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Development of the Perceived Low-Carbon Building Literacy Scale for Adult Building Users: A Validity and Reliability Study

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Abstract

Buildings' operational energy demand depends not only on technical systems but also on occupant knowledge, behaviour, and participation. This study developed and evaluated a self-report measure of perceived low-carbon building literacy among adult building users. An exploratory sequential mixed-methods design combined semi-structured interviews with 20 users of residential, office, educational, and public buildings and quantitative scale validation. Qualitative analysis yielded four themes and 16 categories, which, together with the literature, informed 35 candidate items. Following appraisal by eight experts and a pilot test with 45 users, a 32-item questionnaire was administered to independent samples for exploratory factor analysis (n = 350) and confirmatory factor analysis (n = 400). The final 20-item instrument comprised four factors accounting for 62.40% of the variance. Model fit was satisfactory (χ^2/df = 1.35; RMSEA = 0.030; CFI = 0.984; TLI = 0.981; SRMR = 0.038). Overall internal consistency was α = 0.908, and subscale α ranged from 0.837 to 0.858. The instrument offers a promising measure of perceived knowledge, reported energy-efficient practices, technology/data competence, and low-carbon engagement; its self-report nature should be considered when interpreting scores.

Keywords: low-carbon buildings; building users; energy literacy; carbon literacy; scale development; occupant behaviour; mixed methods

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1. Introduction

The construction sector plays a key role in policies to combat climate change. This is because a significant proportion of global energy consumption and greenhouse gas emissions stems from buildings. According to the IPCC, in order to reduce the environmental impact of buildings, it is first necessary to reduce energy demand and improve energy efficiency. The wider adoption of renewable energy is also one of the key measures supporting this process [1]. The International Energy Agency, for its part, regards energy consumption in buildings as a key indicator for monitoring the transition to a low-carbon building stock. In this context, it is also important to monitor the direct and indirect emissions resulting from energy use [2]. The technical specifications of a building alone are not sufficient to achieve low-carbon targets.

The quality of the building envelope and the efficiency of the mechanical systems are important. Renewable energy technologies also contribute to building performance. However, user behaviour is also a key factor in energy consumption [3]. The way users regulate indoor temperatures can affect energy consumption [4,5]. The way in which windows and shading systems are used also plays a significant role in this process [5]. Habits relating to lighting and electrical appliances can alter the level of consumption [6]. Furthermore, users need to be able to interpret energy data correctly. It is also important for them to be involved in decisions regarding building management [3,7]. These factors can lead to discrepancies between the performance anticipated at the design stage and the performance achieved during actual use [4–7].

The designed energy performance does not always correspond to the actual consumption figures recorded during use. This situation has led to increased discussion in building research regarding performance discrepancies and the influence of user behaviour. This is because design calculations and energy simulations are usually carried out on the basis of pre-determined usage assumptions. However, the daily preferences, habits and comfort expectations of the building's occupants may differ from these assumptions. This, in turn, causes energy consumption during the operational phase to deviate from the predicted level [4,5]. It is therefore incorrect to view users merely as passive consumers of energy. Users interact directly with building technologies, adjust indoor environmental conditions to suit their own needs, and gain experience regarding energy use. In some cases, they also participate in the building's shared management processes. The successful implementation of low-carbon targets also depends to a large extent on this interaction. It is important for users to understand how energy systems work. However, translating this knowledge into everyday behaviour is just as essential as possessing the knowledge itself.

Perceived Literacy in Low-Carbon Buildings

In the literature, energy literacy is generally defined as the ability to understand energy sources, how energy is produced, and consumption processes. However, the concept is not limited to simply possessing knowledge on these topics. The application of this knowledge to everyday choices, attitudes and practices is also regarded as an integral part of energy literacy [8,9]. In carbon literacy, the focus is on understanding the sources of emissions and the consequences they entail. The concept also encompasses an individual's ability to recognise and assess their own carbon footprint and to make choices that could reduce it [10].

Both types of literacy form an important foundation for low-carbon living. Conversely, general-purpose metrics may not adequately reflect certain circumstances arising during the use of buildings. The regulation of indoor environmental comfort is one such example. The use of building systems, the interpretation of energy data and participation in operational decision-making should also be assessed within this context. Consequently, there is a need to address building-specific information and behaviours in a more holistic manner.

In this study, low-carbon building literacy is not limited solely to the level of knowledge. Skills developed during the use of buildings, everyday behaviours and participation in decision-making processes have also been assessed as part of the concept. The first aspect of this is understanding energy consumption in buildings and the carbon emissions resulting from this consumption. Another aspect is the ability of users to adopt practices that consume less energy without completely sacrificing their comfort. In some cases, solutions that do not require energy consumption may also be preferred. It is also important to be able to interpret data relating to building performance and understand what this data signifies. The same applies to the information provided by smart building systems. As regards the participatory aspect of the concept, the involvement of users in carbon reduction decisions

taken at building level is a key consideration. It is expected that this participation will not be merely formal, but will be based on awareness and a sense of responsibility.

In this study, perceived low-carbon building literacy has been defined as a construct based on adult building users' assessments of their own knowledge and competence (as shown in Figure 1). This construct encompasses the perceived level of knowledge regarding building energy and carbon issues. Energy-efficient practices reported to be adopted in day-to-day building use are also included in the definition. In addition, the ability to understand low-carbon technologies and energy data has been addressed. Users' tendencies to participate in and take responsibility for building-level carbon reduction processes also constitute another dimension of the construct.

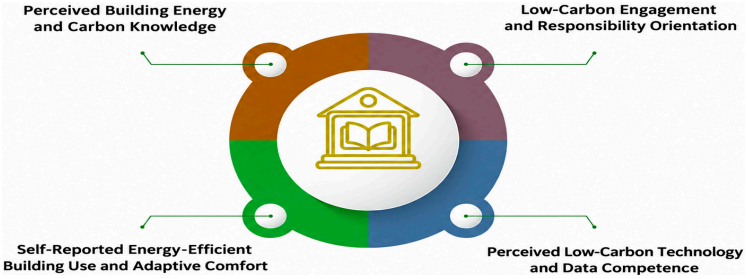


Figure 1. The dimensions of the self-report profile developed within the framework of the scale (The figure was created using Canva, version 4.235).

The first component of the framework relates to the extent to which users consider themselves informed about energy consumption and carbon emissions in buildings. The second component focuses on everyday use. Here, the behaviour that users report adopting with the aim of reducing energy consumption whilst maintaining their comfort is examined. The third component covers perceived competence in understanding and interpreting data relating to energy performance, smart systems and low-carbon building technologies. The final component relates to participation and accountability. The propensity to participate in building management decisions aimed at reducing energy consumption and carbon emissions, to support low-carbon practices and to report observed energy wastage is assessed under this component.

The dimensions of the scale fall within the same conceptual framework. However, these dimensions are not considered to be equivalent indicators that can be used interchangeably. Perceived knowledge and competence form a single component. The daily practices and participation tendencies reported by users, on the other hand, reflect different aspects of low-carbon building literacy. For this reason, when interpreting the scale scores, the sub-dimensions have been assessed separately.

The inclusion of reported practices and engagement in this construct reflects how low-carbon building literacy is defined and measured in the present study. It does not imply that knowledge and behaviour are the same. Previous research on energy literacy has examined cognitive, affective and behavioural dimensions together [8,9]. Following this perspective, perceived low-carbon building literacy is understood here as a combination of individuals' reported understanding of building-related issues, confidence in their knowledge, everyday practices and willingness to take part in collective efforts. F2 focuses on the energy-efficient practices that respondents report in their daily lives, rather than behaviours observed or verified by the researchers. F4 addresses attitudes towards participation and shared responsibility, along with a single item concerning a reported practice. Therefore, it should not be interpreted as evidence of actual participation in building management or decision-making. These dimensions were included because the use of building-related knowledge in

everyday life is influenced not only by what individuals know, but also by the opportunities, responsibilities and practical constraints they encounter [11,12].

The Theory of Planned Behaviour states that attitudes, intention and an individual's perceived control over their behaviour are influential in the emergence of a behaviour [11]. In the environmentally meaningful behaviour approach however, the focus is not solely on individual characteristics The opportunities offered and the constraints imposed by the context in which the behaviour occurs are also taken into account. These two approaches did not form the basis of the study's direct measurement model. Rather, they were used to explain why perceived knowledge and competence, reported usage behaviours and participation propensity were treated as separate components [12].

There are very few assessment tools that address the various aspects of low-carbon building literacy. The self-report profile developed in this study comprises four dimensions: Perceived Building Energy and Carbon Knowledge, Self-Reported Energy-Efficient Building Use and Adaptive Comfort, Perceived Low-Carbon Technology and Data Competence, and Low-Carbon Engagement and Responsibility Orientation. It is considered that there is a need for an assessment tool that addresses these dimensions collectively, whilst also being easy to administer and concise. Of course, the validity and reliability of such a tool must be demonstrated with sufficient evidence. The tool to be developed could be used for various purposes. For example, it could help identify the areas where users require support prior to building refurbishment works. It could also be utilised in examining the impact of energy feedback systems on users. The management of campuses and public buildings, the preparation of user training programmes, and research into building performance are other potential areas of application.

The scale developed in this study is intended to complement existing approaches rather than replace them. DeWaters and Powers [8] examine energy literacy through cognitive, affective and behavioural dimensions, whereas van den Broek [9] identifies different aspects of household energy literacy, including device-related, action-related, financial and multifaceted literacy. Studies on carbon capability address individuals' understanding of emissions and their engagement with climate change issues in a broader social context [10]. Other research has focused on how building occupants use heating, cooling, lighting and windows [4–7], as well as how people understand and respond to energy-monitoring information [13–15]. Although these studies provide a useful background, they do not all offer psychometric instruments that can be directly compared with the present scale. What distinguishes the proposed scale is its focus on building use and its assessment of several related aspects within a single instrument. These include perceived knowledge of energy and carbon issues, self-reported practices in adapting building use, confidence in interpreting energy performance certificates and monitoring data, and attitudes towards participation in building-level decisions. The four subscales allow these aspects to be examined separately across different building-use settings. Importantly, the scale reflects how individuals perceive and report their own knowledge and practices, rather than measuring actual knowledge or recorded energy consumption. Further research is therefore needed to compare its performance with existing instruments and determine whether it provides additional explanatory value.

The aim of this study was to develop a valid and reliable self-report scale for adult building users. The scale assesses users' perceived levels of knowledge regarding building energy and carbon issues, their reported daily practices relating to energy-efficient use, and their perceived competence in interpreting energy data and low-carbon technologies. Users' propensity to participate in low-carbon practices at the building level has also been included within the scope of the scale. To this end, answers were sought to the following questions:

(RQ1) How do building users describe their experiences of participating in building management, drawing on their knowledge of low-carbon buildings, daily energy consumption, building technologies and data?
(RQ2) Do the items developed on the basis of qualitative findings and the literature adequately represent the defined self-reported low-carbon building literacy profile?
(RQ3) Is the four-dimensional structure identified by EFA being validated using CFA in an independent sample?
(RQ4) Are the item discrimination, convergent and discriminant validity, and internal consistency reliability of the scale's sub-dimensions adequate?

2. Materials and Methods

In the study, an exploratory sequential mixed-methods design, structured according to the scale development process, was employed [16]. The process began with a qualitative phase, followed by a quantitative phase (Qualitative–Quantitative).

In the first stage, the experiences of building users with regard to low-carbon buildings were examined. In this context, users' levels of knowledge and daily practices were considered. Their use of technology and energy data, as well as their participation in management processes, were also investigated. The findings derived from the qualitative data were evaluated in conjunction with the relevant literature and theoretical explanations. As a result of this evaluation, the item pool for the scale was prepared [17].

The quantitative phase began with the collection of expert opinions and the conduct of a cognitive pilot study [18]. This was followed by exploratory factor analysis (EFA), using established scale-development recommendations [19] and parallel analysis to evaluate the number of factors [20]. The resulting structure was tested using confirmatory factor analysis (CFA) on a different study group [19]. At this stage, item analyses and reliability and validity assessments were also carried out [17,18]. Independent working groups were used in the EFA and CFA analyses. This reduced the risk of over-fitting that might arise from using the same data both to identify the structure and to validate it.

2.1. Exploratory Qualitative Phase

2.1.1. Qualitative Research Group

Twenty adult building users took part in the qualitative phase of the study. Participants were selected using maximum diversity sampling, one of the purposeful sampling approaches. Diversity in terms of age and gender was ensured within the study group. The type of building under consideration and the participants' usage status of the building were also taken into account during the selection process. To participate in the study, individuals were required to be at least 18 years of age. Furthermore, participants were required to have been using the building in question for at least six months and to spend at least 20 h per week there. To protect the participants' anonymity, codes ranging from K1 to K20 were used. The distributions of the study group's characteristics are presented in Figure 2.

2.1.2. Interview Form and Data Collection

The theoretical dimensions of low-carbon building literacy were taken as the basis when preparing the semi-structured interview form. Studies addressing the energy-related behaviours of building users were also reviewed. The draft form was submitted to four experts for evaluation. Two of the experts specialise in building energy and building physics, one in sustainability, and one in qualitative research. Pilot interviews were subsequently conducted with two building users. Based on these interviews, technical terminology was made more accessible. The final version of the form contains eight open-ended questions.

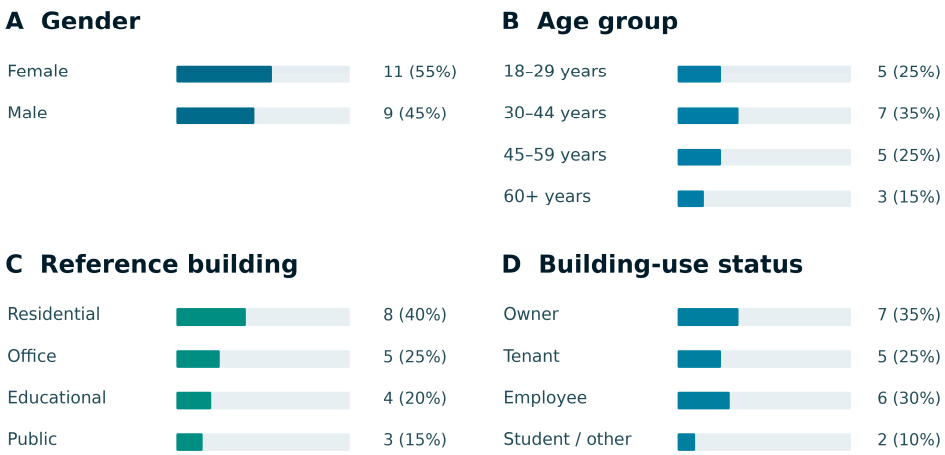


Figure 2. Qualitative study group scale (The figure was created using Canva).

The interview questions were designed to determine participants' perceptions of low-carbon buildings. Heating, cooling and lighting practices were also discussed during the interviews. Furthermore, methods of natural ventilation and the use of daylight were examined. Participants were asked about their experience of evaluating energy data and their knowledge of low-carbon technologies. Their behaviour in recognising energy wastage and reporting it to the relevant departments was also investigated. Finally, the focus was on their experiences of participating in decisions relating to building management. The interviews lasted between 25 and 38 min. Audio recordings were made with the participants' consent, and the recordings were transcribed verbatim. It was observed that repetition in the data became apparent after the 17th interview. Three further interviews were conducted to verify that data saturation had been achieved and to maintain participant diversity.

2.1.3. Integration of Qualitative and Theoretical Findings

The conversion of qualitative findings into questionnaire items was undertaken by comparing interview-derived categories with the literature-based item list. A review of building energy performance, occupant behaviour, energy and carbon literacy, adaptive comfort, smart meter feedback, energy performance certificates, and building management yielded 29 preliminary statements. Content analysis of the 20 interviews identified 52 codes, which were organized into 16 categories and four themes (Table 2). The categories were considered against the preliminary statements to identify content already represented, statements requiring clearer wording, and aspects of building use that were insufficiently covered. The frequencies reported in Table 2 indicate the number of interviewees mentioning each category; they were not used as numerical thresholds for generating or retaining items.

This comparison led to nine additional candidate statements informed by the interviews; three statements with overlapping content were then merged, resulting in a 35-item integrated pool ($29 + 9 - 3 = 35$). Interviewees' difficulties with energy performance certificates and smart meter displays informed items assessing perceived interpretation competence rather than factual test performance or technology ownership. Accounts of adaptive comfort practices shaped wording about low-energy adjustments, while limited control over building systems, reporting of energy waste, and expectations of management feedback informed items relating to participation, responsibility, and monitoring. Table 3 provides representative links between qualitative findings, item-development decisions, and corresponding items retained in the final scale. Appendix D documents the complete 35-item pool and subsequent retention or removal decisions. These links indicate content contributions from the qualitative phase, rather than exclusive qualitative origins for individual items.

The item pool was submitted for review to eight experts. The experts work in the fields of building energy systems, architecture and building physics. Experts from the fields of sustainability, environmental education and measurement and evaluation also participated in the assessment process. The experts were asked to classify each item as 'necessary', 'useful but not necessary' or 'not necessary'. Item-level content validity ratios (CVRs) were calculated using Lawshe's method [21]: $CVR = (n_e - N/2)/(N/2)$, where n_e is the number of experts rating an item as "essential" and N is the total number of experts (N = 8).The changes in the number of items throughout the scale development process are presented in Figure 3.

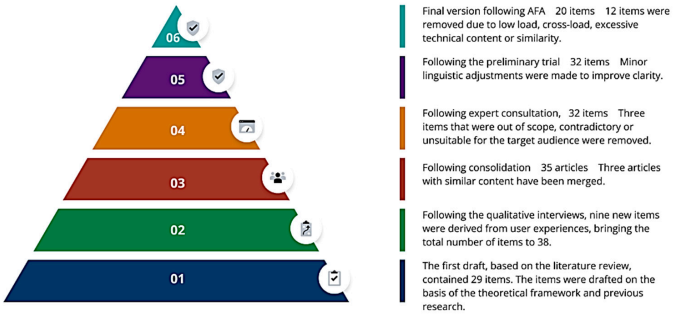


Figure 3. Changes in the number of items during the scale development process.(The figure was created using Canva (version 4.235).

The cut-off score for the eight-member expert panel was set at 0.75. The three items scoring below this value were removed from the form. In line with the experts' recommendations, some statements were reworded. Following these adjustments, a 32-item pilot questionnaire was produced. For the 20 items retained in the final scale, item-level content validity ratios (CVRs) ranged from 0.75 to 1.00. Following Lawshe's method [21], the scale-level content validity index (CVI) was calculated as the arithmetic mean of these 20 CVRs and was 0.900 (see Section 3.3).

A five-point Likert-type scale was used in the questionnaire. The response options were organised as follows: "1 = Strongly disagree", "2 = Disagree", "3 = Undecided", "4 = Agree" and "5 = Strongly agree". The decision to exclude reverse-keyed items was made at expert review, before the pilot. Specifically, two reverse-keyed candidates (M6 and M35; Appendix D, Table A3) were removed because they were judged conceptually narrow or ambiguous: M6 implied that electricity was the sole source of building-related emissions, while M35 assigned responsibility for reducing energy use solely to building management. In addition, research indicates that reverse-keyed or negated statements may introduce interpretation difficulties and wording-related method effects [22,23]. Accordingly, we retained direct, consistently keyed wording to facilitate interpretation across adult users with varying familiarity with energy terminology. No reverse-keyed items were included in the 32-item pilot or the final 20-item scale. This was a design choice rather than evidence from a direct comparison of item formats; potential acquiescence bias remains a limitation.

2.2. Preliminary Trial

A pilot study was conducted with 45 adult building users. None of these participants had taken part in the preceding semi-structured individual qualitative interviews. The study group comprised individuals of different ages and with different patterns of building use. Participants were asked to evaluate the items in terms of clarity and ease of response. Their views on the extent to which the items corresponded with their own experiences of the building were also recorded.

During the cognitive interviews, the meaning of the term 'archetype' was explained. Participants were asked to answer the questions whilst thinking of the building they used most frequently. This building could be a residential property, an office, an educational institution or a public building. The time taken to complete the form ranged from 8 to 11 min. No items were removed following the pilot study. However, brief explanations were added to the technical terms appearing in four items.The demographic characteristics and building-use profiles of the participants in the pilot study (n = 45) are presented in Figure 4.

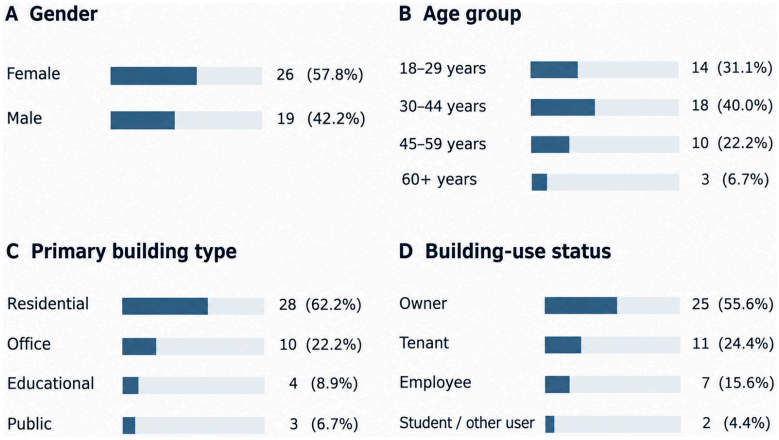


Figure 4. Demographic characteristics and building-use profiles of participants in the pilot study (n = 45).The figure was created using Canva (version 4.235).

2.3. Quantitative Participants and Data Collection

Quantitative data were collected online using Google Forms. The target population of the study consisted of adults aged 18 years and older who regularly use a building. To be eligible for participation, individuals were required to have used the building for at least six months and to spend a minimum of 20 h per week in that building. To enhance participant diversity, individuals using residential, office, educational, and public buildings were recruited. Accordingly, a combination of convenience sampling and criterion sampling was employed, with participants voluntarily taking part in the study.The demographic characteristics and building-use profiles of the participants in the EFA and CFA groups are presented in Table 1.

Table 1. Demographic distributions within the EFA and CFA working groups.

Variable	Category	EFA n = 350, n (%)	CFA n = 400, n (%)
Gender	Female	201 (57.4)	226 (56.5)
	Male	149 (42.6)	174 (43.5)
Age	18–29	112 (32.0)	126 (31.5)
	30–44	136 (38.9)	157 (39.3)
	45–59	78 (22.3)	88 (22.0)
	60 and over	24 (6.9)	29 (7.3)
Archetype	Residential	221 (63.1)	248 (62.0)
	Office	76 (21.7)	91 (22.8)
	Education/public sector	53 (15.1)	61 (15.3)
Type of use	Owner	198 (56.6)	223 (55.8)
	Tenant/other occupier	152 (43.4)	177 (44.3)

Ethical Considerations and Informed Consent

Approval for the study was granted by the Social Sciences and Humanities Scientific Research and Publication Ethics Committee of İnönü University (31 July 2026; meeting no. 16; decision no. 16). All study participants were adults aged 18 years or older, and their participation was voluntary. Informed consent was obtained from all participants. In the qualitative phase, participants consented to audio recording of the semi-structured interviews, and participant codes (K1–K20) were used to protect anonymity. In the quantitative phase, questionnaires were administered online through Google Forms to volunteers who met the study eligibility criteria.

2.4. Data Analysis

Qualitative data were analysed using a content analysis process [24,25]. Theoretical and data-driven codes were developed. These codes were used to identify categories and themes. The validity of the analysis was supported by expert review, the researcher's diary, a decision trail and direct quotations [26]. In addition, independent coding and participant validation were carried out [27]. The themes identified were incorporated into the item development process. Qualitative and quantitative findings were linked to one another at different stages of the research. Firstly, the categories derived from the interviews were reflected in the item pool in a traceable manner. Secondly, the factors emerging from the quantitative analysis were compared with the qualitative themes.

Prior to the quantitative analyses, the data set was examined in detail. Missing responses and response patterns where the same option was consistently selected were checked. Unusually short response times were also assessed. Furthermore, outliers across multiple variables were identified. The skewness and kurtosis values of items with a five-point rating scale were examined [28].

The initial online survey pool comprised 775 submissions containing responses to the 32 candidate items. Data screening was conducted sequentially to ensure that each excluded case was counted only once. First, eight records with at least one unanswered scale item were excluded ($n = 8$). Second, seven respondents who selected the same response category across all 32 items were identified as exhibiting invariant responding and were excluded ($n = 7$). Third, five questionnaires completed in less than 180 s, as determined by recorded start and submission times, were excluded due to unusually short completion times ($n = 5$). Fourth, multivariate outliers were assessed using Mahalanobis squared distance calculated across the 32 questionnaire items. Five additional cases exceeding the chi-square critical value at $p < 0.001$ ($df = 32$; $\chi^2 = 62.49$) were excluded ($n = 5$). Subsequently, the distributions of all 32 items were examined for normality using skewness and excess kurtosis criteria ($|skewness| \leq 2$ and $|excess\ kurtosis| \leq 7$). All items satisfied these criteria, and no further exclusions were required. Overall, 25 unique cases were excluded during data screening ($8 + 7 + 5 + 5$), resulting in a final sample of 750 valid responses. The final data set was divided into two independent, non-overlapping subsamples: 350 participants for exploratory factor analysis (EFA) and 400 participants for confirmatory factor analysis (CFA).

The suitability of the data set for factor analysis was assessed using the KMO coefficient and Bartlett's sphericity test. It was anticipated that the factors would be interrelated. For this reason, the principal axis factorisation method and the Promax oblique rotation technique were used [29,30]. Several criteria were taken into account when determining the number of factors. These were theoretical relevance, eigenvalues, the slope-accumulation plot and the results of parallel analyses [20]. It was stipulated that, for an item to be included in a factor, its principal factor loading must be at least 0.40. For items loaded onto more than one factor, a difference of at least 0.20 between the

loading values was required. Furthermore, the criterion that each factor must consist of at least three items was adopted.

The structure obtained from the EFA was tested on an independent CFA sample. The robust maximum likelihood estimation method was used in the analyses [31]. The model's fit to the data was assessed using the χ^2/df, CFI, TLI, RMSEA, and SRMR values [32]. The CFA provided a confirmatory assessment of the proposed measurement model [33], and RMSEA was interpreted using established model-fit guidance [34]. The validity of the items was examined using adjusted item–total correlations. For item discrimination, groups comprising the lower and upper 27% of the total-score distribution were formed. The item scores of these groups were compared using an independent-samples *t*-test.

Composite reliability (CR) and average variance extracted (AVE) values were used to assess convergent validity [35]. Cronbach's alpha [36] and McDonald's omega [37] coefficients were calculated to determine the internal consistency of the scale. Discriminant validity was examined using the Fornell–Larcker criterion [35] and the heterotrait–monotrait ratio (HTMT) [38].

3. Results

3.1. Findings from Qualitative Content Analysis

The analysis of the interview data identified 52 open codes. These codes were grouped under 16 categories and four main themes. The themes identified are consistent with the areas defined in the theoretical framework. However, it was observed that participants struggled to apply their knowledge to day-to-day decisions regarding building use. Participants also face various difficulties in influencing building management decisions. The identified categories and the number of participants who mentioned them are shown in Table 2.

Table 2. Themes, categories, and frequencies identified through qualitative content analysis.

Theme	Category	f
Building energy and carbon data	Linking heating, cooling and electricity to the main sources of carbon emissions	18
	Being aware that insulation, windows and draughts affect energy consumption	14
	Failure to fully understand the energy performance certificate/class	15
	Failure to distinguish between operational and embedded carbon	17
Energy-efficient use and optimised comfort	Switch off lights and appliances that are not in use	19
	Limiting heating and cooling temperature settings	15
	Making the most of daylight and natural ventilation	14
	Energy-saving adaptive behaviours such as clothing, shading and changing location	10
Low-carbon technology and data literacy	Using the bill as a basic energy feedback tool	16
	Inability to interpret smart meter/monitoring screen data	13
	General knowledge of technologies such as solar energy and heat pumps	15
	The need for simple and action-oriented guidance for automation systems	12

Table 2. *Cont.*

Theme	Category	f
Participation and low-carbon responsibility	Reporting energy wastage or a fault to the relevant person	16
	Willingness to participate in the building management's energy-related decisions	14
	Feeling that you have limited control over the building, whether as a tenant or an employee	13
	Expecting regular feedback on consumption and common rules from management	15

The participants' comments showed that they predominantly associated the concept of carbon with electricity consumption and energy bills. K4 expressed their view on this matter as follows: "When I hear the word 'carbon', the first thing that comes to mind is my electricity bill; I don't know how much carbon is generated by different uses." This statement demonstrates that having a general awareness of carbon does not always equate to practical knowledge. For this reason, the items in the 'knowledge' dimension were not designed solely to assess environmental awareness. The items also take into account whether users understand the relationship between how they use building systems and the carbon impact resulting from that use.

Participants frequently mentioned that they switched off unused lights and electrical appliances. In contrast, adaptive comfort measures were mentioned less frequently. In shared buildings, it is not always possible to put individual preferences into practice. K9 explained this situation as follows: "I want to switch off the air conditioning, but the temperature in the office is set centrally, so I can't change it on my own." This view demonstrates that energy consumption behaviour cannot be explained by individual intentions alone. For this reason, the user's level of control over the building's systems and their usage status within the building have also been taken into account within the scope of the study.

It was found that participants had a general awareness of renewable energy technologies. However, it was observed that they experienced difficulties in explaining how these technologies work and in assessing energy data. A similar situation applies to energy consumption displays and energy performance certificates. K13 described the difficulty they faced in the following words: "There are numbers on the meter; I can see them going up and down, but I don't know what determines whether they're high or not." This view demonstrates that simply having access to a technology is not sufficient to understand the data it provides. For this reason, technology use and data literacy have been assessed as separate areas of competence within the framework.

Participants stated that they were keen to report energy wastage to the relevant departments and to contribute to joint decision-making processes. However, it was noted that they were uncertain about how to contact the management. K18 described the situation as follows: "If the management showed us our monthly consumption, we could discuss together where we are spending too much." This view highlighted users' expectations of having access to their energy data and receiving regular feedback from the management. Accordingly, provisions relating to monitoring energy consumption, requesting feedback and sharing responsibility have been added to the scale pool.

3.2. Transfer of Qualitative Findings to the Item Pool

To clarify the interface between the qualitative and quantitative phases, Table 3 traces representative interview findings to the decisions made when operationalizing the construct as self-report statements. The table identifies related item codes and their dimensions in

the final 20-item scale; it does not imply that every retained item arose exclusively from an interview or that all nine newly drafted statements survived item reduction. In particular, participants' requests for management feedback helped inform the broader monitoring content, but retained item M28 assesses support for regular energy-consumption monitoring, not actual receipt of feedback. Similarly, reports of limited control among tenants and employees informed the consideration of participation opportunities, while retained item M29 assesses willingness to participate rather than the degree of control available. Table A3 in Appendix D lists the initial candidate items and the grounds for their retention or removal.

Table 3. Links between qualitative categories and item development.

Qualitative Finding	Item-Development Decision	Related Retained Item(s) and Dimension
Difficulty understanding energy performance certificates/classes	Operationalize self-assessed ability to interpret a performance rating and understand certificate information, rather than objective technical knowledge.	M5 (F1): interpret performance rating; M20 (F3): understand EPC information.
Difficulty interpreting smart meter or monitoring-display data	Focus on perceived interpretation of consumption data, not access to or ownership of the technology.	M19 (F3): interpret monitoring data.
Limited use of adaptive comfort strategies	Emphasize low-energy comfort adaptations rather than willingness to sacrifice thermal comfort.	M14 (F2): try clothing, shading and other non-energy-consuming adaptations.
Limited control over systems among tenants or employees	Include participation in collective decisions as a distinct orientation, without claiming to measure actual control.	M29 (F4): willingness to participate in management decisions.
Reporting energy waste or faults	Represent an action reported by the user when energy waste is observed.	M32 (F4): report energy-wasting faults or practices.
Expectation of regular feedback from management	Consider transparency and consumption monitoring; direct requests for feedback were not retained as a separate final item.	M28 (F4): support for routine monitoring (an indirect, not identical, correspondence).

3.3. Content Validity

In line with expert opinions, the initial pool of 35 items was re-examined. Three items that did not meet the necessary criteria were removed, and a 32-item pilot questionnaire was created. Of the 20 items retained in the final scale, 12 were rated as essential by all eight experts (CVR = 1.00) and eight were rated as essential by seven of eight experts (CVR = 0.75; Table 4). Following Lawshe's method [21], the scale-level Content Validity Index (CVI) was calculated as the arithmetic mean of the item-level CVRs: $CVI = [(12 \times 1.00) + (8 \times 0.75)]/20 = 0.900$. These results summarize the expert panel's judgements of item essentiality.

Table 4. Content validity values for the final items.

Item	Number of Experts Rating "Essential"	CVR
M1	8	1.00
M2	8	1.00
M3	7	0.75
M4	8	1.00
M5	7	0.75
M10	8	1.00

Table 4. *Cont.*

Item	Number of Experts Rating "Essential"	CVR
M11	7	0.75
M12	8	1.00
M13	8	1.00
M14	7	0.75
M19	8	1.00
M20	8	1.00
M21	7	0.75
M22	8	1.00
M23	7	0.75
M28	8	1.00
M29	8	1.00
M30	7	0.75
M31	8	1.00
M32	7	0.75

Note: CVR = Content Validity Ratio (item level); CVI = Content Validity Index (scale level). Following Lawshe's method, CVI is the arithmetic mean of the CVRs for the 20 retained items (CVI = 0.900); N = 8 experts.

3.4. Exploratory Factor Analysis

The suitability of the data for factor analysis was examined using the KMO coefficient and Bartlett's sphericity test. The KMO value of 0.908 indicated a high level of sample adequacy. The Bartlett test was also found to be statistically significant: $\chi^2(190) = 3027.56$, $p < 0.001$. Based on these results, the relationships between the items are suitable for factor analysis.The results of the KMO and Bartlett's tests are presented in Table 5.

Table 5. Results of the Kaiser–Meyer–Olkin and Bartlett's test of sphericity.

Test	Value
Kaiser–Meyer–Olkin (KMO)	0.908
Bartlett χ^2	3027.56
df	190
p	<0.001

In determining the number of factors, the eigenvalues and the findings of the parallel analysis were evaluated together. The first four empirical eigenvalues were found to be above the 95 per cent threshold values derived from random data. The fifth eigenvalue, however, did not exceed the relevant threshold value. These results supported the four-factor structure of the scale. The total variance explained by the initial eigenvalues of the four factors was calculated as 62.40 per cent.The observed eigenvalues and the corresponding parallel analysis thresholds are illustrated in Figure 5.

The observed eigenvalues, parallel analysis thresholds, and corresponding factor-retention decisions are summarized in Table 6.

Table 6. Eigenvalue and parallel analysis results.

Factor	Observed Eigenvalue	Parallel Analysis (95th Percentile)	Decision
1	6.791	1.526	Retained
2	2.157	1.424	Retained
3	1.934	1.351	Retained
4	1.599	1.291	Retained
5	0.702	1.244	Rejected

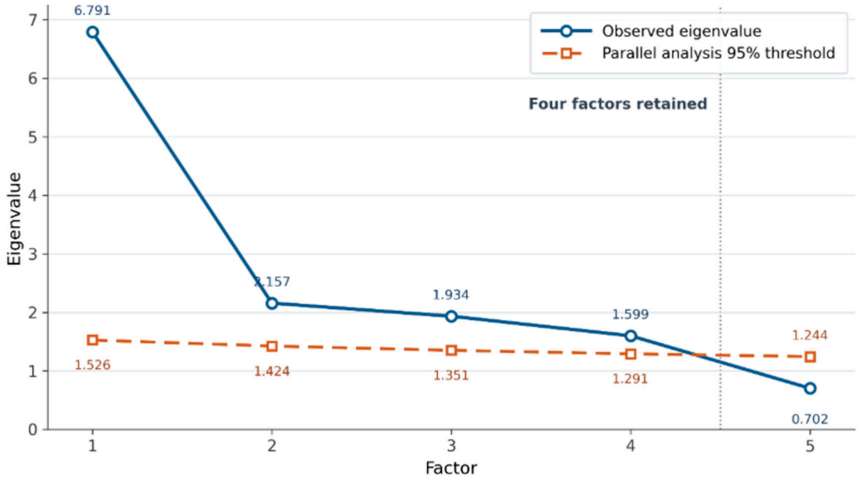


Figure 5. Observed eigenvalues and parallel analysis thresholds. The figure illustrates the observed eigenvalues and the corresponding 95th-percentile reference thresholds obtained from parallel analysis. The first four observed eigenvalues (6.791, 2.157, 1.934, and 1.599) exceeded their respective reference thresholds (1.526, 1.424, 1.351, and 1.291). Conversely, the fifth observed eigenvalue (0.702) fell below its corresponding reference threshold (1.244). These results support the retention of a four-factor structure.The dashed orange line represents the 95th-percentile reference thresholds from parallel analysis, while the solid blue line represents the observed eigenvalues.

The EFA was repeated in stages, taking item properties into account. During this process, a total of 12 items were removed from the scale. The decisions to remove items were based on low factor loadings and differences between cross-loadings of less than 0.20. Items with high technical complexity or content overlapping with other items were also excluded. Ultimately, a four-factor structure, each factor comprising five items, was obtained. The primary factor loadings in the final Promax-rotated pattern matrix ranged from 0.711 to 0.867 (Table 7). The item-level retention and removal decisions across the expert review and EFA stages are documented in Appendix D (Table A3).

Table 7. Final promax rotated pattern matrix for the 20-item scale.

Item	F1	F2	F3	F4
M1	0.753	—	—	—
M2	0.715	—	—	—
M3	0.858	—	−0.106	—
M4	0.733	—	—	−0.107
M5	0.737	—	—	—
M10	—	0.771	—	—
M11	—	0.828	—	—
M12	—	0.793	—	—
M13	—	0.742	—	—
M14	—	0.781	—	—
M19	—	—	0.834	—
M20	0.122	—	0.789	—
M21	—	—	0.831	—
M22	—	—	0.711	—
M23	−0.142	—	0.867	—
M28	—	—	0.111	0.726
M29	—	—	—	0.752
M30	—	—	—	0.783

Table 7. *Cont.*

Item	F1	F2	F3	F4
M31	−0.105	0.109	−0.107	0.788
M32	—	−0.108	—	0.822

Note: F1 = Perceived Building Energy and Carbon Knowledge; F2 = Self-Reported Energy-Efficient Building Use and Adaptive Comfort; F3 = Perceived Low-Carbon Technology and Data Competence; F4 = Low-Carbon Engagement and Responsibility Orientation. Dashes (—) indicate absolute factor loadings below 0.10.

3.5. Relationships Between Factors

Following Promax rotation, it was found that the correlations between the factors ranged from 0.307 to 0.459. The fact that these relationships were positive and of moderate strength indicates that the sub-dimensions are linked to the same conceptual domain. However, the fact that the correlations were not high supports the view that the factors constitute distinct structures.The correlations between the four factors obtained from the EFA are presented in Table 8.

Table 8. EFA factor correlations.

Factor	F1	F2	F3	F4
F1	1.000	—	—	—
F2	0.405	1.000	—	—
F3	0.385	0.459	1.000	—
F4	0.354	0.307	0.411	1.000

3.6. Item Analyses

The mean item scores ranged from 3.23 to 3.71. The standard deviations ranged from 1.07 to 1.21. The adjusted item–total correlations ranged from 0.406 to 0.650. The fact that all correlations were above the 0.30 threshold indicates that the items are sufficiently correlated with the scale as a whole. To examine item discrimination, the bottom and top 27 per cent groups were compared. The scores of the top group were found to be significantly higher on all items, t = 9.44–16.68, $p < 0.001$. These findings support the discriminatory power of the items. The item statistics, corrected item–total correlations, and item discrimination results are presented in Table 9.

Table 9. Item statistics, adjusted item–total correlations and discriminant validity results.

Item	M.	SD	Corrected *r*	t	*p*
M1	3.51	1.11	0.564	14.97	<0.001
M2	3.48	1.11	0.493	11.22	<0.001
M3	3.49	1.11	0.406	9.44	<0.001
M4	3.52	1.13	0.501	11.21	<0.001
M5	3.46	1.16	0.445	10.45	<0.001
M10	3.63	1.10	0.623	14.44	<0.001
M11	3.71	1.07	0.495	10.84	<0.001
M12	3.60	1.18	0.540	12.41	<0.001
M13	3.57	1.12	0.530	12.54	<0.001
M14	3.23	1.09	0.428	9.76	<0.001
M19	3.70	1.14	0.648	16.68	<0.001
M20	3.33	1.17	0.650	16.14	<0.001
M21	3.31	1.18	0.553	12.86	<0.001
M22	3.40	1.14	0.576	14.46	<0.001

Table 9. *Cont.*

Item	M.	SD	Corrected *r*	t	*p*
M23	3.32	1.21	0.466	11.83	<0.001
M28	3.43	1.11	0.527	11.68	<0.001
M29	3.59	1.13	0.548	13.97	<0.001
M30	3.60	1.14	0.497	11.03	<0.001
M31	3.58	1.10	0.414	9.62	<0.001
M32	3.67	1.16	0.441	10.62	<0.001

3.7. Confirmatory Factor Analysis

The four-factor measurement model identified through EFA was tested using CFA on an independent sample of 400 participants. The analysis yielded a $\chi^2(164) = 221.43$ and a $\chi^2/df = 1.35$. The other fit indices were RMSEA = 0.030, CFI = 0.984, TLI = 0.981 and SRMR = 0.038. A combined assessment of the fit indices indicates that the four-factor model fits the data well.

Confirmatory factor analysis (CFA) was conducted to evaluate the original 20-item, four-factor model identified in the independent EFA sample. A review of the CFA records confirmed that the model was tested without any subsequent modifications. Specifically, modification indices were not used to adjust the model, no additional cross-loadings were introduced, and residual covariances between items were not freely estimated. Correlations between the four latent factors were permitted, as specified in the original measurement model. The fit indices presented in Table 10 and the standardised factor loadings reported in Table 11 therefore reflect the model in its original form. By retaining the initial factor structure rather than making adjustments based on modification indices, the analysis limits the possibility of fitting the model to characteristics specific to the sample. This approach also provides a stronger basis for interpreting the CFA results as confirmatory evidence for the proposed measurement structure.

Table 10. CFA model fit indices.

Index	Calculated Value	Interpretation
χ^2/df	1.35	Good Fit
RMSEA	0.030	Good Fit
CFI	0.984	Good Fit
TLI	0.981	Good Fit
SRMR	0.038	Good Fit

Table 11. Standardised CFA loads and error variances.

Factor	Item	Standardized Loading	Error Variance	z	*p*
F1	M1	0.798	0.364	—	—
F1	M2	0.775	0.399	15.89	<0.001
F1	M3	0.740	0.453	15.07	<0.001
F1	M4	0.706	0.501	14.31	<0.001
F1	M5	0.685	0.531	13.80	<0.001
F2	M10	0.810	0.344	—	—
F2	M11	0.757	0.427	15.70	<0.001
F2	M12	0.755	0.429	15.66	<0.001
F2	M13	0.686	0.530	13.99	<0.001
F2	M14	0.666	0.556	13.52	<0.001
F3	M19	0.835	0.302	—	—

Table 11. *Cont.*

Factor	Item	Standardized Loading	Error Variance	z	*p*
F3	M20	0.772	0.404	16.75	<0.001
F3	M21	0.700	0.509	14.83	<0.001
F3	M22	0.701	0.508	14.85	<0.001
F3	M23	0.660	0.565	13.77	<0.001
F4	M28	0.757	0.427	—	—
F4	M29	0.743	0.448	14.14	<0.001
F4	M30	0.739	0.454	14.06	<0.001
F4	M31	0.676	0.543	12.86	<0.001
F4	M32	0.643	0.587	12.21	<0.001

The standardised factor loadings for the items ranged from 0.643 to 0.835. All freely estimated loadings were found to be statistically significant ($p < 0.001$). The error variances of the items ranged from 0.302 to 0.587. These results support the view that the observed items adequately reflect the latent variables to which they are linked.

3.8. Reliability, Convergent and Discriminant Validity

The internal consistency of the subscales was examined using Cronbach's alpha and McDonald's omega coefficients. The alpha values ranged from 0.837 to 0.858. The omega coefficients ranged from 0.837 to 0.859. Cronbach's alpha for the scale as a whole was calculated as 0.908. The composite reliability (CR) values for all factors were above 0.80. All average variance extracted (AVE) values also exceeded the 0.50 threshold. These findings support the conclusion that the scale possesses internal consistency and convergent validity.

4. Discussion

In this study, a 20-item, four-factor self-report instrument was developed to assess perceived low-carbon building literacy among adult building users. The four dimensions reflect perceived building-related energy and carbon knowledge, endorsement of energy-efficient building-use practices, perceived technology and data competence, and low-carbon engagement and responsibility orientation.

The interpretation of these factors requires distinguishing a multidimensional operational profile from a claim about the causal structure of literacy. Including F2 and F4 in the measured profile is defensible within broad energy-literacy approaches that encompass application and engagement [8,9], but alternative theoretical models may instead treat behaviour and participation as consequences or correlates of knowledge and competence. The present cross-sectional design and factor analyses cannot discriminate between these causal interpretations. Accordingly, the factors are described as related, non-interchangeable domains of perceived low-carbon building literacy, not as proven stages of a knowledge-to-action pathway. In particular, F2 contains self-reports of practices, and F4 combines orientations with an account of reporting energy waste; neither demonstrates objectively verified behaviour or governance involvement.

A key methodological strength of this study is the use of two independent quantitative samples for factor exploration and confirmation. The exploratory factor analysis (EFA; n = 350) was used to identify the four-factor, 20-item structure, whereas confirmatory factor analysis (CFA; n = 400) tested that structure in a separate sample rather than reusing the data from which it was derived. This independent-sample validation reduces the risk of over-fitting to sample-specific patterns and strengthens evidence that the four-factor measurement model is reproducible beyond the initial exploratory sample. The good fit obtained in the CFA sample (χ^2/df = 1.35; RMSEA = 0.030; CFI = 0.984; TLI = 0.981; SRMR = 0.038;

Table 10) provides additional support for its structural validity. Nevertheless, because both samples were recruited using nonprobability sampling within the same study context, this internal cross-sample evidence should not be interpreted as demonstrating generalizability to all building user populations or settings.

Various sources were drawn upon when compiling the item pool for the study. The literature was reviewed and expert opinions were sought. In addition, qualitative interviews were conducted with building users. The items were thus based on the users' everyday experiences. The resulting scale was subsequently tested using validity and reliability analyses.

The qualitative findings suggested that participants were familiar with common energy-saving practices, particularly switching off unused lighting and electrical appliances (19 of 20 participants). However, difficulties were frequently reported in understanding energy performance certificates (15 of 20), interpreting smart meter data (13 of 20), and distinguishing between operational and embodied carbon emissions (17 of 20; Table 2). These figures describe the number of participants mentioning each category rather than results of an objective knowledge test or direct observations of behaviour. Uncertainty about participation in building management also emerged.

Taken together, the interviews suggest that familiarity with everyday energy-saving practices should not be equated with perceived competence in interpreting building-specific energy and carbon information. The findings support examining these facets, together with participation orientations, within a multidimensional self-report profile. Because general environmental awareness was not measured as a separate variable, the study cannot determine whether such awareness alone explains building-specific knowledge or competence.

During the qualitative phase, the scope of the construct was examined in relation to users' reported everyday building experiences. Their accounts highlighted difficulties with energy performance certificates and consumption displays, suggesting a need to assess perceived competence in interpreting and acting upon building-specific energy information, in addition to perceived familiarity with basic energy and carbon concepts. These qualitative insights informed the wording and content of the candidate items.

The interviews also suggested that opportunities to influence building systems differ between users, particularly tenants and staff. Whereas some users reported being able to adjust temperature settings or appliances, others described limited control. Accordingly, the initial item pool included participation, energy-waste reporting, and feedback-related content. In the final 20-item instrument, the fourth factor includes support for consumption monitoring (M28), willingness to participate in decisions (M29), and self-reported reporting of energy waste (M32); it does not contain a separate item directly measuring requests for management feedback. The four qualitative themes broadly corresponded in content to the four factors identified by EFA. This conceptual correspondence supports interpretation of the factor structure but was not tested as a statistically significant association.

The first dimension, Perceived Building Energy and Carbon Knowledge, assesses users' perceived understanding of the relationship between building energy use and carbon emissions. Its items cover the perceived role of heating and cooling systems in building-related carbon emissions (M2), the contribution of insulation, windows, and air leakage to energy use (M3), the distinction between operational and embodied carbon, and the interpretation of energy performance ratings. It does not test detailed technical operating principles or objective factual knowledge. This focus situates the cognitive aspect of energy literacy within building use [8,9]. Thus, higher scores indicate stronger self-assessed knowledge and competence rather than demonstrated mastery of building-energy concepts.

The second dimension, Self-Reported Energy-Efficient Building Use and Adaptive Comfort, concerns respondents' endorsement of energy-efficient building-use practices and

adaptive comfort strategies. The items address switching off unused electrical equipment, avoiding extreme heating or cooling settings, limiting unnecessary window opening while systems operate, using daylight and natural ventilation where appropriate, and trying non-energy-consuming comfort adaptations (M10–M14). Occupant-behaviour research identifies heating, cooling, window use, and lighting preferences as relevant to building-energy performance [4–6]. However, endorsement of these questionnaire statements is not equivalent to observed behaviour or measured energy savings. The study also did not directly assess health outcomes or achieved thermal comfort; accordingly, the instrument should not be presented as demonstrating that energy-efficient practices eliminate conflicts with health or comfort.

The third dimension focuses on the extent to which users consider themselves capable of understanding low-carbon technologies and energy data. This dimension covers the use of smart meters and the understanding of information contained in energy performance certificates. The ability to assess renewable energy technologies and building automation systems is also addressed. Perceived competence in comparing different building renovation options is another component of this dimension. The increasing use of digital systems in buildings has made access to technology crucial. However, simply having access to the system is not enough in itself. Users must understand what the energy data provided means and be able to make decisions based on this information when necessary [13–15]. Traditional user behaviour scales often give limited consideration to technological and data interpretation skills. This dimension focuses on this shortcoming. However, the trait being measured is not performance on an actual task; rather, it reflects participants' self-assessments of their own competence.

Recent studies have highlighted the importance of data-driven approaches in predicting building energy consumption, estimating CO_2 emissions, and supporting long-term energy efficiency and renovation planning [39–41]. Although these studies primarily focus on the technical performance of buildings, they also contribute to understanding the growing importance of energy-related information in building management. However, the availability of such information does not necessarily mean that building users can effectively interpret these data or apply them in their daily practices. In this context, the third dimension of the scale developed in the present study, Perceived Low-Carbon Technology and Data Competence (F3), offers a complementary perspective by assessing users' perceived competence in understanding energy-related data and low-carbon building technologies. Therefore, evaluating building users' perceived competencies alongside technical approaches may help identify educational needs and support more informed participation in building energy management processes.

An apparent difference between the two phases concerns energy-monitoring data: 13 of the 20 interviewees mentioned difficulty interpreting smart meter information (Table 2), whereas the corresponding self-report item M19 had a mean of 3.70 on the five-point response scale in the quantitative sample (Table 9). Because the phases involved different participants and the questionnaire assessed self-perceived rather than demonstrated competence, these results should not be interpreted as a direct contradiction.

The fourth dimension, Low-Carbon Engagement and Responsibility Orientation, addresses support for regular monitoring of building energy use, willingness to participate in management decisions, consideration of efficiency when selecting a building, support for low-carbon renovation, and self-reported reporting of energy-wasting faults or practices (M28–M32). These items therefore cover both participation orientations and a reported action; they are not restricted to willingness to participate. Participants' reports of limited authority over building systems, especially among tenants and staff, help explain why the dimension extends beyond individual control over appliances or thermostats. The

framework also recognizes the relevance of opportunities and constraints in the building context [11,12]. However, the factor does not measure actual participation in building governance or independently verify reports of energy-waste reporting.

The quantitative analyses supported the four-factor structure of the scale. Parallel analysis provided evidence for retaining four factors (Table 6), while confirmatory factor analysis (CFA) conducted on an independent sample demonstrated good model fit (Table 10). Cronbach's alpha, McDonald's omega, composite reliability (CR), and average variance extracted (AVE) values supported the reliability and convergent validity of the scale, whereas the Fornell–Larcker and HTMT results provided evidence of discriminant validity (Tables 12–14). Although the overall Cronbach's alpha coefficient was 0.908, separate interpretation of the subscales is recommended given the multidimensional structure of the instrument.

Table 12. Reliability and convergent validity coefficients.

Dimension	n	α	ω	CR	AVE
Perceived Building Energy and Carbon Knowledge	5	0.858	0.859	0.859	0.550
Self-Reported Energy-Efficient Building Use and Adaptive Comfort	5	0.854	0.855	0.855	0.543
Perceived Low-Carbon Technology and Data Competence	5	0.854	0.855	0.855	0.542
Low-Carbon Engagement and Responsibility Orientation	5	0.837	0.837	0.837	0.508
The scale as a whole	20	0.908	—	—	—

Discriminant validity was assessed using the Fornell–Larcker criterion and HTMT ratios. It was found that the square root of the AVE for each factor was higher than the inter-factor correlations. The HTMT values ranged from 0.473 to 0.623 and remained below the 0.85 threshold. These results provide evidence supporting discriminant validity among the four correlated sub-dimensions.

Table 13. Fornell–Larcker Discriminant Validity Matrix.

Factor	F1	F2	F3	F4
F1	0.742	—	—	—
F2	0.490	0.737	—	—
F3	0.476	0.528	0.736	—
F4	0.495	0.501	0.632	0.713

Note: The values on the diagonal represent the square root of the AVE; the values below the diagonal represent the factor correlations.

Table 14. HTMT values.

Factor	F1	F2	F3	F4
F1	1.000	—	—	—
F2	0.490	1.000	—	—
F3	0.473	0.524	1.000	—
F4	0.490	0.502	0.623	1.000

The findings of this study should also be considered in relation to existing measurement approaches. Previous energy literacy scales have incorporated behavioural dimensions alongside knowledge and attitudes [8,9], while research on carbon capability has examined engagement with broader climate-related issues [10]. The scale developed in this study focuses specifically on building use, bringing together perceived knowledge of energy and carbon issues, everyday practices related to indoor comfort, confidence in using building technologies and interpreting energy data, and attitudes towards participation in building-related decisions. Although the four-factor structure and reliability results provide initial support for the scale, they do not demonstrate that it performs better than existing instru-

ments or that it can predict actual energy savings. This distinction is particularly important because some items already address self-reported practices. Future studies examining the relationship between scale scores and occupant behaviour should therefore rely on independently observed behaviours or other outcomes that do not overlap with the scale items. Comparisons with related measures and further criterion-related validity studies would help clarify the scale's contribution and practical usefulness.

Practical Implications

For practical use, the four subscales should be considered separately rather than combined into a single literacy score. Although the scale showed high overall internal consistency (Cronbach's $\alpha = 0.908$), each subscale measures a different aspect of perceived low-carbon building literacy. Combining them into one score could make it difficult to identify areas where building users need additional support. For instance, an individual may frequently report energy-efficient practices and adjustments to indoor comfort conditions (F2) but feel less confident in understanding smart meter readings, energy-monitoring displays or Energy Performance Certificates (F3). An overall score may hide this difference, leading to general awareness programmes instead of more focused guidance on interpreting building energy information. Similarly, a strong sense of responsibility and willingness to participate in building-related decisions (F4) does not necessarily indicate greater perceived knowledge of energy and carbon issues (F1).

Reporting the mean score for each subscale on a 1–5 scale would therefore provide a more useful picture of users' perceived strengths and support needs. Building managers and educators could use these profiles to identify training priorities, make energy feedback easier to understand and encourage users to participate in decisions about building management. However, these scores reflect individuals' own assessments and reported practices. They should not be taken as evidence of objectively demonstrated knowledge, actual energy-saving behaviour or measurable reductions in carbon emissions. Further research is needed to determine how effectively these profiles can support the design and evaluation of educational and building-management interventions.

5. Conclusions

This study resulted in a 20-item self-report scale designed to assess perceived low-carbon building literacy among adult building users. The scale comprises four dimensions: Perceived Building Energy and Carbon Knowledge; Self-Reported Energy-Efficient Building Use and Adaptive Comfort; Perceived Low-Carbon Technology and Data Competence; and Low-Carbon Engagement and Responsibility Orientation. Each dimension addresses a different aspect of how individuals understand and interact with the buildings they use. The scale brings together perceived knowledge, reported energy-efficient practices, confidence in understanding building technologies and energy data, and orientations towards participation and responsibility. It is important, however, to distinguish these self-reported characteristics from objectively demonstrated knowledge, actual energy-saving behaviour, or measurable reductions in energy consumption.

The qualitative interviews played an important role in shaping the scale. Although participants were familiar with everyday energy-saving practices, many described difficulties understanding energy performance certificates, interpreting smart meter information, or distinguishing operational carbon from embodied carbon. Their experiences also revealed differences in the extent to which building users could influence building systems and management decisions. Some participants had little control over how energy was used in their buildings, despite recognizing opportunities for improvement. These accounts helped establish the relevance of participation and responsibility as a separate dimension. The

qualitative findings informed the content of the scale, while the subsequent factor analyses provided the statistical basis for evaluating its structure.

The quantitative results were encouraging. Exploratory factor analysis identified four factors explaining 62.40% of the total variance, and confirmatory factor analysis using an independent sample indicated good model fit. Cronbach's alpha coefficients for the subscales ranged from 0.837 to 0.858, while McDonald's omega coefficients ranged from 0.837 to 0.859. The overall Cronbach's alpha was 0.908, although this value should not, on its own, be taken as justification for combining the four dimensions into a single score. Composite reliability (CR) and average variance extracted (AVE) values were consistent with acceptable convergent validity, and the Fornell–Larcker and HTMT results supported discriminant validity. Taken together, these findings suggest that the four subscales have satisfactory initial psychometric properties in the samples examined. Further evidence is nevertheless needed before the instrument can be considered suitable for all building user populations and research settings.

Several aspects of the study should be taken into account when interpreting these results. The scale is based on participants' own assessments, which may be affected by social desirability or difficulties recalling everyday practices. It does not directly test knowledge or record actual energy use behaviour. The use of convenience and criterion-based sampling also limits the extent to which the findings can be generalized to other populations or building types. Another limitation is the absence of comparisons with measured energy consumption, carbon emissions, or observed occupant behaviour. Such comparisons would help establish whether the perceptions captured by the scale are associated with differences in building performance. The cross-sectional design also leaves questions about the stability of scores over time. Test–retest reliability and measurement invariance across demographic groups and building types have yet to be examined. In addition, the English-language version cannot be assumed to have the same psychometric properties as the administered version without further validation. Addressing these issues in future research would help clarify the scale's applicability and practical value in different building contexts.

Study Limitations

Several limitations should be considered when interpreting these findings. First, the convenience and criterion-based sampling strategy limits the generalizability of the results to other building user populations and contexts. Second, the measure relies on self-report: it does not objectively assess knowledge or verify actual energy-saving behaviour, and responses may be influenced by recall and social-desirability biases. Criterion-related validity was not evaluated using external indicators, such as observed occupant behaviour, measured energy consumption, or carbon emissions. Third, the cross-sectional design did not permit evaluation of test–retest reliability or the stability of scores over time; measurement invariance across demographic groups and building types was also not examined. Finally, the English-language version presented in Appendix C has not undergone separate linguistic and psychometric validation and should not be assumed equivalent to the administered version. Future research should address these gaps through more diverse samples, external validation measures, repeated assessments, subgroup analyses, and independent validation of the English version.

The use of consistently keyed items also warrants consideration. Although this choice was made to reduce the potential confusion and wording effects associated with reverse-keyed statements, it does not control for acquiescence (a general tendency to agree with questionnaire statements). Acquiescence was not directly measured in this study and may affect the interpretation of self-reported scores. Future work should examine response-style effects and, where appropriate, compare alternative item-wording formats without compromising content validity.

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Informed Consent Statement: Informed consent was obtained from all participants involved in the study. Consent for audio recording was also obtained from participants in the qualitative interviews.

Data Availability Statement: The data supporting the findings of this study include quantitative questionnaire responses and qualitative interview materials. Requests for access to de-identified quantitative survey data may be directed to the corresponding author and will be considered on a case-by-case basis, subject to participants' consent, institutional ethics requirements, and applicable data-protection obligations. Audio recordings and full interview transcripts are not made publicly accessible to protect participants' confidentiality.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Semi-Structured Interview Form

The following questions should be answered by considering the residential, office, educational, or public building that you use most frequently. When necessary, follow-up prompts such as "Could you explain this with an example?" and "What factors influence your decision in this situation?" may be used.

1. In your opinion, what characteristics distinguish a low-carbon building from other buildings?
2. How would you explain the relationship between energy consumption and carbon emissions in a building?
3. What practices do you pay attention to when using heating, cooling, lighting, window, and shading systems?
4. What methods do you use to reduce energy consumption while maintaining your comfort?
5. How do you interpret and evaluate the information provided in electricity or natural gas bills, smart meters, energy monitoring displays, or Energy Performance Certificates (EPCs)?
6. What do you know about low-carbon technologies such as solar energy systems, heat pumps, building automation systems, and similar technologies?
7. What do you do when you notice energy waste or a technical problem in a building? Do you have the authority to make decisions or report such issues?
8. How should building users participate in building management decisions regarding energy efficiency and carbon emission reduction?

Appendix B. Bina Kullanıcıları İçin Düşük Karbonlu Bina Okuryazarlığı Ölçeği

Aşağıdaki ifadeleri, en sık kullandığınız konut, ofis, eğitim veya kamu binasını düşünerek yanıtlayınız. Her ifade için size en uygun seçeneği işaretleyiniz. 1 = Hiç katılmıyorum, 2 = Katılmıyorum, 3 = Kararsızım, 4 = Katılıyorum, 5 = Tamamen katılıyorum.

Table A1. Turkish version of the final 20-item scale.

No	Kod	F	Madde	Yanıt
1	M1	F1	Binalarda kullanılan enerjinin karbon salımlarıyla ilişkisini açıklayabilirim.	1 2 3 4 5
2	M2	F1	Isıtma ve soğutma sistemlerinin bina kaynaklı karbon salımlarındaki rolünü bilirim.	1 2 3 4 5
3	M3	F1	Yalıtım, pencere özellikleri ve hava sızıntılarının bina enerji tüketimini nasıl etkilediğini anlayabilirim.	1 2 3 4 5
4	M4	F1	Bir binanın kullanım aşamasındaki (operasyonel) karbon salımları ile yapım sürecindeki gömülü karbonu ayırt edebilirim.	1 2 3 4 5
5	M5	F1	Bir binanın enerji performans sınıfının ne ifade ettiğini yorumlayabilirim.	1 2 3 4 5
6	M10	F2	Kullanmadığım mekânlardaki aydınlatma ve elektrikli cihazları kapatırım.	1 2 3 4 5
7	M11	F2	Isıtma ve soğutma sistemlerinde gereğinden yüksek veya düşük sıcaklık ayarlarından kaçınırım.	1 2 3 4 5
8	M12	F2	Isıtma ya da soğutma sistemi çalışırken kapı ve pencereleri gereksiz yere açık bırakmam.	1 2 3 4 5
9	M13	F2	Uygun koşullarda gün ışığı ve doğal havalandırmadan yararlanırım.	1 2 3 4 5
10	M14	F2	Isıl konforumu artırmak için önce enerji tüketmeyen uyum davranışlarını (kıyafet, gölgeleme vb.) denerim.	1 2 3 4 5
11	M19	F3	Akıllı sayaç veya enerji izleme ekranındaki tüketim verilerini yorumlayabilirim.	1 2 3 4 5
12	M20	F3	Bir binanın enerji kimlik belgesindeki temel bilgileri anlayabilirim.	1 2 3 4 5
13	M21	F3	Güneş enerjisi, ısı pompası ve benzeri düşük karbonlu bina teknolojilerinin temel işlevlerini bilirim.	1 2 3 4 5
14	M22	F3	Bina otomasyon sistemlerinin enerji tüketimini azaltmak için nasıl kullanılabileceğini anlayabilirim.	1 2 3 4 5
15	M23	F3	Bir binada yapılabilecek enerji verimliliği iyileştirmelerini (yalıtım, aydınlatma, sistem yenileme vb.) karşılaştırabilirim.	1 2 3 4 5
16	M28	F4	Yaşadığım veya çalıştığım binada enerji tüketiminin düzenli olarak izlenmesini desteklerim.	1 2 3 4 5
17	M29	F4	Bina yönetiminin enerji verimliliği ve karbon azaltımı kararlarına katılmaya istekliyim.	1 2 3 4 5
18	M30	F4	Konut veya çalışma alanı seçerken binanın enerji verimliliğini dikkate alırım.	1 2 3 4 5
19	M31	F4	Bina yenilemelerinde düşük karbonlu ve dayanıklı çözümlerin tercih edilmesini desteklerim.	1 2 3 4 5
20	M32	F4	Binada enerji israfına yol açan bir arıza veya uygulama fark ettiğimde ilgili kişilere bildiririm.	1 2 3 4 5

Puanlama F1 = Maddeler 1–5; F2 = Maddeler 6–10; F3 = Maddeler 11–15; F4 = Maddeler 16–20.

Ters madde bulunmamaktadır. Her alt boyut için madde puanlarının toplamı veya ortalaması ayrı ayrı hesaplanmalıdır. Alt boyut toplam puanları 5–25, ortalama puanları ise 1–5 arasında değişmektedir. Yüksek puan, ilgili boyutta daha yüksek algılanan bilgi/yeterlik, daha sık bildirilen enerji verimli uygulama veya daha güçlü katılım yönelimi anlamına gelmektedir.

Appendix C. Low-Carbon Building Literacy Scale for Building Users

Instructions: Please respond to the following statements by considering the residential, office, educational, or public building that you use most frequently. For each statement, select the response option that best reflects your level of agreement.

Response scale: 1 = Strongly Disagree, 2 = Disagree, 3 = Neither Agree nor Disagree, 4 = Agree, 5 = Strongly Agree.

Table A2. English version of the final 20-item scale.

No.	Code	Factor	Item	Response
1	M1	F1	I can explain the relationship between energy consumption in buildings and carbon emissions.	1 2 3 4 5
2	M2	F1	I understand the role of heating and cooling systems in building-related carbon emissions.	1 2 3 4 5
3	M3	F1	I can understand how insulation, window characteristics, and air leakage affect a building's energy consumption.	1 2 3 4 5
4	M4	F1	I can distinguish between a building's operational carbon emissions and the embodied carbon associated with its construction.	1 2 3 4 5
5	M5	F1	I can interpret what a building's energy performance rating indicates.	1 2 3 4 5
6	M10	F2	I turn off lights and electrical appliances in spaces that are not in use.	1 2 3 4 5
7	M11	F2	I avoid setting heating and cooling systems to unnecessarily high or low temperatures.	1 2 3 4 5
8	M12	F2	I avoid leaving doors and windows unnecessarily open while heating or cooling systems are operating.	1 2 3 4 5
9	M13	F2	I make use of daylight and natural ventilation whenever conditions are appropriate.	1 2 3 4 5
10	M14	F2	To improve my thermal comfort, I first try adaptive behaviors that do not require energy consumption (e.g., adjusting clothing or using shading).	1 2 3 4 5
11	M19	F3	I can interpret energy consumption data displayed on smart meters or energy monitoring systems.	1 2 3 4 5
12	M20	F3	I can understand the basic information provided in a building's Energy Performance Certificate (EPC).	1 2 3 4 5
13	M21	F3	I understand the basic functions of low-carbon building technologies, such as solar energy systems and heat pumps.	1 2 3 4 5
14	M22	F3	I can understand how building automation systems can be used to reduce energy consumption.	1 2 3 4 5
15	M23	F3	I can compare energy efficiency improvements that could be implemented in a building (e.g., insulation, lighting upgrades, and system replacements).	1 2 3 4 5
16	M28	F4	I support the regular monitoring of energy consumption in the building where I live or work.	1 2 3 4 5
17	M29	F4	I am willing to participate in building management decisions concerning energy efficiency and carbon emission reduction.	1 2 3 4 5
18	M30	F4	I consider a building's energy efficiency when choosing a residential or working space.	1 2 3 4 5
19	M31	F4	I support the adoption of low-carbon and durable solutions in building renovations.	1 2 3 4 5
20	M32	F4	When I notice a malfunction or practice that causes energy waste in a building, I report it to the relevant individuals or authorities.	1 2 3 4 5

Factor labels: F1 = Perceived Building Energy and Carbon Knowledge; F2 = Self-Reported Energy-Efficient Building Use and Adaptive Comfort; F3 = Perceived Low-Carbon Technology and Data Competence; F4 = Low-Carbon Engagement and Responsibility Orientation.

Scoring Instructions: F1 = Items 1–5; F2 = Items 6–10; F3 = Items 11–15; F4 = Items 16–20. There are no reverse-coded items. For each subscale, item scores should be calculated separately as either a sum or a mean. Subscale total scores range from 5 to 25, whereas mean scores range from 1 to 5. Higher scores indicate stronger perceived knowledge or competence, greater endorsement of the listed energy-efficient practices, or stronger low-carbon engagement and responsibility orientation within the respective dimension.

Appendix D. Initial 35-Item Pool and Item Retention/Removal Decisions

Table A3. Initial 35-item pool and item retention/removal decisions.

No.	Candidate Dimension	Item	Decision/Rationale
1	Perceived Building Energy and Carbon Knowledge	I can explain the relationship between energy consumption in buildings and carbon emissions.	Retained in the final scale
2	Perceived Building Energy and Carbon Knowledge	I understand the role of heating and cooling systems in building-related carbon emissions.	Retained in the final scale
3	Perceived Building Energy and Carbon Knowledge	I can understand how insulation, window characteristics, and air leakage affect a building's energy consumption.	Retained in the final scale
4	Perceived Building Energy and Carbon Knowledge	I can distinguish between a building's operational carbon emissions and the embodied carbon associated with its construction.	Retained in the final scale
5	Perceived Building Energy and Carbon Knowledge	I can interpret what a building's energy performance rating indicates.	Retained in the final scale
6	Perceived Building Energy and Carbon Knowledge	I believe that carbon emissions from buildings result solely from electricity consumption.	Expert review: Reverse-worded and conceptually narrow statement
7	Perceived Building Energy and Carbon Knowledge	I can calculate a building's total energy consumption in detail without technical assistance.	EFA: Excessively technical for the target population
8	Perceived Building Energy and Carbon Knowledge	I can explain the relationship between climate change and building design through detailed regulatory provisions.	EFA: Excessively technical and low factor loading
9	Perceived Building Energy and Carbon Knowledge	I understand the indirect energy and carbon impacts of water use in buildings.	EFA: Cross-loading
10	Self-Reported Energy-Efficient Building Use and Adaptive Comfort	I turn off lights and electrical appliances in spaces that are not in use.	Retained in the final scale
11	Self-Reported Energy-Efficient Building Use and Adaptive Comfort	I avoid setting heating and cooling systems to unnecessarily high or low temperatures.	Retained in the final scale
12	Self-Reported Energy-Efficient Building Use and Adaptive Comfort	I avoid leaving doors and windows unnecessarily open while heating or cooling systems are operating.	Retained in the final scale
13	Self-Reported Energy-Efficient Building Use and Adaptive Comfort	I make use of daylight and natural ventilation whenever conditions are appropriate.	Retained in the final scale

Table A3. *Cont.*

No.	Candidate Dimension	Item	Decision/Rationale
14	Self-Reported Energy-Efficient Building Use and Adaptive Comfort	To improve my thermal comfort, I first try adaptive behaviors that do not require energy consumption (e.g., adjusting clothing or using shading).	Retained in the final scale
15	Self-Reported Energy-Efficient Building Use and Adaptive Comfort	I do not leave electrical appliances in standby mode.	EFA: Overlapping content/redundancy
16	Self-Reported Energy-Efficient Building Use and Adaptive Comfort	I prefer taking the stairs instead of the elevator when traveling between nearby floors.	EFA: Context-dependent and cross-loading
17	Self-Reported Energy-Efficient Building Use and Adaptive Comfort	I am willing to completely sacrifice my indoor comfort when necessary to save energy.	EFA: Extreme and unrealistic statement
18	Self-Reported Energy-Efficient Building Use and Adaptive Comfort	I regularly compare monthly building energy bills.	Expert review: Unsuitable for users without access to energy bills
19	Perceived Low-Carbon Technology and Data Competence	I can interpret energy consumption data displayed on smart meters or energy monitoring systems.	Retained in the final scale
20	Perceived Low-Carbon Technology and Data Competence	I can understand the basic information provided in a building's Energy Performance Certificate (EPC).	Retained in the final scale
21	Perceived Low-Carbon Technology and Data Competence	I understand the basic functions of low-carbon building technologies, such as solar energy systems and heat pumps.	Retained in the final scale
22	Perceived Low-Carbon Technology and Data Competence	I can understand how building automation systems can be used to reduce energy consumption.	Retained in the final scale
23	Perceived Low-Carbon Technology and Data Competence	I can compare energy efficiency improvements that could be implemented in a building (e.g., insulation, lighting upgrades, and system replacements).	Retained in the final scale
24	Perceived Low-Carbon Technology and Data Competence	I can diagnose technical malfunctions in heating, ventilation, and air conditioning (HVAC) systems.	EFA: Requires specialized technical expertise
25	Perceived Low-Carbon Technology and Data Competence	I can calculate the life-cycle carbon emissions of a building.	EFA: Excessively technical and low factor loading
26	Perceived Low-Carbon Technology and Data Competence	I can quantitatively compare building materials based on their embodied carbon values.	EFA: Cross-loading between knowledge and technology dimensions
27	Perceived Low-Carbon Technology and Data Competence	I can assess data security risks associated with smart building systems.	EFA: Outside the core scope of the scale
28	Low-Carbon Engagement and Responsibility Orientation	I support the regular monitoring of energy consumption in the building where I live or work.	Retained in the final scale

Table A3. *Cont.*

No.	Candidate Dimension	Item	Decision/Rationale
29	Low-Carbon Engagement and Responsibility Orientation	I am willing to participate in building management decisions concerning energy efficiency and carbon emission reduction.	Retained in the final scale
30	Low-Carbon Engagement and Responsibility Orientation	I consider a building's energy efficiency when choosing a residential or working space.	Retained in the final scale
31	Low-Carbon Engagement and Responsibility Orientation	I support the adoption of low-carbon and durable solutions in building renovations.	Retained in the final scale
32	Low-Carbon Engagement and Responsibility Orientation	When I notice a malfunction or practice that causes energy waste in a building, I report it to the relevant individuals or authorities.	Retained in the final scale
33	Low-Carbon Engagement and Responsibility Orientation	I am willing to pay higher costs for low-carbon building practices under all circumstances.	EFA: Potential bias associated with economic circumstances
34	Low-Carbon Engagement and Responsibility Orientation	I try to encourage other building users to adopt low-carbon behaviors.	EFA: Social desirability and cross-loading
35	Low-Carbon Engagement and Responsibility Orientation	Reducing a building's energy consumption is solely the responsibility of the building manager.	Expert review: Reverse-worded and ambiguous statement

Note: EFA = Exploratory Factor Analysis. "Retained in the final scale" indicates items included in the final 20-item version of the scale.

Appendix E. Informed Voluntary Consent Form

Research Title	Development of the Perceived Low-Carbon Building Literacy Scale for Adult Building Users: A Validity and Reliability Study
Participant Information	Dear Participant, You are invited to participate in a scientific research study investigating perceived low-carbon building literacy among adult building users. This study aims to assess your perceived knowledge of energy consumption and carbon emissions in buildings, your self-reported energy-efficient building-use practices, your perceived competence in understanding low-carbon technologies and interpreting energy data, and your willingness to participate in low-carbon initiatives. As part of this study, you will be asked to complete a questionnaire based on the residential, office, educational, or public building that you use most frequently.
Eligibility Criteria	To participate in this study, you must be at least 18 years old, have used the relevant building for at least six months, and spend a minimum of 20 h per week in that building.
Voluntary Participation	Your participation in this study is entirely voluntary. You may choose not to participate or discontinue the questionnaire at any time before submission. Your decision will not result in any penalties or adverse consequences.
Confidentiality and Data Use	The information you provide will be used for scientific research purposes. Your responses will be handled in accordance with institutional ethical requirements and applicable data-protection regulations. The research findings will be presented in a manner intended to protect your confidentiality and prevent your direct identification. You may discontinue the questionnaire before submitting your responses. If you have questions about how your information will be stored, who may access it, or whether you can withdraw your responses after submission, you may contact the research team.

Ethics Committee Approval	This study was approved by the Social Sciences and Humanities Scientific Research and Publication Ethics Committee of İnönü University (approval date: 31 July 2026; meeting no. 16; decision no. 16).
Voluntary Participation Consent	☐ I confirm that I have read and understood the information provided above. I understand the purpose of the study, the voluntary nature of my participation, and my right to discontinue the questionnaire before submission. I confirm that I am at least 18 years old and voluntarily agree to participate in this research. **Consent Option: I agree.**

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