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AI-Enabled Smart Buildings and Digital Energy Literacy: The DEL-EQ Framework for Equitable Adoption

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ABSTRACT

The rapid rise of smart building technologies powered by artificial intelligence (AI), the Internet of Things (IoT), and dynamic pricing systems is transforming energy use from a passive to an interactive process. While these innovations promise efficiency and sustainability, they also introduce new digital, cognitive, and ethical demands for building occupants. Traditional models of energy literacy, framed around cognitive, affective, and behavioral dimensions, no longer capture the competencies required in AI-driven systems. To address this gap, this article introduces the Digital Energy Literacy for Equitable Adoption (DEL-EQ) framework, which extends classical energy literacy by adding four critical dimensions: comprehension, interpretation, agency, and trust & ethics. A narrative and integrative literature review highlights how these dimensions interact with moderating factors at the individual, technological, and community levels. The novelty of DEL-EQ lies in situating digital energy literacy as both a technical and a justice-oriented capacity, thereby bridging social science and engineering perspectives. The framework offers actionable policy implications, including literacy thresholds, AI explainability, community-based training, and inclusive design. DEL-EQ thus provides scholars, designers, and policymakers with a conceptual foundation for preventing digital energy inequality and fostering the equitable adoption of smart building technologies.

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1. Introduction

The emergence of smart building technologies has reshaped the relationship between occupants and energy systems. Enabled by advances in artificial intelligence (AI), the Internet of Things (IoT), and data analytics, buildings are no longer passive structures but active participants in energy optimization. AI-driven energy management systems predict usage patterns, adjust heating, ventilation, and cooling operations, and make autonomous decisions to minimize waste [1, 2]. IoT-enabled sensors provide real-time data on occupancy, temperature, and air quality, allowing buildings to respond dynamically to environmental changes [3]. Dynamic pricing algorithms further enhance this adaptability by aligning energy consumption with fluctuating tariffs, thereby reducing costs and supporting grid stability [4, 5]. These innovations hold significant promise for sustainability and efficiency, yet they also impose new cognitive and digital demands on building users [6].

Despite their benefits, smart energy systems raise concerns regarding accessibility, privacy, and equity. As buildings increasingly rely on real-time data flows and algorithmic decision-making, users are expected to interpret system feedback, adjust behaviors, and trust automated processes. For individuals lacking technological competence or adequate digital resources, this complexity can lead to exclusion and disengagement [7]. Traditional frameworks of energy literacy—typically defined through cognitive, affective, and behavioral dimensions [8-11]—do not sufficiently address the technological fluency, data interpretation skills, and ethical awareness now required in smart energy environments.

This gap reflects a broader limitation in existing research. Much of the current literature focuses on the technical performance of smart systems while overlooking the socio-cognitive capacities of users to engage with them [12, 13]. Critical dimensions such as user autonomy, algorithmic transparency, and socio-economic disparities remain underexplored. Without addressing these factors, the diffusion of smart technologies risks exacerbating inequalities by privileging those with advanced digital literacy and marginalizing others with limited access or trust in automation [14, 15].

This study responds to these challenges by proposing the **Digital Energy Literacy for Equitable Adoption (DEL-EQ) model**. The framework extends classical energy literacy by incorporating digital, behavioral, and ethical dimensions, ensuring that energy transitions in smart buildings are both technologically effective and socially inclusive. By emphasizing equity, inclusiveness, and user agency, the DEL-EQ model highlights the competencies required for meaningful participation in AI-enabled energy systems.

Accordingly, this research is guided by four questions:

R.Q.1. How do smart building technologies redefine the competencies required for energy literacy?

R.Q.2. What digital, cognitive, and behavioral dimensions should be incorporated into a digital energy literacy model?

R.Q.3. How do socio-economic disparities influence access to and engagement with AI-driven smart energy systems?

R.Q.4. What frameworks or strategies can mitigate the digital divide and ensure equitable adoption of smart energy technologies?

The significance of this study lies in positioning digital energy literacy as a cornerstone of equitable smart energy adoption. By moving beyond purely technical evaluations, the DEL-EQ framework highlights the practical skills, interpretive capacities, and ethical awareness that enable occupants to act not as passive recipients of automation but as informed and empowered participants in energy transitions. The practical contribution of this research is twofold. First, it provides policymakers and designers with a structured model to identify literacy thresholds, design transparent interfaces, and implement community-based training programs that reduce digital exclusion. Second, it establishes a normative foundation that links energy efficiency with justice, ensuring that smart building innovations contribute not only to technological optimization but also to social inclusion and trust. In this way, the study addresses both scholarly debates and real-world policy needs, providing a framework that bridges engineering performance with societal equity in the era of AI-enabled smart buildings.

2. Literature Review & Conceptual Framework

2.1. Classical Energy Literacy

Energy literacy has long been conceptualized as a three-dimensional construct encompassing cognitive, affective, and behavioral components. The cognitive dimension involves individuals' knowledge and understanding of energy systems, including energy production, transmission, consumption, and awareness of pricing structures and environmental consequences [9, 16]. The affective dimension reflects values, attitudes, and motivations toward energy conservation and sustainability, capturing the extent to which individuals feel responsible for energy-efficient behavior and climate action [8, 17]. The behavioral dimension addresses actual practices, such as reducing unnecessary consumption, investing in efficient technologies, or altering daily routines [10, 11, 18]. These three dimensions together have provided a holistic yet relatively static framework for energy education and policy outreach. However, as smart energy technologies proliferate, this traditional model is increasingly insufficient to capture the digital and interactive competencies now required.

2.2. Digital Expansion in Energy Literacy

The digitization of energy systems demands an expanded framework that incorporates new literacies essential for navigating AI-enabled and data-driven environments. Interface literacy refers to the ability to interpret and interact with digital platforms such as mobile apps, dashboards, and smart home interfaces [12, 19]. Without such skills, even technically advanced systems may remain inaccessible to users.

Data literacy is equally critical, enabling individuals to comprehend real-time feedback, recognize consumption patterns, and evaluate energy usage trends [1, 13]. Smart systems generate continuous flows of granular data, and meaningful participation requires the ability to interpret this information for decision-making.

Algorithmic transparency adds a further layer, highlighting the need to understand how AI-driven systems make decisions, such as adjusting heating schedules or applying dynamic tariffs [20, 21]. While full technical comprehension may not be realistic for most users, at least a basic awareness of algorithmic influence is necessary for trust and accountability.

Finally, behavioral responsiveness emphasizes users' capacity to modify their actions in response to system feedback or automated recommendations, such as reducing demand during peak hours in response to price signals [22, 23]. Taken together, these literacies broaden the classical energy literacy framework and reflect the demands of increasingly digitized energy infrastructures.

2.3. Equity & Socio-Technical Lens

Digital energy literacy must also be examined through an equity-focused, socio-technical perspective. Digital inclusion remains a critical challenge, as access to devices, connectivity, and digital skills is unevenly distributed across socio-economic groups [14]. Without adequate resources, vulnerable communities may be excluded from the benefits of smart energy systems.

Beyond access, socio-technical accessibility addresses the importance of user-centered design. Systems must accommodate diverse needs, including those of the elderly, individuals with disabilities, or people with limited technological experience [15]. Interface usability, multilingual design, and cultural sensitivity are essential to prevent exclusion.

User agency is another key dimension. Energy literacy in digital contexts is not only about compliance with automated systems but also about retaining the ability to override, adjust, and question AI-driven decisions [24]. Without agency, users risk becoming passive recipients rather than active participants.

Trust in AI varies significantly across age, education, and income levels, shaping how individuals perceive and adopt smart technologies [25, 26]. Concerns around data privacy, fairness, and algorithmic opacity often undermine confidence, making trust-building a central component of equitable digital energy literacy.

Furthermore, insights from behavioral economics underscore that individuals' responses to energy feedback are shaped not only by knowledge but also by bounded rationality, heuristics, and nudging mechanisms, which can either facilitate or undermine agency. From a Global South perspective, infrastructural limitations, affordability concerns, and socio-cultural norms significantly condition the development of digital energy literacy, suggesting that equity cannot be assessed solely through Western-centric assumptions. In addition, perspectives from critical AI ethics emphasize algorithmic fairness, bias, and accountability, highlighting the risks of reproducing systemic inequalities through opaque decision-making systems. Incorporating these strands allows DEL-EQ to move beyond descriptive literacies toward a more critical and interdisciplinary synthesis.

3. Methodology

This study employs an exploratory research design, grounded in a narrative and integrative literature review, to conceptualize Digital Energy Literacy (DEL) within the context of smart building environments. The approach was chosen because the field remains emergent, fragmented across disciplines, and insufficiently theorized. An exploratory design enables the mapping of broad conceptual terrain while also identifying critical dimensions that can guide future empirical investigations.

3.1. Data Sources and Search Strategy

The review was conducted across major academic databases—Web of Science, Scopus, and IEEE Xplore—to capture both social science perspectives on literacy and technology, as well as technical studies on smart energy systems. Searches combined keywords such as *"energy literacy," "digital literacy," "smart buildings," "artificial intelligence," "human–AI interaction,"* and *"equitable adoption."* Only peer-reviewed journal articles, conference proceedings, and book chapters published in English between 2016 and 2025 were included to reflect both foundational and the most recent developments in the field.

3.2. Inclusion and Exclusion Criteria

Studies were included if they:

1. Examined frameworks or competencies related to energy literacy or digital literacy.
2. Investigated socio-technical adoption of smart or AI-enabled energy systems.
3. Addressed issues of equity, inclusion, or trust in technology adoption.

Exclusion applied to purely technical optimization studies without human-centered or literacy dimensions, as well as commentaries lacking substantive conceptual contributions.

3.3. Analytical Approach

The selected literature was analyzed through a thematic synthesis and conceptual mapping approach. First, studies were coded according to literacy dimensions (cognitive, affective, behavioral, interface, data, algorithmic transparency, and responsiveness). Next, cross-cutting themes related to equity, inclusion, agency, and trust were identified. Finally, these themes were integrated into a conceptual model, Digital Energy Literacy for Equitable Adoption (DEL-EQ), which synthesizes technical, cognitive, behavioral, and ethical dimensions into a unified framework.

3.4. Rationale for Methodological Choice

This combined narrative–integrative review approach allowed for both breadth and depth. Narrative review techniques enabled mapping across diverse disciplinary sources and identifying underexplored intersections. Integrative synthesis ensured that overlapping concepts from energy studies, digital literacy research, and socio-technical systems theory were consolidated into coherent analytical categories. As such, the methodology goes beyond descriptive aggregation and provides the conceptual grounding necessary to propose a new framework.

3.5. Limitations

The methodology is limited by its reliance on secondary data and by the exclusion of non-English publications, which may omit important regional insights. Nevertheless, by systematically reviewing multiple disciplinary domains and applying thematic synthesis, the study establishes a robust conceptual foundation for future empirical validation of the DEL-EQ model.

4. Findings: DEL-EQ Model Proposal

4.1. Comprehension

The first dimension of the DEL-EQ model, comprehension, refers to the foundational knowledge required to understand the functioning of digital energy systems. At its core, this dimension builds on classical energy literacy, which emphasized knowledge of energy production, transmission, and consumption, and expands it to include the digital and economic components that define smart environments [9, 16].

In smart building contexts, comprehension involves grasping how energy usage is monitored, displayed, and influenced by automated systems. For example, residents must be able to recognize and interpret energy usage metrics such as kilowatt-hour consumption, peak demand indicators, and baseline comparisons with prior periods [13]. These metrics are increasingly embedded in digital dashboards and mobile applications, which provide real-time feedback on consumption trends. Without comprehension of these indicators, users risk becoming passive recipients of system outputs rather than active decision-makers.

Another critical component of comprehension relates to understanding system operations within AI-powered environments. Smart thermostats, lighting systems, and appliances now respond autonomously to environmental inputs, occupancy patterns, and dynamic pricing signals. Users must be aware of how these devices function, what factors influence their automated decisions, and how these decisions translate into both energy savings and financial costs [2, 27]. A failure to comprehend system logic may result in disengagement or mistrust, undermining the intended benefits of energy efficiency.

Comprehension also encompasses awareness of digital tariffs and dynamic pricing mechanisms. Time-of-use pricing, real-time rate adjustments, and demand-response incentives require users to understand fluctuating cost models and the implications for daily routines. For instance, recognizing that running energy-intensive appliances at off-peak times reduces costs is essential for benefiting from such pricing schemes [4, 28]. This literacy is particularly important in ensuring equitable access, as low-income households often face higher risks of energy poverty and may be disproportionately affected by tariff complexity [14].

Finally, comprehension extends beyond technical understanding to include contextual awareness of socio-economic disparities in energy knowledge. Marginalized or low-education communities may lack exposure to energy-related concepts, making them more vulnerable to exclusion in digitalized energy systems [7]. Thus, comprehension is positioned as the most essential starting point of DEL-EQ: without this foundational knowledge, subsequent capacities such as interpretation, agency, and ethical engagement cannot be meaningfully developed.

4.2. Interpretation

The second dimension of the DEL-EQ model, interpretation, goes beyond basic comprehension of energy systems to encompass the ability to make sense of the continuous flows of real-time data and digital feedback generated by smart buildings. In AI-enabled energy environments, consumption is no longer a static, monthly metric but a dynamic, immediate, and interactive phenomenon, communicated through dashboards, mobile applications, and voice assistants [1, 13].

A key element of interpretation is the ability to understand and evaluate visualized data such as graphs, color-coded alerts, and comparative analytics. For example, interfaces often highlight spikes in consumption, identify appliances contributing disproportionately to energy use, or display comparative feedback against household averages [29, 30]. Effective interpretation allows users to recognize consumption patterns, such as seasonal fluctuations or higher weekend usage, and to connect these patterns with behavioral adjustments. Without such skills, the information provided by smart systems risks becoming overwhelming noise rather than actionable insight [31].

Interpretation also entails the cognitive ability to detect trends and anomalies in energy use. For instance, if an interface indicates that HVAC consumption has steadily increased over a month, a user with high interpretation skills may attribute this to reduced system efficiency or environmental factors and decide on appropriate interventions [3]. This capacity to contextualize data links directly to the broader goal of empowering residents to shift from passive consumers to active energy participants [2].

However, interpretation skills are not equally distributed across populations. Research shows that individuals with limited digital literacy or unfamiliarity with data visualization often struggle to derive meaningful conclusions from dashboards or alerts [32]. Older adults and marginalized groups are particularly vulnerable to such barriers, given the prevalence of complex or non-intuitive interface designs [15, 33]. Inadequate interface usability not only hinders interpretation but also reduces motivation to engage, further widening the digital divide [12].

Thus, interpretation is best understood as both a skillset and a design-dependent process. On the one hand, users must be equipped with the competencies to interpret digital signals and feedback. On the other hand, system designers and policymakers must ensure that data representations are accessible, intuitive, and inclusive, accommodating different levels of literacy, language, and cognitive capacity [34, 35]. Within the DEL-EQ model, interpretation plays a bridging role, transforming raw system outputs into meaningful insights that inform agency and enable equitable participation in smart energy ecosystems.

4.3. Agency

The third dimension of the DEL-EQ model, agency, highlights the extent to which individuals retain autonomy and decision-making power in environments increasingly governed by automation and artificial intelligence. While smart technologies are designed to optimize energy use through predictive algorithms and automated adjustments, meaningful engagement requires that users remain empowered to shape, modify, or even reject these system-driven choices [13, 24].

At a practical level, agency refers to the capacity of users to adjust settings, override defaults, and question algorithmic recommendations. For example, while a dynamic pricing system may suggest reducing heating during periods of peak demand, a resident may decide against this due to comfort needs or health considerations [36]. Similarly, users may override automated lighting schedules if they conflict with daily routines, or disable AI-driven appliance controls if they perceive them as intrusive [33, 37]. This ability to exercise discretion ensures that smart systems do not replace human judgment but rather complement it.

Agency also embodies critical engagement with automation. It is not sufficient for users to follow or resist system recommendations; they must be able to understand the rationale behind automated actions and evaluate their alignment with personal, social, or environmental priorities [1, 38]. Without such evaluative capacity, users risk becoming passive consumers subject to algorithmic authority. This risk is particularly acute in contexts where transparency is limited and algorithms operate as “black boxes” [20, 21].

Socio-economic conditions further shape agency. Renters, for instance, may lack the authority to install or modify smart technologies in their homes, while low-income households may face limited options for opting out of unfavorable pricing schemes or investing in alternative technologies [15, 39]. Age and education also play a moderating role, with older adults or individuals with limited digital literacy often feeling less confident in overriding or customizing automated systems [33, 40]. These disparities highlight that agency is not merely an individual trait but is deeply conditioned by structural and institutional arrangements.

Crucially, agency intersects with policy and governance frameworks. Empowerment requires not only transparent and adjustable interfaces but also regulatory protections that safeguard user rights. For example, policies mandating opt-in rather than default enrollment into dynamic pricing programs, or requiring explainability layers in AI-driven dashboards, can enhance user autonomy and prevent coercive reliance on automation [25, 41].

Within the DEL-EQ framework, agency is positioned as the bridge between knowledge and action: comprehension and interpretation provide the basis for understanding, but agency determines whether individuals can translate insights into meaningful, autonomous decisions. By foregrounding user autonomy, the model underscores that equitable participation in smart energy systems requires more than technical skills—it demands the recognition of users as active decision-makers within digital energy transitions.

4.4. Trust & Ethics

The fourth dimension of the DEL-EQ model, trust and ethics, underscores the social legitimacy and moral accountability of AI-driven energy systems, unlike comprehension, interpretation, and agency, which center on user capacities; this dimension highlights the relational dynamics between individuals and the technological systems that govern their daily energy decisions. In smart building environments, trust becomes a prerequisite for adoption: without confidence in the fairness, transparency, and security of automated systems, users are unlikely to engage meaningfully, regardless of their technical competence [25, 26].

A key element of trust lies in algorithmic transparency. AI-enabled platforms are increasingly making decisions that affect comfort, costs, and sustainability outcomes—such as adjusting HVAC schedules, altering tariffs, or reducing appliance loads during peak demand [1, 13]. When these decisions occur without explanation, they risk being perceived as arbitrary or manipulative. Transparency mechanisms, often referred to as "explainability layers", allow users to see why a recommendation is made, what data it draws upon, and what alternatives are available [20, 21]. By demystifying algorithmic processes, such mechanisms foster not only trust but also accountability.

Another central concern is data privacy and security. Smart buildings collect extensive information on occupancy, appliance use, behavioral routines, and even biometric indicators through IoT devices. This level of surveillance raises ethical questions about who owns the data, how it is stored, and whether it might be exploited for commercial or political purposes [42, 43]. Users who fear loss of control over their personal information may disengage entirely, thereby undermining energy efficiency goals. Strong data governance frameworks—emphasizing consent, anonymization, and limited data retention—are therefore essential to ensuring ethical stewardship of user information [41].

Trust and ethics are also conditioned by socio-demographic and cultural differences. Research indicates that older adults, lower-income households, and populations with lower levels of digital literacy often exhibit greater skepticism toward automated systems, perceiving them as intrusive or untrustworthy [41, 44]. In contrast, younger and more digitally fluent groups may demonstrate higher trust but remain vulnerable to overreliance, accepting automated recommendations without critical evaluation [39]. Both extremes present risks: distrust can lead to exclusion, while uncritical trust may diminish user agency. Addressing these disparities requires culturally sensitive engagement, inclusive design practices, and proactive communication strategies tailored to different user groups [14, 33].

Finally, embedding ethics into smart energy governance involves acknowledging the justice dimension of digital transitions. Without explicit safeguards, automation can reproduce structural inequalities by privileging those with advanced literacy and access while marginalizing vulnerable communities [2, 15]. Ethical frameworks must therefore move beyond individual behavior to include systemic accountability, ensuring that technologies serve collective well-being rather than exacerbate social divides. This requires participatory design processes, regulatory oversight, and continuous monitoring of algorithmic fairness [45].

Within the DEL-EQ framework, trust and ethics serve as the normative anchor, ensuring that smart energy systems are not only technically effective but also socially just. By addressing privacy, transparency, and fairness, this dimension ensures that digital energy literacy is inseparable from the broader pursuit of equity and energy justice in the age of smart buildings.

Fig. (**1**) illustrates how DEL-EQ extends the classical model by incorporating comprehension, interpretation, agency, trust, and ethics, while simultaneously embedding equity and digital competencies. This comparison highlights that the DEL-EQ framework does not replace but rather expands upon the classical dimensions of energy literacy by integrating digital, behavioral, and ethical competencies necessary for AI-enabled smart building contexts.

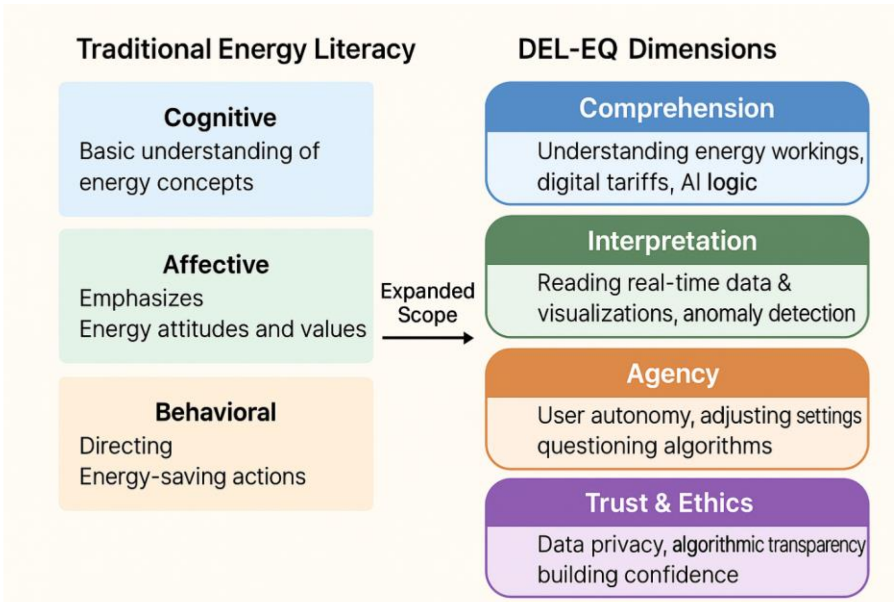

Figure 1: Comparison of classical energy literacy dimensions with the DEL-EQ framework.

4.5. Moderating Factors

The effectiveness of the DEL-EQ model is shaped not only by individual competencies in comprehension, interpretation, agency, and trust but also by a set of moderating factors that determine how these competencies can be acquired and exercised in practice. These factors operate across three interrelated levels—individual, technological, and community—and significantly influence the inclusiveness and equity of digital energy transitions.

4.5.1. Individual Factors

At the individual level, age, income, education, technological exposure, and housing tenure critically shape engagement with smart energy systems. Age is a consistent determinant: older adults are often less confident in interacting with digital dashboards, mobile applications, or AI-driven devices due to physical limitations, unfamiliarity with digital tools, or reduced exposure to ICT during their formative years [33, 40]. These constraints contribute to lower adoption rates and weaker engagement, even in technologically advanced building environments [2].

Income is another decisive factor. Households with higher income can more easily invest in smart appliances, high-speed internet, and complementary digital devices, while low-income households may face constraints in accessing or maintaining such systems [43]. They may also have limited flexibility in responding to dynamic pricing schemes—for instance, being unable to shift consumption to off-peak hours due to rigid work schedules or inadequate insulation [14].

Education strongly correlates with energy and digital literacy. Those with limited educational backgrounds may struggle with technical jargon, data interpretation, or the cognitive demands of algorithmic transparency [46, 47]. By contrast, higher education levels are associated with greater awareness of sustainability and stronger capabilities to interpret system feedback [18].

Housing tenure also introduces asymmetries: renters typically have less authority to install or modify smart systems and may have reduced incentives to engage with energy optimization if utility costs are included in rent agreements [15, 39]. These socio-demographic disparities underscore the need to tailor smart energy policies and interventions to diverse user conditions.

4.5.2. Technological Factors

The design and architecture of smart building systems function as powerful moderators of digital energy literacy. Smart buildings that conceal energy management entirely within automated systems limit opportunities for users to learn and engage, whereas transparent, interactive, and customizable interfaces enhance user understanding and participation [48, 49].

Interface usability is particularly critical. Dashboards or applications overloaded with technical detail, unclear feedback loops, or non-intuitive icons discourage engagement, especially among older users or those with lower digital literacy [34, 35]. By contrast, interfaces designed with universal accessibility principles, such as multilingual options, visual and auditory prompts, and screen-reader compatibility, can democratize access to DEL [50].

The interoperability of technologies also matters. When smart devices and platforms operate in silos, requiring multiple logins or fragmented applications, users often experience frustration and disengagement [51]. Conversely, seamless integration across devices fosters confidence and reinforces learning. In this way, technological design is not merely a neutral infrastructure but an active determinant of whether DEL can develop equitably across user populations [1, 13].

4.5.3. Community and Societal Factors

Beyond individual and technological conditions, community-level support mechanisms play a vital role in mediating the development of DEL. Structured digital literacy programs, peer-to-peer workshops, and training sessions organized by local governments, housing associations, or NGOs can significantly enhance user capacity to engage with smart energy systems [52, 53].

Trusted intermediaries such as social workers, educators, and community energy champions are particularly effective in bridging the gap between technical information and user comprehension, translating complex system outputs into culturally and linguistically accessible knowledge [54]. Community-driven approaches, including participatory design projects, energy cooperatives, or neighborhood energy forums, further promote a sense of ownership and strengthen trust in AI-driven systems [55].

Policy frameworks can reinforce these efforts by mandating inclusive engagement measures during technology rollouts—such as free internet access in public housing, mandatory orientation sessions, or funding for community-based energy literacy initiatives [56]. Without such structural support, smart energy transitions risk reproducing existing inequalities rather than correcting them [13, 49].

4.5.4. Synthesis

In the DEL-EQ framework, moderating factors highlight that digital energy literacy is not a purely individual attribute, but a context-dependent construct shaped by socio-demographic, technological, and community conditions. At the individual level, inequalities in age, income, education, and housing determine baseline access to resources. At the technological level, design and usability either facilitate or obstruct engagement. At the community level, support mechanisms and participatory structures enable inclusive learning and sustained adoption. Recognizing these moderators is essential for ensuring that the promise of smart energy systems does not reinforce existing disparities but instead contributes to a more equitable energy future.

As illustrated in Fig. (**2**), the model positions comprehension, interpretation, agency, and trust & ethics as core literacy dimensions, surrounded by moderating factors at the individual, technological, and community levels, and linked to four key policy and design implications for equitable adoption in AI-enabled smart buildings. The DEL-EQ framework is conceptualized as a layered model that integrates core literacy dimensions, moderating factors, and policy implications, thereby bridging technical efficiency with social equity.

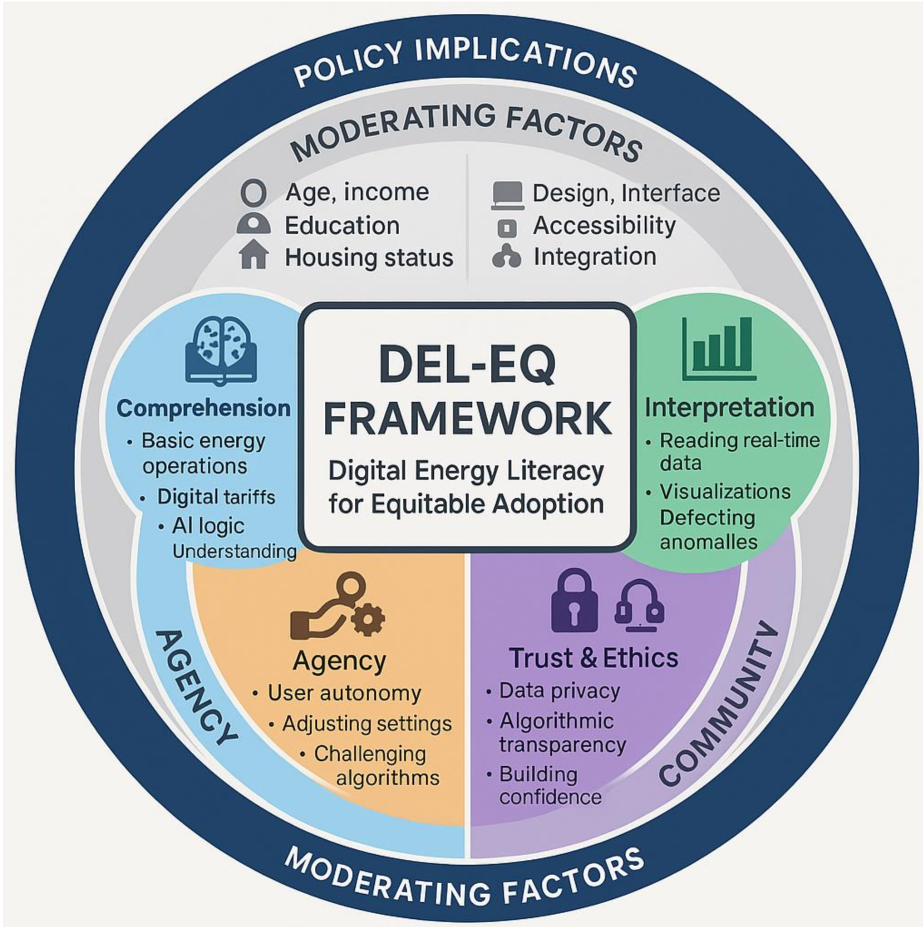

Figure 2: The DEL-EQ (Digital Energy Literacy for Equitable Adoption) framework.

Importantly, the DEL-EQ dimensions operate in a sequential and interdependent manner: comprehension is the foundation upon which interpretation builds; interpretation enables informed agency; and sustained engagement requires trust & ethics. Moderating factors influence these relationships by either facilitating or constraining progression between dimensions. For example, inadequate interface design (a technological factor) may prevent comprehension from translating into interpretation, while low trust (a community factor) may nullify agency. This causal logic highlights DEL-EQ as a dynamic, layered system rather than a set of isolated capacities.

4.6. Operationalization of DEL-EQ

To facilitate empirical validation, each DEL-EQ dimension can be translated into measurable indicators:

- Comprehension: knowledge of smart system functions, tariff structures, and energy metrics (e.g., correct interpretation of kWh, peak/off-peak costs).
- Interpretation: ability to correctly identify trends, anomalies, and actionable insights from dashboards or mobile apps (e.g., scorecards based on visualization literacy tests).
- Agency: degree of control and override capacity exercised by users (e.g., frequency of manual adjustments, confidence in altering system settings, survey-based perceived autonomy scales).
- Trust & Ethics: user-reported confidence in AI systems, awareness of data privacy, and evaluation of explainability layers (e.g., Likert scales on fairness, transparency, and perceived ethical safeguards).

These indicators provide the basis for a hierarchical evaluation system, enabling future empirical research to test the DEL-EQ framework systematically. For example, a household interpreting a dynamic tariff dashboard (interpretation) may choose to override an automated appliance schedule (agency), while also evaluating whether the recommendation aligns with their comfort and privacy preferences (trust & ethics). These operational pathways transform DEL-EQ from a conceptual framework into a set of testable and policy-relevant competencies (Table **1**).

Table 1: Core DEL-EQ dimensions and example indicators.

Dimension	Definition	Example Indicators	Illustrative Case
Comprehension	Foundational knowledge of digital energy systems and tariffs	Correctly interpret kWh readings; awareness of dynamic pricing	Understanding off-peak washing machine use
Interpretation	Ability to interpret real-time dashboards and feedback	Identify anomalies or trends in dashboards	Detecting higher HVAC use during the winter months
Agency	User autonomy and override capacity in AI-mediated systems	Frequency of manual adjustments; perceived control	Overriding automated thermostat settings for comfort
Trust & Ethics	Confidence in AI fairness, transparency, and data privacy	Awareness of explainability layers; trust in data governance	Accepting the tariff change due to a transparent rationale

5. Discussion

5.1. Comparison with Existing Literature

The DEL-EQ model builds directly on classical energy literacy frameworks, traditionally conceptualized through cognitive, affective, and behavioral dimensions [8-10]. These frameworks emphasized awareness of energy systems, pro-environmental values, and conservation actions, but largely overlooked the digital and interactive competencies now required in AI-driven environments. By introducing comprehension, interpretation, agency, and trust & ethics as core dimensions, DEL-EQ responds to the increasing demand for digital skills, algorithmic awareness, and socio-ethical engagement in smart building contexts.

This approach aligns with calls for more data- and interface-oriented literacy in recent work [12, 13], and supports the recognition that algorithmic transparency and behavioral responsiveness are essential for meaningful participation [20, 22]. At the same time, DEL-EQ departs from prior models by explicitly embedding equity, positioning digital literacy not as an individual attribute alone but as a socially mediated construct shaped by access, inclusion, and trust [14, 15]. This marks a divergence from much of the technically focused smart building literature, which often treats users as homogeneous actors without accounting for socio-economic disparities [2, 44].

Unlike adoption-focused frameworks such as the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT), which primarily emphasize perceived usefulness, ease of use, and behavioral intention, the DEL-EQ framework extends beyond initial acceptance to address the ongoing literacies required for meaningful and equitable participation. While TAM and UTAUT provide explanatory power for predicting technology adoption, they do not sufficiently capture competencies related to algorithmic transparency, user agency, and equity in digital contexts. DEL-EQ thus complements rather than replaces these models by situating adoption within a broader socio-technical and justice-oriented perspective.

While existing models of digital inclusion emphasize access and basic digital skills, classical energy literacy frameworks focus on cognitive, affective, and behavioral dimensions. In contrast, the DEL-EQ framework explicitly integrates algorithmic transparency, user agency, and trust & ethics as non-negotiable capacities for participation in AI-mediated energy systems. Unlike TAM and UTAUT, which primarily address adoption intentions and user acceptance, DEL-EQ extends the analysis to long-term engagement, equity, and justice outcomes. This positions DEL-EQ not as a replacement for these models but as a justice-oriented and AI-specific extension that situates adoption within broader socio-technical and normative processes.

5.2. Theoretical Implications

The model advances debates on energy citizenship by reconceptualizing users as more than consumers responding to tariffs. Instead, DEL-EQ frames them as active participants capable of questioning, modifying, and co-shaping energy systems [25]. This contributes to socio-technical participation theories that stress the need for inclusive engagement in infrastructure transitions [52]. Furthermore, the trust & ethics dimension resonates with the growing literature on AI ethics and algorithmic accountability, emphasizing transparency, data privacy, and fairness as non-negotiable foundations of public legitimacy [21, 41, 45].

By integrating behavioral, cognitive, and normative elements, DEL-EQ provides a framework that bridges engineering and social sciences, encouraging interdisciplinary collaboration. For instance, while engineers focus on optimizing smart building efficiency, social scientists can highlight issues of equity, trust, and user agency, ensuring that efficiency gains do not exacerbate inequality [49, 53].

5.3. Risks and Challenges

The findings highlight critical risks of algorithmic exclusion. When interfaces are inaccessible, data feedback is overly complex, or algorithms are opaque, users lacking advanced digital or interpretive skills may be marginalized. Vulnerable groups—such as older adults, renters, and low-income households—face particular disadvantages in benefiting from cost savings or efficiency opportunities [33, 40]. Such dynamics risk reinforcing digital energy inequality, where technological innovation amplifies rather than mitigates socio-economic disparities [14, 37].

A second challenge concerns the erosion of user autonomy. While automation promises efficiency, it may reduce user agency if individuals cannot override or question algorithmic decisions [24, 36]. This tension between efficiency and autonomy echoes broader debates in human–AI interaction, raising concerns that an uncritical reliance on automation could weaken active citizenship in energy transitions.

5.4. Bridging Dimensions

By foregrounding both digital competence and equity, DEL-EQ bridges otherwise siloed discussions between social sciences and engineering disciplines. While technical studies demonstrate the optimization potential of AI-enabled buildings [1, 44], they often neglect the human and social dimensions of adoption. Conversely, social science research has highlighted issues of inequality and participation but seldom provided systematic frameworks for literacy in AI-mediated contexts [54, 55]. DEL-EQ integrates these strands by positioning literacy as a socio-technical capacity—one that must be co-produced by users, designers, and policymakers alike.

While the present study emphasizes socio-technical literacy, integrating engineering insights is crucial for effective implementation. For instance, energy system efficiency, grid stability, and building automation protocols provide the technical foundation upon which user literacy develops. DEL-EQ does not dismiss these technical dimensions but reframes them within a user-centered equity lens. Future iterations of the framework should incorporate system-level technical indicators (e.g., interoperability standards, response latency of IoT devices, fault tolerance in AI controls) to ensure that literacy dimensions remain grounded in engineering realities.

5.5. Limitations

Several limitations of this study must be acknowledged. First, the DEL-EQ framework is conceptual and has not yet been empirically validated. While grounded in an integrative review, the model requires testing across different building typologies (e.g., public housing, student dormitories) and national contexts to assess its applicability and robustness [49]. Second, the review is restricted to English-language literature, which may underrepresent perspectives from regions where digital divides are most pronounced. Third, while the model highlights moderating factors, it does not quantify their influence; future research should employ mixed-methods approaches, combining surveys, ethnographic studies, and behavioral experiments to measure how age, income, education, and interface design concretely shape digital energy literacy.

Despite these limitations, the DEL-EQ framework provides a valuable foundation for future interdisciplinary research and policy. It identifies competencies that must be fostered, risks that must be mitigated, and equity dimensions that must be prioritized to ensure that smart building technologies contribute to just and sustainable energy transitions.

As a conceptual framework, DEL-EQ does not yet incorporate empirical data. This is a deliberate choice given the nascent state of AI-enabled smart building adoption. Nevertheless, this limitation constrains external validity: without testing in real-world contexts, the framework remains theoretical. Explicit acknowledgment of this boundary highlights the necessity for interdisciplinary collaboration to transition from conceptualization to implementation.

6. Conclusion

6.1. Key Findings

This study has proposed the Digital Energy Literacy for Equitable Adoption (DEL-EQ) model as a comprehensive framework to address the inadequacies of classical energy literacy in the era of smart buildings. By incorporating comprehension, interpretation, agency, and trust & ethics, the model expands literacy from a narrow focus on knowledge and behavior toward a multidimensional construct that captures digital, cognitive, and normative capacities.

The central conclusion is that smart building technologies hold the potential to empower individuals and communities, but without deliberate attention to equity, they also risk deepening digital energy divides. DEL-EQ highlights that literacy in this context cannot be reduced to technical competence; it must be understood as a socially mediated capacity shaped by inclusiveness, accessibility, and trust.

6.2. Policy and Design Implications

The findings underscore the need for policy and design measures that place equity at the center of smart energy transitions. Four key directions emerge:

- **Literacy thresholds:** Establishing minimum digital competence benchmarks to ensure that no user is excluded from participation.
- **AI explainability layers:** Integrating transparent and user-friendly explanations of algorithmic decisions into energy dashboards and applications.
- **Community-based literacy training:** Providing locally organized training and support mechanisms, particularly for vulnerable groups, to enhance digital energy literacy.
- **Inclusive design principles:** Developing accessible interfaces with multi-language options, visual and auditory cues, and universal accessibility features that accommodate diverse literacy levels and user needs.

Fig. (**3**) illustrates how the model translates into four actionable directions for equitable smart energy adoption: literacy thresholds, AI explain ability layers, community-based training, and inclusive design principles. These findings emphasize that the DEL-EQ framework not only advances theoretical understanding but also provides clear, actionable pathways for policymakers and designers to prevent digital energy inequality and support inclusive adoption.

- Literacy thresholds: Governments could establish baseline digital energy literacy benchmarks through standardized assessments, similar to existing financial literacy surveys, and require utilities to provide accessible training when users fall below these thresholds.
- AI explainability: Regulators can mandate “explainability layers” in building management dashboards, providing tiered explanations (basic for lay users, advanced for technical audiences).

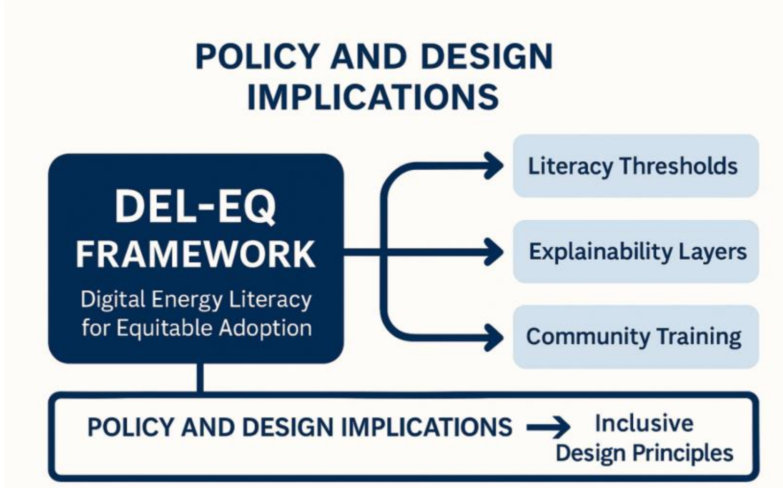

Figure 3: Policy and design implications of the DEL-EQ framework.

- Community-based training: Local municipalities and housing cooperatives can implement peer-to-peer “energy mentor” programs with measurable key performance indicators such as training uptake and reduction in digital exclusion gaps.
- Inclusive design: Cost–benefit analyses can guide investments in multilingual interfaces, accessibility tools, and cross-platform integration, ensuring that inclusive design is not treated as optional but as a compliance requirement.

6.3. Future Research

Future studies should focus on validating and refining the DEL-EQ model in empirical settings. This includes testing the framework across different building typologies, such as public housing, commercial complexes, and student residences, as well as in diverse national and cultural contexts. Comparative research could shed light on how socio-economic and cultural variations shape digital energy literacy.

In addition, behavioral experiments exploring nudging strategies, feedback design, and long-term engagement patterns would contribute to a deeper understanding of how users interact with AI-driven systems. Ultimately, interdisciplinary approaches that combine engineering, social sciences, and policy studies will be essential to ensure that digital energy literacy evolves as both a technical and a social capacity, capable of supporting equitable and sustainable energy futures. Future research should adopt a multi-stage validation strategy, beginning with the survey-based operationalization of DEL-EQ indicators, followed by controlled experiments that test comprehension and interpretation tasks, and culminating in field trials conducted across public housing or university dormitories. Mixed-methods approaches—combining quantitative literacy scores with qualitative ethnographic observations—can further refine causal mechanisms within the model. While this study is conceptual, future work should include pilot studies or case-based empirical validation of the DEL-EQ framework. For instance, testing DEL-EQ indicators in public housing or university dormitories could reveal how comprehension, interpretation, agency, and trust differ across socio-demographic groups. Similarly, small-scale pilot programs could evaluate whether community-based training improves residents’ ability to engage with AI-enabled dashboards. Such empirical testing is critical for refining DEL-EQ and demonstrating its practical value.

Conflict of Interest

The authors declare that they have no relevant financial or non-financial competing interests to disclose.

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