ISSN: 2347-7431
EPRA International Journal of Climate and Resource Economic Review
-Peer Reviewed Journal
Volume: 14 | Issue:2 |February 2026 || SJIF Impact Factor (2026): 8.714 || Journal DOI: 10.36713/epra1213

ENERGY EFFICIENCY IN U.S. CONSTRUCTION: A SYSTEMATIC REVIEW AND THEMATIC SYNTHESIS OF GREEN BUILDING TECHNOLOGIES AND PERFORMANCE OUTCOMES

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Article DOI: https://doi.org/10.36713/epra26270
DOI No: 10.36713/epra26270

ABSTRACT--
Background: *Buildings account for a high share of U.S. energy use; therefore, the construction industry is a key player in enabling U.S. national decarbonization and grid demand reduction.*
Objective: *This review makes a systematic and thematic synthesis of quantitative evidence regarding the implementation of green building technologies in buildings deployed in the U.S. from 2011-2025, with an emphasis on metered or validated (through simulation) energy performance metrics.*
Methods: *Using a structured process for screening studies, selecting eligible studies, and evaluating design, 22 eligible studies were identified covering U.S. single-family homes, commercial offices, K-12 (including school campus) learning facilities, federal facilities, military bases, and campus case studies. Interventions were grouped either under HVAC/mechanical systems, building envelope retrofits, certification systems impact, renewable integration, and validated energy modelling.*
Results: *HVAC and control system upgrades, including packages validated by Lawrence Berkeley National Laboratory, were proven to have the highest and most consistent HVAC energy reductions (unit level at 57 - 61%). Residential Deep Energy Retrofits, evaluated by Less and Walker (2024), achieved an average net-site energy savings of 47% by making large airtightness improvements. Targeted envelope upgrades (storm windows, interior glazing, internal test surfaces, installation, etc.) were tested in Seattle historical homes and offset 22% of the HVAC load. In contrast, studies that measured LEED certification indicated high levels of predicted vs. actual performance variability, negligible average source-energy savings in federal and Chicago benchmarking cohorts, and, in some instances, 17% higher consumption in LEED-certified schools. Modelling studies by the National Institute of Standards and Technology Net Zero Energy Residential Test Facility confirmed that over-prediction errors as large as 25% were due to occupancy assumptions.*
Conclusion: *Targeted, metered, and commissioned technologies provide the most reliable energy-efficiency payback in high-performance construction in the United States. Certification, in the absence of sub-metering and commissioning, and ongoing validation, merely assures expectations but does not assure results.*
KEYWORDS: *Building Energy Efficiency, HVAC Controls, Retrofitting of Envelope, LEED- Performance Gap, NZEB Validation.*--

1.0 INTRODUCTION

Buildings are responsible for a significant portion of the energy used in the United States, and the construction sector is a big player in driving long-term operational demand. Recent studies confirm that residential and commercial buildings are jointly responsible for more than one-quarter of total end-use energy in the US, highlighting the centrality of both electricity and space conditioning loads associated with them (Langevin et al., 2021). Over the past two decades, efforts to reduce building energy use have accelerated through federal and state efficiency policies, national green building programs, and advances in high-performance construction technologies. Research efforts have focused on Energy Use Intensity (EUI) reduction, thermal performance, and decarbonization strategies of building operations supported by simulation and empirical research from national laboratories and academic institutions (Azari et al., 2024).

Technological interventions for energy-efficient buildings range from mechanical systems, envelope components, digital controls, to distributed energy generation. High efficiency HVAC systems, advanced insulation assemblies, high-performance glazing, and smart building automation are key technologies that have shown high potential for finding site and source energy savings if validated with measured consumption or developed through calibrated energy modelling from metered data (Azari et al., 2024). Programs such as LEED and ENERGY Star have institutionalized targets as measures of efficiency, but questions arise about the scale of actual program performance improvements that are due to certification pathways. While studies of simulations and model-based assessments provide additional and up-to-date information for efficiency scenarios, metered and utility-validated quantitative results, including percent energy savings and documented changes in EUI on reduction, are earmarked to estimate and serve as a reliable indicator of real building function (Leite Ribeiro et al., 2025).

Previous literature reviews of green building in the United States have often focused on policy trends, occupant behaviour, and factors related to technology adoption. Still, very few have been systematically filtering for quantitative energy performance metrics based on empirical metered data or validated simulations. This leaves a critical gap in the synthesis of the measurable performance outcomes across the varied building typologies in US construction. To bridge this gap, the current systematic review analysis is conducted, a collection of peer-reviewed publications published between 2011 and 2025, strictly focusing on U.S. buildings, quantitative energy efficiency effects, and green building technology that would affect performance results. Specifically, that theory synthesizes evidence on HVAC and mechanical efficiency, high-performance building envelopes, building automation and control systems, integrating renewable energy, the effectiveness of certification systems, and validated modelling approaches reporting quantitative energy performance. By giving the uppermost priority or meta-defined empirical metrics and validated simulation results, this review offers a strict comparison of the performance result outcomes to establish directional technology influence and sample back reliability and evidence-based matters in national green building research and practice.

2.0 METHODS

2.1 Protocol and Study Design

This systematic review protocol was developed and implemented to synthesize empirical evidence of energy efficiency performance outcomes related to green building technologies that are used in construction in the US. The review was carried out in accordance with the principles of systematic evidence synthesis, as described in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (Page et al., 2021), to ensure rigour, transparency, and reproducibility. Although this review was not prospectively registered, a structured protocol was created before study screening in order to guide the search strategy, evaluation of eligibility, data extraction, and synthesis.

2.2 Eligibility Criteria

Studies were considered eligible if they **(1)** considered energy efficiency/energy performance outcomes in buildings built or retrofitted in the United States between 2011 and 2025, **(2)** considered at least one green building technology (e.g. HVAC systems, insulation, glazing, building automation systems, renewable energy integration, or certification systems of LEED or ENERGY Star, etc.), **(3)** reported quantitative energy performance metrics including but not limited to Energy Use Intensity (EUI) or percent energy savings, and **(4)** derived outcomes from metered/billing data or validated simulation/modelling approaches. Eligible buildings included residential, commercial, and institutional typologies. Only publications that were written in English and contained empirical results or validated simulation findings with quantitative metrics were included. Studies were excluded if they **(1)** were conducted outside of the United States, **(2)** did not present quantitative energy performance outcomes, **(3)** were theoretical, getting policy-only or qualitatively analysed without validated performance metrics, or **(4)** focused on off-building-related energy efficiency applications (i.e., transportation or manufacturing sectors).

2.3 Sources of Information and Search Strategy

A targeted and expanded literature search was carried out using various bibliographic online databases to identify the peer-reviewed academic publications supported by national laboratory reports and validated case studies to provide additional evidence coverage. The main sources of information were the scholarly indexing platforms Scopus, Web of Science Core Collection, and the public academic repository Google Scholar, as well as US national research outputs from the national laboratories of the US Department of Energy, such as the research outputs published by the research institutions National Renewable Energy Laboratory and Lawrence Berkeley National Laboratory. The search was a combination of controlled vocabulary and keyword strings relating to energy efficiency, building performance, measured energy use, simulation validation, HVAC systems, high-performing envelopes, building automation, renewable energy integration, and certification frameworks. The final search syntax was in the following terms: "energy efficiency," "energy use intensity," "EUI," "energy savings," "LEED," "ENERGY star," "HVAC performance," "building envelope efficiency," "insulation retrofit," "glazing energy performance," "building automation systems," "renewable energy in buildings," "US construction," and

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"retrofitted or new building energy performance," Boolean operator (AND/OR) and publication year range (2011-2025) filters. A structured screening pool was created for retrieved records, which were all imported for staged evaluation.

2.4 Selection and Screening Process of Study

Search results were screened in a multi-stage process with the purpose of applying screening eligibility criteria with precision. In a first step, a removal of duplicates was performed based on the use of automated mechanisms (Zotero) and manual checks. Second, screening of titles and abstracts was carried out in order to rule out studies that were clearly ineligible because of geography, language, and the lack of quantitative building energy performance measures. Third, full-text articles were considered to ensure **(1)** U.S.-based building relevance, **(2)** inheritance of data metered/billing that was valid simulation outcomes, and **(3)** reporting of quantitative metrics (e.g., EUI, percent savings, or validated modelling outcomes). Screening disagreements were resolved based on direct consensus discussion instead of third-party adjudication in order to ensure there is more methodological consistency. Only final validated studies were included in the evidence synthesis.

2.5 Extraction of data and Data Items

A structured data extraction framework was created before review synthesis to ensure standardization of the capture of quantitative and contextual performance data. The extracted data fields were author(s) and Year, Study Type or U.S. Construction Sector, Green Building Technology/Strategy, and Key Performance Outcome or Finding. Extraction was completed manually in a standardized tabular structure so that studies could be compared across studies and thematically grouped.

2.6 Thematic Classification and Synthesis of the Evidence

Included studies were thematically grouped into primary technology or intervention focus to allow for the structuring of a qualitative and quantitative evidence synthesis. The themes predefined were HVAC and mechanical systems, building envelope efficiency strategies (insulation, air sealing, and high-performance glazing), integration of renewable energy in buildings, building automation and control systems, certification system impact studies (eg, LEED, ENERGY Star), and validated modelling/simulation studies reporting outcomes of energy performance. Findings across studies were compared descriptively in terms of reported performance metrics and the contextual features of buildings. Due to the broad methodological heterogeneity of the variation of measurement approach, modelling assumptions, technology combinations, and building typologies, statistical meta-analysis was not a priority, and emphasis was given to validated quantitative outcome comparison, directional consistency of energy performance impact, and identification of clusters of influential evidence.

2.7 Quality Considerations

Although not assessed according to a formal risk-of-bias scoring using a numerical scale, required as part of the measured or validated simulation, included studies were required to have quantitative measures, and prioritisation in screening was given to peer-reviewed outputs and national laboratory reporting to maximise evidence reliability. Influential papers were considered depending on recurrence in references, visibility in databases, and adoption in the national US energy efficiency discourse.

3.0 RESULTS

3.1 Study Characteristics

A total of 22 studies met the inclusion criteria, spanning the publication period from 2011 to 2025. The included literature encompasses a diverse range of U.S. building typologies, including commercial offices, K–12 schools, federal facilities, and single-family residential units. The evidence base consists of large-scale empirical analyses of billing data, validated field tests from national laboratories (e.g., LBNL, PNNL), and post-occupancy evaluations. A comprehensive summary of the included studies, their specific interventions, and key validated performance outcomes is presented in **Table 1**.

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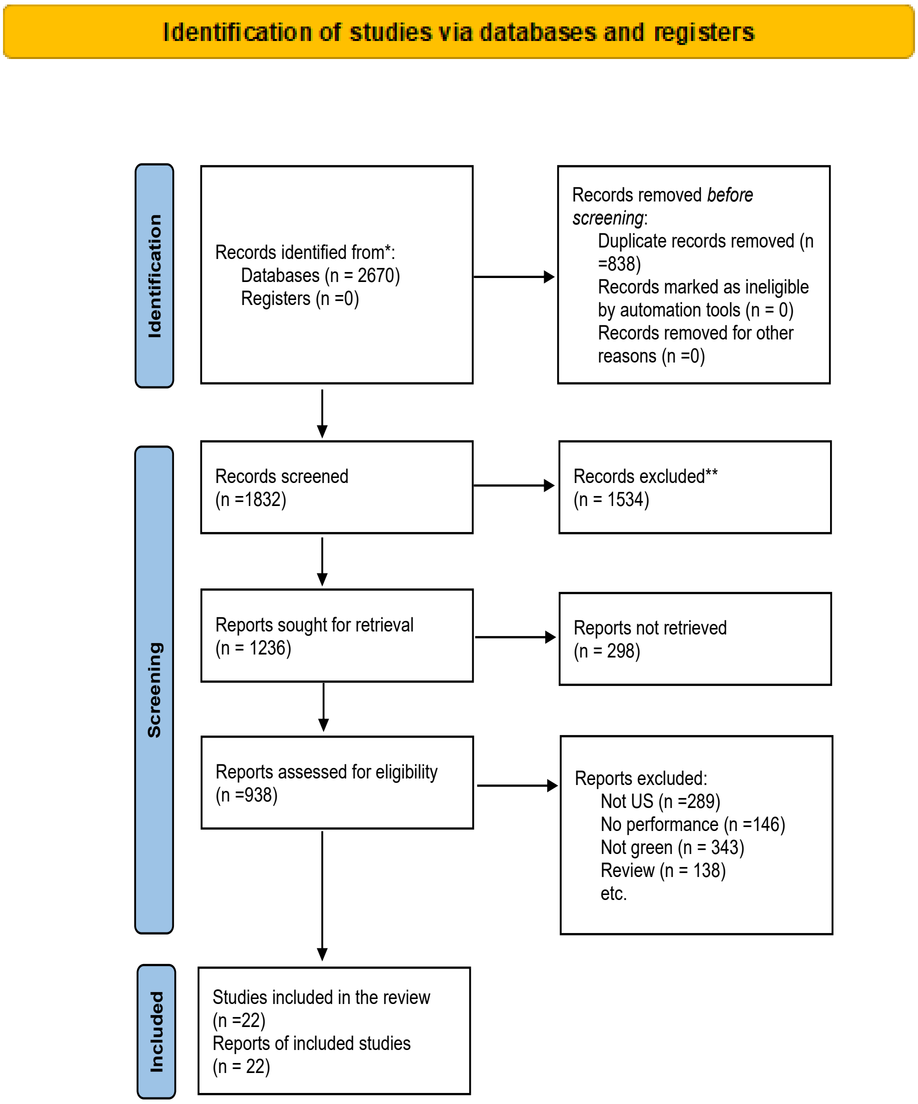

Figure 1 PRISMA flow diagram summarizing the study selection process.

Table 1. Characteristics and Key Findings of Included Studies

Author(s) & Year	Study Type/U.S. Construction Sector	Green Building Technology/Strategy	Key Performance Outcome/Finding
Less and Walker (2024)	Meta-analysis of 116 single-family homes in the U.S.	Deep Energy Retrofits (DER) (e.g., airtightness, insulation)	Achieved average annual net-site energy savings of 47% and net-source energy savings of 45%. Reported a substantial 63% average reduction in airtightness.
Mathew et al. (2023)	Laboratory testing (LBNL) for U.S. Commercial Buildings	Rooftop Unit (RTU) Replacement Package (advanced controls, high-efficiency filters)	Demonstrated an average of 61% daily HVAC energy savings when applied in U.S. commercial buildings.
Langevin et al. (2021)	National technical potential assessment (U.S. Building Stock)	Building Energy Efficiency and Flexibility Measures	Co-deployment of efficiency and flexibility measures has the technical potential to avoid up to 742 TWh of annual electricity use and 181 GW of daily net peak load by 2030.
Clay, Severnini, and Sun (2021)	Empirical analysis of retrofitted U.S. Federal Buildings	LEED Certification for existing building retrofits	Found no statistically significant energy savings on average for LEED-certified federal buildings, but those with higher energy scores did show greater efficiency.

Chuang et al. (2021)	Residential Field Study (Southern California)	Active and Passive Cooling Approaches (heat pump water heaters, window films, cool coatings)	Reduced heat index hazard hours by 95-99% but increased total energy costs (20-60%) due to shifts in electricity demand.
Shin et al. (2019)	Case Study (Fort Hood Army Base, U.S. Office Building)	Net Zero Energy Building (NZEB) (high-performance envelope, efficient HVAC/lighting, PV)	The renovated NZEB portion achieved energy savings of 37% to 50% compared to the un-renovated portion of the building.
Liang, Qiu, and Hu (2019)	Survey of U.S. Commercial Buildings Facility Managers	LEED and Energy Star Certification	Identified the primary reasons for the energy performance gap as occupant behaviour, lack of sub-metering, and technology failure.
Scofield and Doane (2018)	Data-Driven Analysis (Chicago Benchmarking Data)	LEED Certification	Found LEED-certified buildings use no more source energy than similar conventional buildings; LEED-certified schools used 17% more source energy.
Goetzler et al. (2017)	U.S. DOE Technology Assessment (Commercial Buildings)	57 HVAC Technology Options	Commercial HVAC systems can save ~10% energy using advanced sensors, heat pumps, and system designs.
Hu (2017)	Literature Review & Case Study (Maryland K–12 School)	Energy Retrofit Strategies (e.g., space heating load reduction)	Confirmed that U.S. K–12 schools spend over $8 billion annually on energy. Recommended space heating load reduction and air quality improvement as two of the most effective strategies.
Kneifel and Webb (2016)	Statistical Modelling (NIST NZERTF, U.S.)	Net-Zero Energy Building (NZEB) statistical prediction model	Net-zero and highly efficient residential buildings are achievable with existing conventional technologies.
Chen, Kleinman, and Dial (2015)	Case Study (U.S. University Campus)	LEED Certification and Energy Modelling	Found one of three LEED buildings consumed twice the predicted energy usage, underscoring the gap between modelled design and actual operational performance.
Zarghami and Ahmad (2014)	Configurational Analysis of 1,248 U.S. Buildings	LEED Rating System	LEED underutilizes key sustainability categories and lacks regional specificity and credit clarity.
Katipamula et al. (2013)	Field-Test (Eight U.S. Building Sites)	Advanced Rooftop Control (ARC) Retrofit	Achieved an average of 57% reduction in normalized annual RTU energy consumption across the eight test sites.
Knox and Widder (2013)	Field Study (Single historic home in Seattle, WA)	Interior Storm Windows	Resulted in a 22% reduction in HVAC energy use and improved occupant thermal comfort.
Stoppel and Leite (2013)	Case Study/Review (U.S. Government Buildings)	Building Energy Model (BEM) Performance of LEED Buildings	Found that models over-predicted energy consumption in two studied buildings by 14% and 25% respectively, attributing error to incorrect assumptions like air-conditioning schedules.
Menassa et al. (2012)	Post-Occupancy Evaluation (U.S. Navy Buildings)	LEED Certification	Found that 9 of 11 LEED-certified U.S. Navy buildings failed to achieve the required 30% savings and generally showed *more* electricity consumption than national averages.
Blanchard et al. (2012)	Evaluation (Seven Pacific Northwest Homes)	Deep Energy Retrofits (DER)	Actual energy savings averaged 43%, which was *more* than the 31% modelled average, but still highlighted large discrepancies between modelled and actual performance.

Beauregard et al. (2011)	Post-Occupancy Evaluation (Seven New England LEED Homes)	LEED Certified Homes	Only ~50% of LEED commercial buildings meet predicted energy performance; gap between design and actual use
McCoy et al. (2018)	Longitudinal Study (U.S. Low-Income Households)	Green Building Incentives (Energy Efficiency measures)	Showed that green building incentives resulted in financial savings of $648 per year for low-income households, representing a 26.6%–37.5% reduction of energy expenditure.
Yu et al. (No Date)	Comparative Simulation/Field Test (Maryland, U.S. and 16 U.S. Climate Zones)	Variable Refrigerant Flow (VRF) vs. Variable Air Volume (VAV) Systems	VRF systems consumed between 27.1% and 57.9% less energy than central VAV systems in a Maryland office building case study. VRF generally saves more energy across U.S. climate zones, particularly in hot and mild climates.
Leite Ribeiro et al. (2025)	Systematic Review (Global/U.S. LEED Context)	LEED Certification Framework	Highlighted the significant energy performance variability in LEED-certified buildings, often influenced by occupancy and the gap between predicted and actual consumption, despite using U.S. standards like ASHRAE 90.1.

3.2 Green Building Certifications and the Energy Performance Gap
A major group of studies assessed the operational performance of LEED-certified buildings to realize a significant discrepancy between modelling in the design phase and actual energy consumption (Leite Ribeiro et al., 2025). Evidence with respect to the effectiveness of certification in reducing source energy is mixed. In a study of Chicago benchmarking data, LEED-certified buildings were found to use no less source energy than comparable conventional buildings: LEED-certified schools used 17% more source energy than their non-certified counterparts (Scofield & Doane, 2018). In a similar evaluation of U.S. Navy buildings, 9 of 11 LEED-certified facilities showed no success in meeting the 30% savings targets, and many of these buildings actually used higher than national averages for electricity (Menassa et al., 2012).

However, the "performance gap" does not look very clear through certification levels and scoring. While overall comparisons found there was no statistically significant amount of savings for federal LEED retrofits on average, buildings with higher energy scores in the certification framework did show greater post-certification efficiency (Clay et al., 2021). Discrepancies are often described as the result of modelling errors; for example, a case study of two federal residences (dormitories) found modelling errors that resulted in excess prediction of energy use by 14% to 25% with incorrect assumptions about occupancy and schedules (Stoppel & Leite, 2013). This was supported by campus-level data, in which twice the predicted energy was consumed by a LEED building (Chen et al., 2015), underscoring the disparity between simulated and real-life.

3.3 HVAC Systems and Advanced Controls
Interventions that focused on HVAC modernization and controls were shown to have the most consistent and high magnitude quantitative savings. In the case of laboratory testing of a full package of rooftop unit (RTU) replacement, involving sophisticated control methods and high-efficiency filters, it was proven that the overall facilities of the roof location involve distillation on 61% of the average compensation. Similarly, field tests of Advanced Rooftop Control (ARC) retrofits for eight sites led to a 57% reduction of normalized annual RTU energy consumption (Katipamula et al., 2013).

Comparative investigations of system typology further supported the changeover to decentralized high-efficiency systems. Variable Refrigerant Flow (VRF) systems were found to have energy consumption up to 27.1%-57.9% lower than central Variable Air Volume (VAV) systems in office settings, and the performance advantages of VRF systems were maintained in different US climate zones (Yu et al., 2016).

3.4 Building Envelope and Deep Energy Retrofits (DER)
Research on residential building envelopes has shown that deep energy retrofits (DER) offer huge energy demand reductions, although financial and behavioural factors have an impact. A meta-analysis of 116 single-family homes in the U.S. showed 47% average net-site energy savings and 45% net-source savings annum, which are largely attributed to an airtightness reduction of 63% (Less & Walker, 2014). Smaller-scale interventions also worked;

the installation of interior storm windows in a historic home led to a 22% decrease in energy use in the home's heating, ventilation, and air conditioning system (Knox & Widder, 2013).
From an economic perspective, the efficiency measurements of green materials used in poor housing were shown to yield $648 in financial savings each year per unit of housing, equating to a 26.6% to 37.5% reduction in annual residential spending on energy (McCoy et al., 2018). However, the impact of envelope upgrades can be reduced by the "rebound effect." One study found that when active and passive cooling upgrades led to a 95-99% decrease in heat index hazard hours, they sometimes increased the overall energy cost by 20-60%, because of changes in occupant consumption behaviour (Chuang et al., 2021).

3.5 Net Zero Energy and Connection to the Grid
Studies of Net Zero Energy Buildings (NZEB) validated the treatability of aggressive Net Zero Energy Buildings utilisation through a combination of high-performance envelopes with renewables integration (naturally, where modelling needs to be strong). At the Fort Hood Army Base, savings of 37% to 50% compared to the un-renovated section were achieved in the NZEB portion of an office building (Shin et al., 2019). Looking at more than just individual buildings, the co-deployment of the efficiency and flexibility measures throughout the U.S. building stock combined was estimated to hold up to 742 TWh of annual electricity use in 2030 (Langevin et al., 2021).

4.0 DISCUSSION
4.1 Overview of Energy Efficiency Performance
This empirical review combined information on energy efficiency outcomes of green building technologies in the U.S. construction industry. 22 studies were identified as eligible to be included in this review. The combined feature of synthesis is the demonstration that there is a dual reality with certain high-performance technologies and deep energy retrofits demonstrating consistent large magnitude energy savings, but contrasting with the highly variable operation of whole-building green certification systems. The most successful interventions had a focus on systems that were specific, measurable, and controllable, including advanced HVAC systems and specific envelope upgrades, which reported on energy savings that were consistently in the range of 22% to 61% (Knox & Widder, 2013; Mathew et al., 2023). On the other hand, evidence for the universality of the effectiveness of building certification in the absence of other maker-policy tools to encourage performance improvements is equivocal.

4.2 The Energy Performance Gap in Certification
One of the main conclusions from this review is the gap in "energy performance" of buildings certified under programs such as LEED that remains ever-prevalent (Liang et al., 2019). Several studies confirmed that the mere act of certification is not a good translation to predicted energy savings. Data analysis showed that, on average, LEED certified buildings in Chicago used no more source energy than their conventional counterparts (LEED schools, in one instance, using 17% more) (Scofield & Doane, 2018). This gap is further supported by post-occupancy evaluations of federal facilities, in which nine out of eleven certified Navy buildings failed to achieve their 30% savings targets (Menassa et al., 2012) and in which data from the campus-level indicated that one LEED building used twice its predicted usage(Chen et al., 2015).

The contributing factors are complex, highlighted in the extraction of the data. Model errors, due to wrong assumptions related to occupancy and scheduling, are an important technical reason, so models tend to over-predict consumption by as much as 25% (Stoppel & Leite, 2013). Critically, the role of occupant behaviour is non-trivial (Liang et al., 2019). This means that certification frameworks must place themselves on a stronger footing concerning operational commissioning, sub-metering, and long-term energy management, instead of placing themselves on a very large foundation concerning design phase modelling (Leite Ribeiro et al., 2025). The nuance, however, is that the buildings scoring more highly on internal energy within the certification system did show greater levels of efficiency, suggesting that strong pursuit of the energy credits is a key, rather than minimal, compliance (Clay et al., 2021).

4.3 High-Impact Technologies- HVAC and Envelope
In radical contrast to the variability found in the results from certification activities, targeted technologies have shown high and reliable performance impacts. The modernization of the HVAC and mechanical systems is confirmed as a major lever for efficiency in the US commercial sector. Field and lab tests consistently showed that advanced controls and high-efficiency replacements (for RTUs), such as Advanced Rooftop Controls (ARC), produced typical savings in the RTU energy consumption +57% to 61%. The technological superiority of

decentralized systems, such as Variable Refrigerant Flow (VRF), was also endorsed based on energy consumption, reducing 27.1% to 57.9% in comparison to conventional VAV systems (Yu et al., 2016).
For the residential sector, the effectiveness of Deep Energy Retrofits (DER), combining the air sealing and envelope upgrades, is well supported. Meta-analyses revealed DER to achieve a consistent average net site energy savings of 47% (Less & Walker, 2014). This validates the fundamental principle of the maximum efficiency that reducing load (through a tighter envelope) is a prerequisite. Moreover, these green building measures are economically viable, leading to actual savings on an annual basis for households, especially for low-income housing(McCoy et al., 2018). However, findings also caution that musical envelope efficiency can be eroded by the rebound effect: the enhanced thermal comfort causes enhanced energy-consuming behaviours (Chuang et al., 2021)

4.4 Performance of Whole Buildings and Systems Integration

Studies of Net Zero Energy Buildings (NZEBs) and detailed strategies provide information that holistic and integrated strategies can enable the most aggressive performance goals to be achieved, especially if validated data is utilized. The positive renovation of a US office building in NZEB saved up to 50% compared to its baseline (Shin et al., 2019). Furthermore, the result of the national evaluation of the effectiveness of the combination of efficiency and flexibility measures highlights the effect at the macro-level, which would indicate enormous technical potential to avoid 742 TWh of annual electricity use in the entire building stock in the United States(Langevin et al., 2021). These results strengthen the intuitive conclusion that the greatest quantity of energy impacts in the field is seen when high-efficiency system components are combined in a system-level approach directed toward deep decarbonization and grid responsiveness.

4.5 Limitations of the Review

This systematic review was constrained by a lack of homogeneity in the methodological quality of the included studies. Due to wide variance in building typologies (commercial vs. residential), climate zones, measures (metered data vs. validated simulation models), and the particular combination of technologies analyzed, statistical meta-analysis was not an option. Therefore, synthesis is based on a descriptive comparison of substantiated quantitative outcomes that seek the direction and magnitude consistency of reported savings. A second limitation is the inclusion of only English-language published evidence and the selective inclusion of any national laboratory-reported evidence or peer-reviewed published evidence, which, while adding strength to the coverage of the evidence, creates variability in reporting standards.

5.0 CONCLUSION

Green building technologies present a validated pathway to significant energy savings in U.S. construction, with HVAC controls and building envelope retrofits offering the most consistent and substantial quantitative returns. Moving forward, policymakers and practitioners should prioritize robust operational verification and data-driven management to close the observed energy performance gap in whole-building certification systems.

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