a typical residential unit, thus identifying the existence of the problem. While a single case study provides a preliminary indication, it does not allow for in-depth analysis and definitive conclusions. To address this limitation, the current investigation examines a larger sample of 15 typical residential units, enabling a more comprehensive exploration of the problem. Note that the energy balance in iSBEM-Cy is based on average weather conditions, which is a common approach in building energy cost–benefit analyses using typical meteorological data (Bellia et al., 1998).

The objective of this study is to assess the energy performance of standard residential units in Cyprus by utilizing a detailed methodology that incorporates both simulation (iSBEM-Cy) and actual data. Thus, 15 typical partially insulated residences in Limassol were selected, ranging from small apartments of 70 square meters to houses of 220 square meters, a sample that represents the common building types in Cyprus. Before analysing the energy performance, details regarding passive envelope components, construction materials, and electromechanical systems are gathered. Monthly electricity and oil consumption data are then examined. The results of simulations conducted with iSBEM-Cy are categorised into primary energy consumption for heating, cooling, lighting, and domestic hot water based on standardised operation schedules and climatic conditions. By comparing the real-world data with the simulated results, deviations are identified, which are crucial for evaluating the effectiveness of the iSBEM-Cy system.

To ensure clarity and scientific rigor, the methodological framework of this study is presented in Fig. 1. It outlines each stage of the process, from data collection and energy bill analysis to simulation and comparative evaluation. This structured approach provides transparency and replicability, reinforcing the study's contribution beyond a typical case analysis.

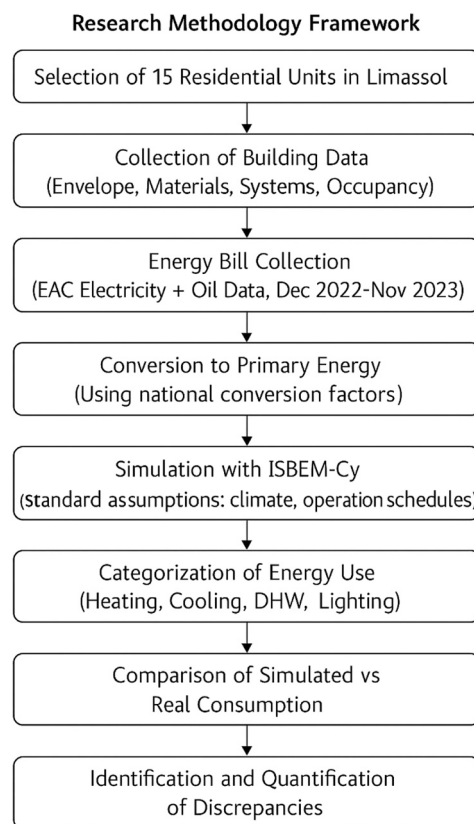


Fig. 1. the methodological framework of this study is presented here, outlining each stage of the process, from data collection and energy bill analysis to simulation and comparative evaluation.

3.1. Cyprus building stock and case studies under investigation

In Cyprus, the majority of buildings are two stories, and the average home size for the last 10 years has been 190 square meters, according to the Cyprus Statistical Service [www.cystat.gov.cy] (Dimitriou et al., 2020). The majority of the building stock in Cyprus was built before 2008 and does not have thermal insulation. Cyprus has been gradually introducing thermal insulation laws since 2008, which require all new construction to comply with nZEB standards starting in 2020 (Pettrakkas et al., 2021). According to Pettrakkas et al. (2021) (Pettrakkas et al., 2021) and Vassiliades (2023) (Vassiliades, 2023), the average thermal conductivity coefficient value for the external walls is 1,4 W/(m²k), for roofs 3,3 W/(m²k), for load-bearing structures 2,8 W/(m²k), for floors 2, 0 W/(m²k), and windows 6,0 W/(m²k). The new standards demand that all the new buildings as well as the renovated ones, will have a maximum thermal conductivity coefficient of 0,4 W/(m²k), except for the windows, which can be up to 2,25 W/(m²k).

As only a small portion of Cypriot buildings satisfy nZEB requirements, and 34 % of the country's building stock lacks thermal insulation (Pettrakkas et al., 2021), the building chosen for this study is meant to represent the transitional stage between pre-2008 non-insulated buildings and nZEB standards. This choice aims to reflect the broader trends in the Cypriot residential sector. Thus, 15 partially insulated, 70–220 square-meter, houses in Limassol, Cyprus, were selected to typify the country's residential building stock. Specifically, 60 % of them had roofs with no insulation, 73 % had walls with no insulation and 80 % of them had double glazing in their windows. This data is presented in detail in Table 1. Comprehensive data regarding the structure of the buildings and the kind and performance of its electromechanical equipment were gathered. The total energy consumption of each residence was determined by converting the monthly electricity

Table 1
The thermal characteristics of the materials of the buildings under study.

| Case | Area (m ²) | | Roof / Ceiling | Exterior walls | Load Bearing Structure (W/m ² K) | Interior walls | Exterior Floors | Interior Floors | Windows ^a |
|---------|------------------------|------------------------------|----------------|----------------|---|----------------|-----------------|-----------------|----------------------|
| Case 1 | 162.75 | U-Value [W/m ² K] | 1.90 | 1.39 | 3.33 | 2.13 | 1.01 | 1.00 | 3.80 |
| | | Cm [kJ/(m ² K)] | 225.00 | 120.00 | 225.00 | 95.00 | 93.00 | 92.25 | |
| Case 2 | 207.00 | U-Value [W/m ² K] | 0.38 | 1.39 | 3.33 | 1.79 | 0.37 | 1.85 | 3.80 |
| | | Cm [kJ/(m ² K)] | 224.00 | 120.00 | 225.00 | 95.00 | 210.00 | 210.00 | |
| Case 3 | 115.79 | U-Value [W/m ² K] | 2.52 | 1.39 | 3.33 | 1.79 | 1.29 | - | 3.80 |
| | | Cm [kJ/(m ² K)] | 230.00 | 120.00 | 225.00 | 95.00 | 210.00 | - | |
| Case 4 | 113.00 | U-Value [W/m ² K] | 2.52 | 1.39 | 3.33 | 2.13 | 1.12 | 1.85 | 3.80 |
| | | Cm [kJ/(m ² K)] | 230.00 | 120.00 | 225.00 | 97.00 | 95.00 | 210.00 | |
| Case 5 | 133.00 | U-Value [W/m ² K] | 2.77 | 1.95 | 3.23 | 1.66 | 0.84 | 2.00 | 3.80 |
| | | Cm [kJ/(m ² K)] | 230.00 | 192.00 | 223.00 | 192.00 | 181.30 | 232.00 | |
| Case 6 | 177.33 | U-Value [W/m ² K] | 0.41 | 0.44 | 0.53 | 1.38 | - | 0.41 | 2.80 |
| | | Cm [kJ/(m ² K)] | 92.96 | 120.00 | 225.00 | 140.00 | - | 92.96 | |
| Case 7 | 76.00 | U-Value [W/m ² K] | 0.47 | 0.37 | 1.70 | 1.24 | 0.52 | - | 3.70 |
| | | Cm [kJ/(m ² K)] | 228.00 | 116.00 | 162.00 | 116.00 | 333.30 | - | |
| Case 8 | 67.94 | U-Value [W/m ² K] | 2.73 | 0.42 | 3.04 | 1.24 | - | 1.97 | 3.80 |
| | | Cm [kJ/(m ² K)] | 225.00 | 45.00 | 217.50 | 120.00 | - | 199.30 | |
| Case 9 | 223.00 | U-Value [W/m ² K] | 2.52 | 1.95 | 3.23 | 1.79 | 1.29 | - | 3.80 |
| | | Cm [kJ/(m ² K)] | 230.00 | 192.00 | 223.00 | 95.00 | 210.00 | - | |
| Case 10 | 98.32 | U-Value [W/m ² K] | 2.73 | 1.39 | 3.04 | 1.79 | 1.76 | - | 3.80 |
| | | Cm [kJ/(m ² K)] | 225.70 | 120.00 | 225.00 | 119.00 | 198.30 | - | |
| Case 11 | 143.20 | U-Value [W/m ² K] | 0.58 | 1.39 | 3.33 | 1.79 | 0.49 | 2.14 | 3.80 |
| | | Cm [kJ/(m ² K)] | 11.25 | 120.00 | 225.00 | 120.00 | 71.73 | 71.73 | |
| Case 12 | 128.40 | U-Value [W/m ² K] | 0.34 | 1.39 | 3.04 | 1.79 | 1.49 | - | 4.30 |
| | | Cm [kJ/(m ² K)] | 217.50 | 120.00 | 225.00 | 120.00 | 222.00 | - | |
| Case 13 | 168.63 | U-Value [W/m ² K] | 2.73 | 1.39 | 3.33 | 1.79 | 1.12 | 1.85 | 3.80 |
| | | Cm [kJ/(m ² K)] | 225.70 | 120.00 | 225.00 | 120.00 | 95.00 | 210.00 | |
| Case 14 | 114.55 | U-Value [W/m ² K] | 1.21 | 1.39 | 3.33 | 1.79 | - | 1.04 | 6.10 |
| | | Cm [kJ/(m ² K)] | 240.00 | 120.00 | 225.00 | 95.00 | - | 64.32 | |
| Case 15 | 220.56 | U-Value [W/m ² K] | 0.65 | 0.42 | 0.42 | 1.79 | 0.69 | - | 2.60 |
| | | Cm [kJ/(m ² K)] | 7.20 | 105.00 | 105.00 | 85.00 | 197.90 | - | |

^a The windows throughout the building are double-glazed, with a Solar Heat Gain Coefficient (SHGC) of 0.76 and a Visual Transmittance (VT) of 0.80, except of Case 14, which is single glazed, with a SHGC of 0.89 and a VT of 0.91.

bills from the Electricity Authority Cyprus (EAC) and oil consumption into primary energy. The electromechanical systems' anticipated operating times and energy efficiency were utilised to divide the overall energy consumption into four categories: heating, cooling, lighting, and domestic hot water. The iSBEM-Cy program was then used to simulate the energy performance based on standard operating schedules and meteorological conditions. The results, segmented into primary energy consumption categories, were compared with real-world consumption data to identify discrepancies between actual and simulated energy use for each residence.

3.2. Data collection

The initial data collection phase centres on the buildings' passive elements, beginning with the envelope. The chosen buildings' envelopes include simple brick walls, non-insulated columns, and non-insulated concrete roofs in their majority. Most of the windows are double-glazed standard units without any additional thermal insulation. A calculation of the building components' U-Values and thermal mass (Cm) was done using the standard Cyprus Building Energy Performance Calculation Methodology (Cyprus Energy Agency, 2015). The features of

the current envelope elements are listed in Table 1.

Bills from the EAC were used to record the overall annual energy use, allowing a comparison between simulated and real energy consumption. The period of choice is from December 2022 to November 2023, with bimonthly consumption records. To align with the iSBEM-Cy results, the recorded data—as supplied by EAC—is transformed into primary energy and reported as primary energy per square metre. With a few outliers, which employ a diesel boiler with an efficiency ratio of 0.90 for heating, most of the homes are cooled and heated by split unit systems.

4. Results

The results presented in this chapter concern the comparison of the data from both on-site measurements and program simulations. Each consumption subcategory is analysed separately (heating, cooling, lighting, domestic hot water) and in total, initially highlighting the difference between measured and simulated consumption. Subsequently, this difference is analysed as a percentage, indicating how close the actual situation is to the program's results. Specifically, if the two results match completely, the percentage will be 100%. The lower the match, the smaller the percentage. Additionally, the average match for

all case studies in each energy consumption category is presented, allowing us to see how well the software performs in each category.

4.1. Heating

This chapter presents the results of the heating loads. In Fig. 2, the actual and simulated consumptions are displayed. Overall, it is observed that the software performs relatively well, as the absolute values of the loads are quite close, with only minor exceptions (i.e. Case 3). This general alignment suggests a reasonable accuracy in the simulation tool for heating demands, which will be further examined in the discussion section.

Subsequently, Fig. 3 presents the percentage match between the simulated and actual conditions. In this case, the variations per case study are indicated and range from 3 % to 97 %, resulting in an average match of approximately 42 %, which is marked by the horizontal line. It is noteworthy that the average match for heating loads is the highest compared to the other loads, indicating that the software has a relatively satisfactory ability to predict user behaviour.

4.2. Cooling

This chapter presents the results of the cooling loads. In Fig. 4, the actual and simulated consumptions are displayed. Overall, it is observed that the software does not perform well, as the absolute values of the loads are not close, with some minor exceptions (i.e. Case 4 and Case 8). This discrepancy suggests a systematic under- or overestimation trend in the simulation tool's cooling predictions, which warrants further analysis.

Subsequently, Fig. 5 presents the percentage match between the simulated and actual conditions. In this case, the variations per case study are indicated and range from 1 % to 44 %, resulting in an average match of approximately 14.5 %, which is marked by the horizontal line. It is noteworthy that the average match for cooling loads is the lowest compared to the other loads, indicating that the software cannot sufficiently predict user behaviour in terms of cooling loads. This deviation will be discussed in more detail in the following section, where possible causes and implications are explored.

4.3. Lighting

This chapter presents the results for the lighting loads. In Fig. 6, the actual and simulated consumptions are displayed. Overall, it is observed that the software does not perform well, as the absolute values of the

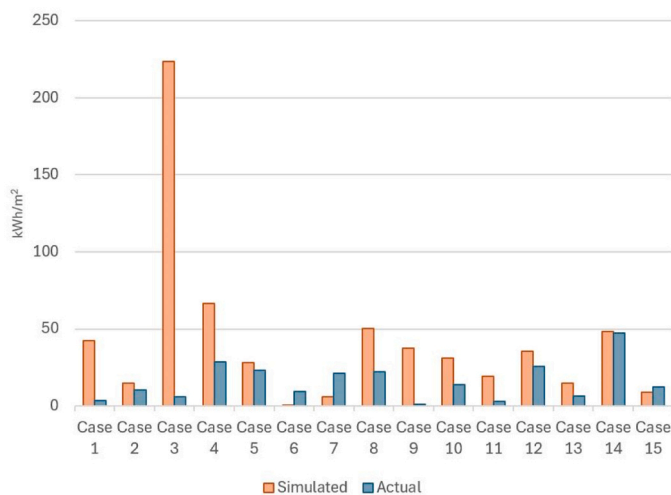


Fig. 2. Comparative presentation of heating consumption. The simulated loads are shown in orange, while the actual measurements are depicted in light blue.

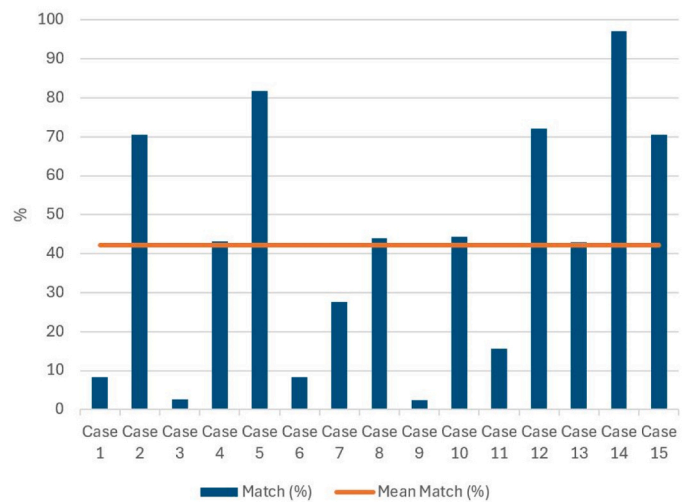


Fig. 3. The matching percentage between the simulated and actual conditions for the heating loads. The variations per case study are indicated in blue columns and the average matching is marked by an orange horizontal line.

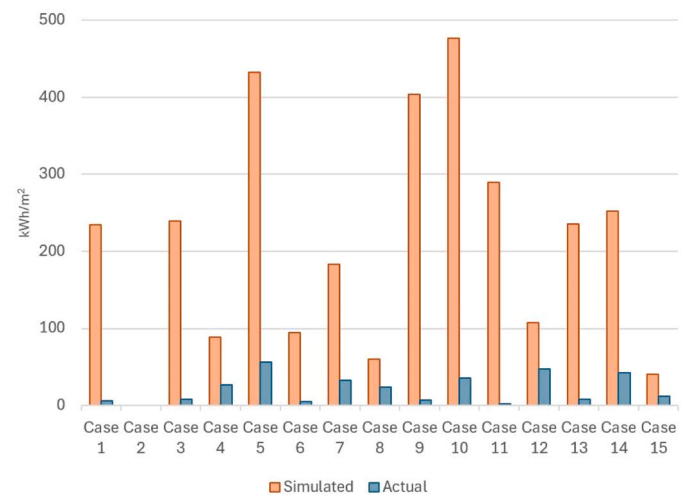


Fig. 4. Comparative presentation of heating consumption. The simulated loads are shown in orange, while the actual measurements are depicted in light blue.

loads are not close, with a minor exception (i.e. Case 12), thus indicating a potential systematic mismatch between assumed lighting schedules in the simulation tool and real occupant usage patterns.

Subsequently, Fig. 7 presents the percentage match between the simulated and actual conditions. In this case, the variations per case study are indicated and range from 3 % to 56 %, resulting in an average match of approximately 15 %, which is marked by a horizontal line. It is noteworthy that the average match for lighting loads is the second lower compared to the other loads, indicating that the software cannot sufficiently predict user behaviour in terms of lighting loads, raising concerns in relation to the fixed assumptions on lighting operation embedded in the simulation tool.

4.4. Domestic hot water

This chapter presents the results of the domestic hot water loads. In Fig. 8, the actual and simulated consumptions are displayed. Overall, it is observed that the software has fluctuations in performance regarding these loads, since there are examples for which it performs well, as the absolute values of the loads are quite close (i.e. Case 2, Case 8, Case 12, Case 14 and Case 15) and examples for which it does not perform well,

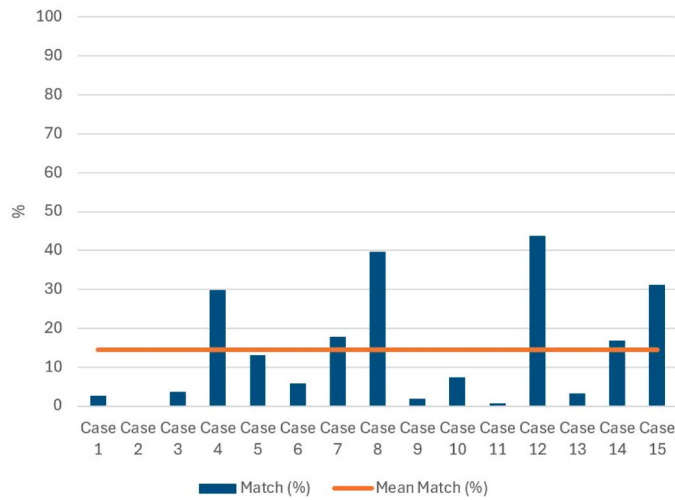


Fig. 5. The matching percentage between the simulated and actual conditions for the cooling loads. The variations per case study are indicated in blue columns and the average matching is marked by an orange horizontal line.

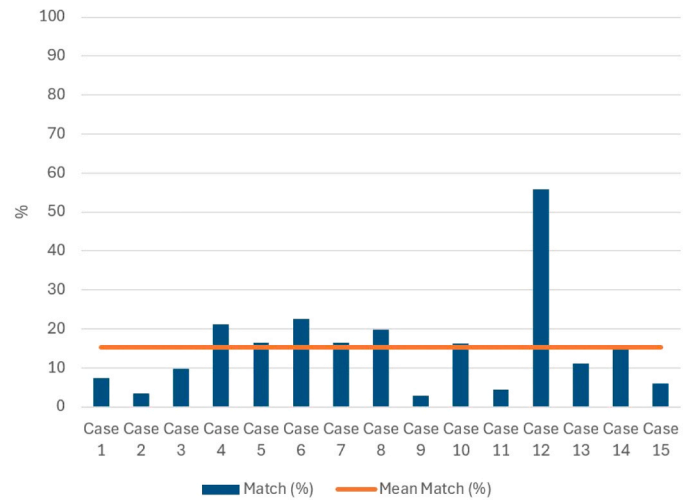


Fig. 7. The matching percentage between the simulated and actual conditions for the lighting loads. The variations per case study are indicated in blue columns and the average matching is marked by an orange horizontal line.

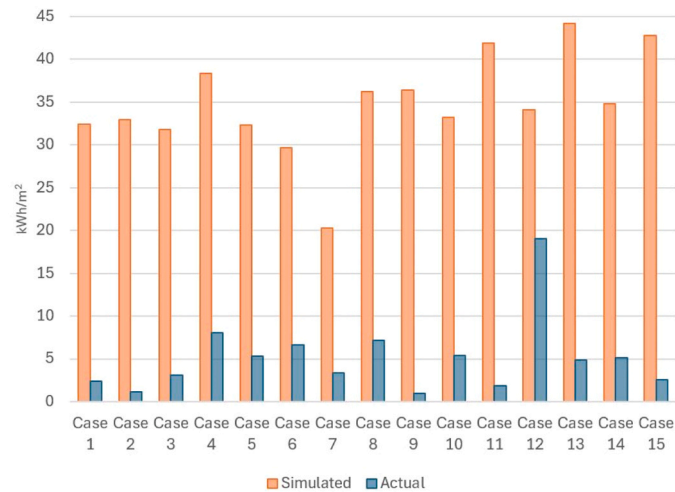


Fig. 6. Comparative presentation of lighting consumption. The simulated loads are shown in orange, while the actual measurements are depicted in light blue.

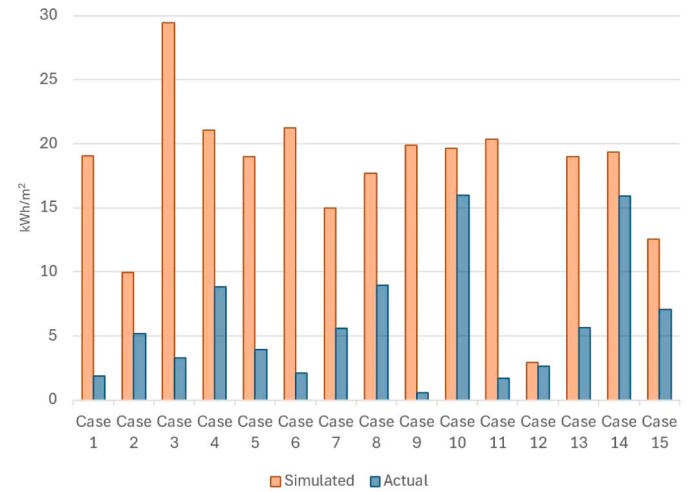


Fig. 8. Comparative presentation of domestic hot water consumption. The simulated loads are shown in orange, while the actual measurements are depicted in light blue.

as the absolute values of the loads are not close (i.e. Case 1, Case 3, Case 5, Case 6, Case 9, Case 11 and Case 13), suggesting that the model may be more sensitive to user behaviour assumptions in this load category.

Subsequently, Fig. 9 presents the percentage match between the simulated and actual conditions. In this case, the variations per case study are indicated and range from 3 % to 90 %, resulting in an average match of approximately 39 %, which is marked by a horizontal line. It is noteworthy that the average match for domestic hot water loads is the second highest compared to the other loads, indicating that the software has a relatively satisfactory ability to predict user behaviour, underscoring the influence of unpredictable usage patterns.

4.5. Total

This section presents the total results. In Fig. 10, the actual and simulated consumptions are displayed. Overall, it is observed that the software has fluctuations in performance regarding these loads, since there are examples for which it performs well, as the absolute values of the loads are quite close (i.e., Case 8 and Case 12) and examples for which it does not perform well, as the absolute values of the loads are not close (i.e., Case 1, Case 3, Case 9 and Case 11).

Subsequently, Fig. 11 presents the percentage match between the simulated and actual conditions. In this case, the variations per case study are indicated and range from 2 % to 53 %, resulting in an average match of approximately 21 %, which is marked by a horizontal line. It is noteworthy that the average match for the total loads is relatively low, indicating that the software cannot sufficiently predict the user behaviour patterns for the majority of the loads. This raises concerns about the reliability of aggregated simulation outputs, especially when such data is used to inform renovation strategies and energy policy.

5. Discussion

To assess the dependability of iSBEM-Cy in real-world applications and pinpoint inconsistencies that can compromise its efficacy, this study compared measured and simulated energy data for 15 dwellings. Notable variations between the simulated and real energy consumption were found in the study for several categories, including lighting, heating, cooling, and domestic hot water. Notably, cooling loads showed the highest deviation, while heating loads exhibited the least variance. Domestic hot water and lighting loads displayed moderate

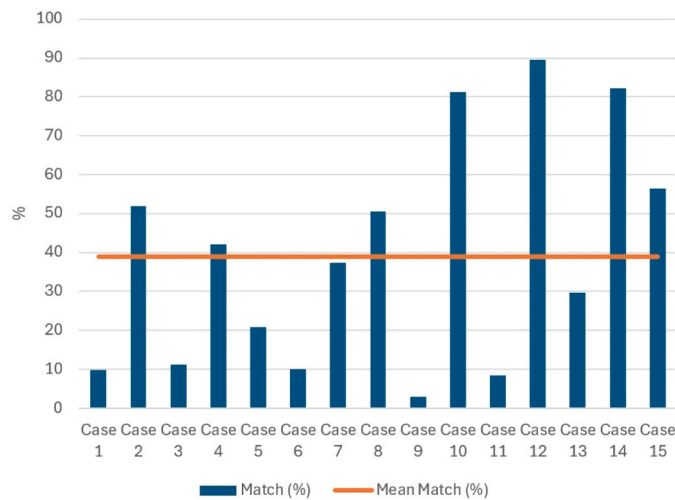


Fig. 9. The matching percentage between the simulated and actual conditions for the lighting loads. The variations per case study are indicated in blue columns and the average matching is marked by an orange horizontal line.

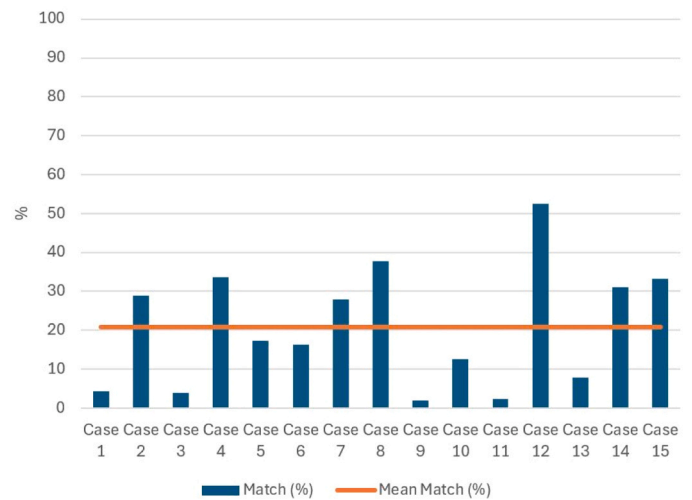


Fig. 11. The matching percentage between the simulated and actual conditions for the total loads. The variations per case study are indicated in blue columns and the average matching is marked by an orange horizontal line.

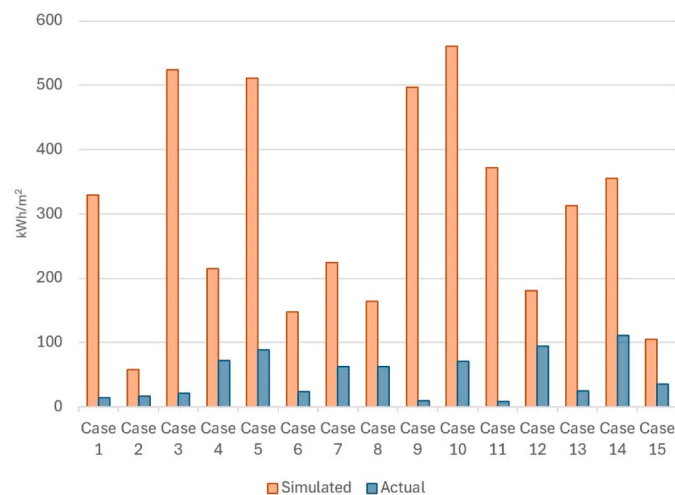


Fig. 10. Comparative presentation of domestic hot water consumption. The simulated loads are shown in orange, while the actual measurements are depicted in light blue.

discrepancies.

The results confirm, as expected, that while the iSBEM-Cy system is a valuable tool for energy performance certification, it does not accurately predict real-world energy usage. It is important to assess this deviation, given that this software is widely used and should have basic credibility regarding absolute energy consumption values. The significant variance in cooling loads suggests that the software may not fully account for occupant behaviour and local climatic conditions. The minimal discrepancies in heating loads imply that this category is more straightforward to model accurately. The moderate discrepancies in DHW and lighting loads highlight the need for more precise modelling of these energy uses. These findings align with previous research indicating challenges in accurately modelling building energy performance. Studies by Monfils et al (Monfils et al., 2016). and Taranu and Verbeeck (Taranu and Verbeeck, 2018) also reported notable differences between simulated and actual energy consumption, particularly due to standard operating conditions used in simulations that do not reflect real-world usage.

The discrepancies identified have important implications for policymakers and practitioners. Accurate energy performance assessments

are crucial for effective policy decisions and the development of energy efficiency regulations. The findings suggest that while iSBEM-Cy provides a useful framework, enhancements are needed to improve its accuracy and reliability. This could involve integrating more detailed user behaviour data and local climatic conditions into the model. Additionally, the study highlights the potential for refining EPC processes to better support energy efficiency improvements and sustainable building practices.

The analysis of iSBEM-Cy highlights areas for improvement, particularly in aligning simulations with real-world usage patterns. The reliance on outdated meteorological data in the software undermines its predictive accuracy, especially as climate conditions evolve. Incorporating updated meteorological datasets could enhance model precision, reflecting current and future climatic scenarios. Additionally, the absence of user behavior models limits the ability to account for diverse usage patterns, such as those in holiday homes versus urban residences. Integrating dynamic user behavior models into iSBEM-Cy would allow for more nuanced predictions tailored to specific occupancy profiles and energy consumption habits. Alternatively, it is suggested to give three consumptions together with the certificate, one as it is now (average user behavior), one for a bad user (20 % worse/increased consumption profile) and one for an energy sensitive user (20 % better/smaller consumption profile).

Furthermore, the comparative methodology of iSBEM-Cy, which evaluates a real building against a standard reference, imposes constraints on the range of configurations and scenarios that can be tested. Expanding the software’s flexibility to include more diverse reference building options could better accommodate the variability in the Cypriot housing stock, enabling more accurate and customized assessments. These enhancements would not only refine simulation accuracy but also bolster the credibility of energy performance certifications in informing policy and practice.

It is important to acknowledge that the selection of 15 representative residential units poses a limitation, as it might not comprehensively capture the diversity of the real estate asset in Cyprus. Furthermore, the emphasis of this paper on particular climatic and operational conditions may restrict the broader applicability of its findings to different regions or types of building. However, it establishes a preliminary methodological step for identifying potential issues in other countries’ EPCs. Future studies could overcome these limitations by increasing the sample size and including a more diverse selection of buildings and conditions. Furthermore, incorporating data from other locations as well, could provide deeper insights into the effectiveness of energy

certification systems.

In summary, this study underscores the need for ongoing improvements in building energy performance models like iSBEM-Cy. While the tool provides a valuable starting point, its accuracy in predicting real-world energy consumption requires enhancement. The findings add to the ongoing dialogue on sustainable construction practices, highlighting the critical role of accurate and reliable energy performance assessments in promoting energy efficiency and minimizing greenhouse gas emissions within the building sector.

5.1. Key performance indicators (KPIs)

To contextualize the implications of our findings, a set of Key Performance Indicators (KPIs) were developed based on the measured and simulated energy consumption data. These KPIs allow for a structured comparison between predicted and actual performance, and offer insights into the broader energy, environmental, and economic impacts of energy certification accuracy in Cyprus:

5.1.1. KPI 1 – Simulation accuracy (%)

$$\text{Accuracy} = \left| \frac{\text{Simulated}}{\text{Actual}} \right| \times 100 \quad (1)$$

The Eq. (1) quantifies the reliability of simulation-based energy performance certificates across heating, cooling, lighting, and domestic hot water (DHW) loads. The overall average simulation accuracy across all categories is 21 %, indicating substantial room for improvement.

5.1.2. KPI 2 – Primary energy deviation (kWh/m²/year)

This represents the absolute average deviation between simulated and actual total energy use. For the 15 buildings studied, the average deviation is 256.1 kWh/m²/year, which can lead to substantial misrepresentation of energy demand during renovation planning. This highlights that iSBEM-Cy cannot be used for absolute energy calculation purposes—something already stated by its provider. However, in practice, many installers or designers use it as such, creating misleading impressions of reality.

5.1.3. KPI 3 – Cost implication of simulation error (€/m²/year)

Using the 2024 average final residential electricity price in Cyprus of €0.33/kWh ([Electricity prices for household consumers.](#)), the deviation translates to an average cost misestimation of approximately 82 €/m²/year, potentially misleading homeowners or policymakers about real operating costs.

6. Conclusions

This paper aimed to assess the accuracy and effectiveness of iSBEM-Cy, the official software used for EPC in Cyprus. The primary focus was not to diminish the credibility of the software, but to highlight discrepancies that arise due to variations in user behaviour. Specifically, the main goal is to assess the reliability of iSBEM-Cy in practical applications and identify areas for improvement. The accuracy of simulations in such software is crucial because, although their primary use is comparative rather than for scientific simulations of energy consumption, their widespread use by many professionals from various fields necessitates a basic level of reliability in this aspect as well. Additionally, the implications of these findings are substantial for policymakers, practitioners, and stakeholders in the building sector. Accurate energy performance assessments are crucial for effective policy decisions and the development of energy efficiency regulations ([Convery, 2011](#)). The study's insights can lead to improvements in energy certification processes, making them more robust and reliable. This, in turn, can lead to more effective and sustainable building energy practices, contributing to broader efforts to enhance energy efficiency and reduce greenhouse gas

emissions in the building sector. It will also indicate the effectiveness of good energy spending habits from the users – a way of educating people to use energy rationally.

The findings revealed significant discrepancies between the simulated and actual energy consumption across various categories, including heating, cooling, lighting, and domestic hot water. Cooling loads exhibited the highest deviation, indicating potential areas where iSBEM-Cy may not fully account for occupant behaviour and local climatic conditions. Conversely, heating loads showed the least variance, suggesting more accurate modelling in this category. These discrepancies underscore the need for enhancements to better reflect real-world energy usage. The results enrich the previous work of the team, which provided some initial indications of the software's weaknesses, now confirmed with greater precision. This current work also complements the work of other researchers, who have noted, among other things, the need for better recording and representation of user habits in such software. Utilizing this methodology for a thorough recording of the energy conditions of a larger sample of residences could provide data to significantly improve the current database of the software, thus yielding even more accurate and realistic results. It should be noted here that achieving complete accuracy is not possible, as it does not align with the primary goal of the software, which is energy certification based on typical use.

This study identifies key areas for advancing iSBEM-Cy, focusing on enhancing its alignment with real-world conditions. Updating meteorological datasets and integrating dynamic user behaviour models are pivotal steps to improve the tool's predictive accuracy and relevance. Additionally, increasing the flexibility of its comparative approach by broadening reference building options could address variability in building typologies. These recommendations provide a roadmap for refining iSBEM-Cy to deliver more accurate and actionable insights, ultimately supporting energy efficiency improvements and sustainable building practices in Cyprus and similar contexts.

Despite the valuable insights offered by this research, several limitations must be acknowledged. First, the study is geographically restricted to Cyprus, which features a specific Mediterranean climate and a largely homogeneous building stock, potentially limiting the generalizability of the findings to other regions with different climatic or building characteristics. Second, the residential sample, although representative of typical local housing types, may not fully capture the variability in construction quality, occupancy patterns, and equipment efficiency across the national building stock. Third, the study relies on a one-year monitoring period, which may not adequately reflect longer-term fluctuations in energy consumption due to anomalous weather events or atypical user behaviour.

Thus, future research could aim to incorporate data from other locations as well, to provide deeper insights into the long-term performance of energy certification systems. Studies could explore the integration of more detailed user behaviour data, as well as three types of user schedules, and local climatic conditions into the iSBEM-Cy model. Additionally, research should investigate the effectiveness of EPCs in other Mediterranean countries and regions with similar climatic conditions to enhance the generalizability of the findings.

Overall, this study emphasizes the need for ongoing improvements in building energy performance models like iSBEM-Cy. While the tool provides a valuable starting point, its accuracy in predicting real-world energy consumption requires enhancement. The results add to the growing body of knowledge on sustainable building techniques by emphasising how crucial precise and trustworthy energy performance assessments are to meeting energy efficiency targets and cutting greenhouse gas emissions. This research supports the development of more effective energy certification systems and an effective way of educating users in using energy rationally, ultimately contributing to a more sustainable built environment.

CRediT authorship contribution statement

Mattheos Santamouris: Methodology, Supervision. **Giovanni Barone:** Validation, Data curation, Writing – original draft, Methodology. **Ioannis Vardopoulos:** Writing – original draft, Conceptualization, Writing – review & editing, Methodology. **Vassiliades Constantinos:** Writing – original draft, Methodology, Conceptualization, Writing – review & editing, Software, Data curation. **Soteris Kalogirou:** Supervision, Conceptualization, Methodology.

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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