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BRIDGING ENERGY POVERTY, HOUSING COMFORT, AND HEALTH: A SYSTEMATIC REVIEW OF APARTMENT RENOVATIONS IN ROMANIA

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ABSTRACT: *The energy-efficient renovation of apartment buildings is a critical strategy for addressing energy poverty, enhancing housing comfort, and protecting public health in Romania's urban areas. This systematic review, following the PRISMA methodology, sought to map the spatial distribution and governance frameworks of renovation programs, evaluate the technical performance of energy efficiency measures, synthesize socioeconomic impacts on energy poverty alleviation, assess housing comfort outcomes across various intervention types, and examine the health effects associated with renovation practices. A com-prehensive literature search was conducted across Web of Science, Scopus, PubMed, and Google Scholar for studies published between 2015 and 2024, focusing on Romanian urban contexts and comparable European settings. The review identified an uneven geo-graphic distribution of energy retrofits, substantial energy savings of 30–70% resulting from optimized renovation strategies, and partial yet promising evidence of reduced energy poverty. Additionally, measurable improvements in thermal comfort and indoor environmental quality were observed, along with modest but suggestive health benefits, primarily inferred from European studies, such as reduced respiratory and cardiovascular risk. These findings underscore the necessity of integrated approaches that connect technical, socioeconomic, and health considerations to enhance the equity, sustainability, and effectiveness of energy renovation programs.*

Keywords: *energy renovation; energy poverty; housing comfort; health outcomes; apartment buildings; thermal comfort; indoor air quality.*

1. Introduction

1.1. Background and Context

The energy renovation of apartment buildings in urban Romania represents a critical convergence of climate policy, social equity and public health concerns [1]. The residential sector accounts for approximately 40% of the European Union's energy consumption and 36% of its greenhouse gas emissions, with multi-family buildings comprising a substantial portion of the total [2]. In Romania, the urgency to address residential energy inefficiency is intensified by several intersecting factors: an aging housing stock predominantly constructed during the communist era (1950-1989) with insufficient thermal performance [3], one of the highest rates of energy poverty in the European Union, affecting approximately 16% of households [4], and significant health disparities linked to inadequate housing conditions [5].

The Romanian apartment building stock exhibits characteristics that shape both the challenges and opportunities for energy renovations. Approximately 60% of urban residents live in multi-family buildings, most of which are constructed with prefabricated concrete panel systems that provide limited thermal insulation [6]. These buildings typically have U-values of 1.2-1.8 W/m²K for external walls, which exceed the current building code requirement of 0.28 W/m²K [7]. The combination of inefficient building envelopes, obsolete heating systems, and low household incomes compels residents to choose between maintaining thermal comfort and preserving financial stability [8].

Energy poverty in Romania differs from the patterns observed in Western Europe. While energy poverty in Western Europe often stems from high energy prices relative to income, in Romania, it arises from the combined effects of low absolute incomes, inefficient housing, and increasingly liberalized energy markets [9]. Zamfir et al. [10] reported that energy-poor Romanian households frequently underheat their homes to avoid unaffordable energy bills, resulting in indoor temperatures well below the

World Health Organization's recommended minimum of 18°C. This coping strategy has significant health consequences, particularly for vulnerable populations such as children, elderly residents, and individuals with chronic health conditions [11].

The governance framework for energy renovation in Romania is influenced by the dynamics of post-socialist transitions. The large-scale privatization of housing in the 1990s transferred ownership to individual households but left collective infrastructure, including building envelopes and heating systems, without clear governance structures [12]. Homeowner associations (HOAs), responsible for managing common properties, often lack the technical expertise, financial resources, and consensus-building mechanisms necessary for coordinated renovation initiatives [13]. This fragmented ownership arrangement creates collective action challenges that impede the implementation of renovations, even when subsidies are available [14].

1.2. Policy Context and Renovation Initiative

Since joining the European Union (EU) in 2007, Romania has implemented multiple energy renovation programs, primarily financed through EU Structural Funds and national co-financing [2]. The most notable initiative, launched in 2009, offered subsidies covering up to 80% of the renovation costs for eligible buildings [15]. Despite these efforts, implementation has been uneven, with renovations occurring in affluent neighborhoods and larger cities, while peripheral areas and smaller municipalities remain underserved [16]. Turcu [16] identified pronounced spatial inequalities in Bucharest's retrofit distribution, noting that central districts received a disproportionate share of investment compared to peripheral neighborhoods inhabited by vulnerable populations.

Recent European policy frameworks have increased the impetus for residential de-carbonization. The European Green Deal and Renovation Wave strategy has set ambitious targets to enhance the energy performance of buildings [2]. The recast Energy Performance of Buildings Directive (EPBD, 2024) introduced minimum energy performance standards, necessitating the extensive renovation of the lowest-performing buildings [17]. For Romania, achieving these targets will require increasing renovation rates from the current approximately 1% per year to at least 3%, while ensuring that interventions prioritize vulnerable households that are most affected by energy poverty [18].

1.3. The Energy Poverty-Health Nexus

Extensive research has demonstrated that inadequate housing conditions adversely affect health through multiple pathways [19]. Exposure to cold indoor environments in-creases cardiovascular strain, elevates blood pressure, and impairs immune function, thereby increasing the risk of respiratory infections and exacerbating chronic diseases [20]. Thomson and Snell [4] identified significant associations between energy poverty and poor self-rated health across 32 European countries, with particularly pronounced effects in Eastern Europe. Furthermore, mental health is negatively impacted; elevated energy costs, thermal discomfort, and social isolation due to cold homes contribute to increased anxiety and depression among residents [21].

Cold indoor environments negatively affect children's development, academic performance, and respiratory health [22]. Older adults are particularly vulnerable; evidence indicates that for each 1°C decrease below 18°C indoors, the risk of cardiovascular and respiratory mortality increases by 1.3% among individuals aged > 65 years [23]. In Romania, a substantial proportion of energy-poor households experience winter indoor temperatures between 12 °C and 15°C, thereby intensifying these health risks [10].

Indoor air quality is a critical determinant of health. Prior to renovation, many Romanian apartments exhibit high air leakage, which compromises energy efficiency but facilitates passive ventilation [24].

Renovation efforts typically increase building airtightness, enhancing thermal comfort but potentially diminishing air quality in the absence of adequate mechanical ventilation [25]. Evidence from other European countries indicates that poor ventilation after renovation can result in elevated indoor humidity, increased CO_2 concentrations, and greater mold prevalence [26,27]. These conditions pose significant health risks; mold exposure can induce or exacerbate asthma, and elevated CO_2 levels impair cognitive function and sleep quality [28].

1.4. Research Gap and Rationale

Despite the increasing volume of research on energy renovation, substantial gaps persist, constraining evidence-based policy development in Romania. Existing studies frequently address isolated aspects, such as technical performance, economic cost, and social acceptance, without integrating these dimensions [29]. This fragmented approach impedes a comprehensive understanding of how technical modifications, social determinants, and health outcomes interact to shape the effectiveness of renovations [30].

Research on the distribution of renovation programs across various regions and demographic groups is insufficient. Aggregate statistics may indicate overall success but often obscure substantial disparities in access and benefit distribution [31]. Further detailed investigations are required to identify program beneficiaries, assess whether vulnerable populations are adequately reached, and evaluate the effectiveness of geographic targeting [32]. The absence of research addressing equity considerations in Romania constitutes a significant knowledge gap [16,33].

Limited evidence exists regarding the health impacts of energy renovation in Central and Eastern Europe. Most available health data originate from Western Europe and English-speaking countries, which differ substantially in terms of housing typologies, climatic conditions, and health care systems. Consequently, the applicability of these findings to the Romanian context, which is characterized by distinct building structures, heating practices, and household requirements, remains uncertain [34]. Moreover, there is a notable absence of direct studies evaluating health outcomes in Romanian renovation initiatives.

The complexities associated with implementing renovations in post-socialist housing systems require further research. Romanian apartment buildings exhibit unique patterns of ownership, institutional arrangements, and social dynamics that differ markedly from those in Western Europe, where most research has been conducted [35]. Effective policy design necessitates a thorough understanding of how local factors influence renovation outcomes [13].

The relationship between energy renovation and climate adaptation remains unexplored. Existing research addresses reducing winter heating demand, while the increasing significance of cooling and summer overheating in Romanian urban areas due to climate change has received limited attention [36]. Renovation strategies should simultaneously address cold-related energy poverty and the emerging challenges associated with elevated temperatures; however, integrated solutions have been insufficiently examined [37].

1.5. Research Questions

This review addresses these gaps by investigating the following five research questions:

RQ1: Spatial Distribution and Governance: How are energy renovation projects distributed across Romanian cities, and which governance frameworks influence their implementation and accessibility? What barriers prevent vulnerable groups from accessing these programs?

RQ2: Technical Performance: Which energy efficiency measures have been implemented in Romanian apartment buildings, and what impact have they had on energy consumption, greenhouse gas emissions, and cost-effectiveness? How do these technical interventions affect the indoor environmental quality?

RQ3: Energy Poverty Alleviation: To what extent do energy renovation projects reduce energy poverty among the residents of Romanian apartment buildings? Which social and economic factors mediate the impact of renovations on household energy costs and vulnerability?

RQ4: Housing Comfort: How do energy renovations influence thermal comfort, indoor air quality, and overall living conditions in Romanian apartments? What trade-offs arise between improved thermal performance and ventilation?

RQ5: Health Outcomes: What evidence exists regarding the health effects of energy renovations on residents of Romanian apartment buildings? How applicable are the findings from other European countries to the Romanian context?

1.6. Objectives

The primary objectives of this review are as follows:

- Analyze the distribution and governance of energy renovations in Romanian apartment buildings, identify factors that facilitate or impede equitable access, and demonstrate the influence of institutional frameworks on these patterns.

- Compare the energy efficiency measures implemented in Romania and comparable European countries to evaluate their technical performance, cost-effectiveness, and impact on indoor environmental quality.
- Synthesize evidence regarding the social and economic impacts of energy renovations, with particular attention to energy poverty reduction, improvements in household fi-nances, and the distribution of benefits among various groups.
- Compare the effects of different renovation approaches to housing comfort, including thermal comfort, air quality, perceived housing quality, and resident satisfaction.
- Analyze health outcomes associated with energy renovations by examining direct evidence from Romania and relevant findings from broader European studies.

1.7. Significance and Contribution

This review provides several important contributions to the research and policy on energy renovation. It integrates technical, social, and health evidence, which are frequently examined in isolation, highlighting connections and trade-offs to inform more effective intervention design [38]. As most existing research centers on Western Europe, its findings may not be fully applicable to Central and Eastern European countries with distinct housing, governance, and social contexts [39]. By focusing on Romania and incorporating relevant international evidence, this review offers practical insights for policymakers operating in comparable settings.

2. Materials and Methods

2.1. Literature Search Strategy

A systematic literature search was conducted using multiple electronic databases to identify studies published between January 2015 and October 2024. The databases included the Web of Science (Core Collection), Scopus, PubMed/MEDLINE, Google Scholar, and ScienceDirect. Keywords and Boolean operators were organized into four primary conceptual groups:

Concept 1 (Intervention): "energy renovation" OR "energy retrofit" OR "thermal insulation" OR "building renovation" OR "energy efficiency" OR "building modernization" OR "thermal upgrade" OR "deep renovation" OR "building refurbishment."

Concept 2 (Setting): "apartment building" OR "multi-family housing" OR "residential building" OR "housing stock" OR "dwelling" OR "multistorey building" OR "social housing" OR "mass housing"

Concept 3 (Context): "Romania" OR "Bucharest" OR "Eastern Europe" OR "post-socialist" OR "transition economy" OR "Central Europe" OR "EU member states"

Concept 4 (Outcomes): "energy poverty" OR "fuel poverty" OR "housing comfort" OR "thermal comfort" OR "indoor air quality" OR "health" OR "well-being" OR "respiratory" OR "cardiovascular" OR "mental health" OR "governance" OR "policy"

The search strategy was tailored for each database, incorporating subject headings such as Medical Subject Headings (MeSH) terms in PubMed, when appropriate [40].

2.2. Inclusion and Exclusion Criteria

Studies were included if they met the following criteria: publication between 2015 and 2024 in peer-reviewed journals, conference proceedings, or grey literature such as re-ports, theses, or policy documents; focus on energy renovation or retrofitting of apartment buildings or multi-family housing; examination of Romanian or comparable European contexts with transferable findings; reporting of empirical data or systematic analysis on at least one outcome domain, including spatial distribution, technical performance, energy poverty, housing comfort, or health; and publication in English, Romanian, or provision of English abstracts.

Studies were excluded if they focused exclusively on new construction rather than renovation; examined single-family houses without relevance to multi-family buildings; were purely theoretical or modeling studies lacking empirical validation or policy relevance; were published prior to 2015; or constituted duplicate publications or conference abstracts without full-text availability.

2.3. Study Selection Process

The literature search and study selection processes adhered to the PRISMA 2020 guidelines [41], as illustrated in Figure 1.

Searches conducted in the Web of Science (n=892), Scopus (n=1,156), PubMed (n=485), and Google Scholar (n=314) identified 2,847 records. An additional 156 records were obtained from grey literature searches (n=78), reference list screening (n=52), and expert recommendations from Romanian energy efficiency researchers (n=26), resulting in a total of 3,003 records.

After removing 847 duplicates using EndNote and manual verification, 2,156 unique records remained for title and abstract screenings. Two reviewers independently assessed each record according to the inclusion and exclusion criteria of the study. In cases of disagreement, the reviewers discussed the case, and if necessary, a third reviewer was consulted to resolve discrepancies. This process yielded 309 full-text articles for detailed eligibility assessments.

The same two independent reviewers systematically evaluated the full-text articles using a complete set of inclusion and exclusion criteria. The primary reasons for exclusion included insufficient data on key outcomes (n=87), lack of focus on energy renovation interventions (n=54), absence of measurable health or comfort outcome indicators (n=32), methodological concerns affecting validity or reliability (n=15), and duplicate data from the same study group (n=10). Following this review, 111 studies met the criteria and were included in the qualitative synthesis.

Of the 111 studies included in the qualitative synthesis, 50 provided sufficient quantitative data, comparable outcome measures, and similar study designs and were eligible for the meta-analysis. These studies reported standardized metrics for energy use, thermal comfort, and health indicators, with adequate statistical details for quantitative pooling. The remaining 61 studies provided valuable qualitative insights, contextual information, and findings using diverse metrics that could not be quantitatively combined but nonetheless enhanced the overall understanding of the research questions.

2.4. Data Extraction

A standardized data extraction form, adapted from the Cochrane Collaboration template, was piloted in five studies before its implementation in the full review [42]. The ex-tracted data included the following:

- Study characteristics included authors, publication year, country/region, study design, data sources, sample size, and study period.
- Intervention characteristics: type of renovation (insulation, windows, heating system, comprehensive), technical specifications, scale (build-ing/neighborhood/city), and implementation period.
- Spatial dimensions: geographic distribution, urban/neighborhood characteristics, accessibility patterns, targeting mechanisms.
- Technical outcomes: energy consumption changes (kWh/m²/year), greenhouse gas emission reductions (kg CO_2/m²/year), cost-effectiveness metrics (€/kWh saved, payback periods), and indoor environmental quality parameters.
- Socioeconomic outcomes: energy poverty indicators (expenditure ratios, subjective measures), household energy expenditure, affordability metrics, and social equity dimensions.
- Comfort outcomes: thermal comfort measures (temperatures, PMV/PPD indices), indoor air quality parameters (CO_2, humidity, pollutants), perceived housing quality, and resident satisfaction.
- Health outcomes: respiratory health indicators, cardiovascular outcomes, mental health measures, overall well-being indicators, and healthcare utilization.
- Governance and policy: Institutional frameworks, financing mechanisms, participation rates, and implementation barriers.
- Methodological quality: Study design appropriateness, sample representativeness, measurement validity, potential biases, and confounding control.

Data extraction was performed by one reviewer, while a second reviewer verified a random sample comprising 20% of the included studies to ensure accuracy and consistency [43].

2.5. Quality Assessment

The methodological quality of the included studies was assessed using criteria adapted from established tools for different study designs [44]. Quantitative observational studies were evaluated using the Modified Newcastle-Ottawa scale, which assesses the selection of groups, comparability, and measurement of outcomes. Intervention studies were assessed using the Cochrane Risk of Bias tool, which assesses selection, performance, detection, attrition, and reporting bias. Qualitative studies were reviewed using the Critical Appraisal Skills Program (CASP) checklist, focusing on research aims, methods, data collection, analysis, and clarity of findings. Mixed-methods studies were evaluated using the Mixed Methods Appraisal Tool (MMAT), which assesses the quality of qualitative, quantitative, and integration components.

Two reviewers independently assessed the study quality and resolved discrepancies through discussion. Studies were not excluded based on quality scores; instead, these ratings informed the evaluation of the evidence strength in the synthesis [45].

2.6. Data Synthesis and Analysis

Given the heterogeneity in study design, interventions, settings, and outcomes, a narrative synthesis was conducted instead of a meta-analysis. The synthesis focused on five primary themes aligned with the research questions: (1) spatial distribution and governance, (2) technical performance and energy efficiency, (3) socioeconomic impacts and energy poverty, (4) housing comfort and indoor environmental quality, and (5) health outcomes and well-being [46].

For each theme, the findings were synthesized by highlighting the key results across studies and identifying the principal trends and differences. Contextual factors, including the setting, intervention type, and population characteristics that influence outcomes, were also examined. The strength and consistency of the evidence were evaluated using the GRADE criteria adapted for systematic reviews [47].

A thematic synthesis was used to identify the principal themes, mechanisms, and relationships across the various domains [48]. Synthesis tables supported the comparison and integration of the findings [49]. When quantitative data were available from multiple studies, ranges and weighted averages were calculated to represent the typical outcomes [50].

The research was conducted at the Center for Social Development and Human Re-sources Research (CSDHRR) at the "1 Decembre 1918" University of Alba Iulia, where the selection protocols for the articles reviewed were documented.

3. Results

3.1. Overview of Included Studies

A systematic search and selection process, conducted in accordance with the PRIS-MA 2020 guidelines, identified 111 studies for qualitative synthesis and 50 for quantitative analysis. Most studies were published between 2015 and 2024, with 68% appearing after 2018, indicating growing scholarly interest in residential energy renovation and its impacts. Of these, 23 studies focused specifically on Romania, while 88 examined com-parable Central and Eastern European countries, including Poland, Hungary, the Czech Republic, and Bulgaria, providing insights applicable to the Romanian context.

The included studies employed diverse research designs, reflecting the multidisciplinary nature of this field. Quantitative observational studies constituted the largest pro-portion (45 studies, 41%), followed by mixed methods approaches (28, 25%), intervention studies with pre-post designs (22, 20%), qualitative case studies (11, 10%), and modelling studies with empirical validation (5, 4%). This methodological diversity enabled a com-prehensive examination of technical, socioeconomic, and health dimensions, although it also posed challenges in synthesizing heterogeneous evidence.

3.2. Spatial Distribution and Governance Frameworks

The analysis of spatial patterns revealed pronounced inequalities in access to and implementation of renovations within Romanian cities. In Bucharest, renovation activities were concentrated in the central and adjacent districts, whereas peripheral neighborhoods, typically inhabited by lower-income residents and characterized by older building stocks, received significantly less investment [16,33]. Comparable trends have been identified in other cities, including Cluj-Napoca, Timi oara, and Ia i, where renovation pro-grams have similarly prioritized central areas over peripheral zones [3].

Governance-focused studies have identified multiple barriers to equitable access to renovations. In privatized multi-family buildings, fragmented ownership structures hinder homeowner associations' ability to coordinate renovation efforts, as these groups frequently lack technical expertise, financial resources, and member consensus [12,51]. Additionally, complex subsidy application processes deter less educated and older homeowners from participating, thereby excluding those most in need of energy efficiency improvements [14].

Financial considerations are critical determinants of renovation. Although Romani-an programs offer substantial subsidies covering up to 80% of costs, the requirement for co-financing frequently proves prohibitive for low-income households [15]. Studies have demonstrated that buildings located in wealthier neighborhoods are significantly more likely to apply for and secure funding, thereby perpetuating disparities in housing quality and energy efficiency [16,52].

Institutional capacity varies considerably across municipalities. Larger cities equipped with dedicated energy efficiency departments achieve higher renovation rates and a more equitable distribution of projects than smaller towns lacking specialized personnel or technical expertise [2]. This disparity indicates that scaling up renovation pro-grams will require substantial investment to strengthen local institutional capacity, in addition to financial support [13].

3.3. Technical Performance and Energy Efficiency Outcomes

A review of the energy performance data from 50 studies indicated substantial reductions in energy use following renovations. Comprehensive retrofit packages incorporating insulation, new windows, and heating system upgrades resulted in an average de-crease of 58% in energy consumption (95% CI: 52-64%, range: 35-78%), corresponding to approximately 142 kWh/m²/year saved [53,54].

Renovations targeting individual components yielded more modest effects: insulation alone reduced energy use by 32% (95% CI: 28-36%), window replacement by 18% (95% CI: 14-22%), and heating system upgrades by 25% (95% CI: 21-29%) [55]. The cost-effectiveness of these interventions varies by type and geographic context. In Romania, comprehensive renovations achieved payback periods of 12–28 years based solely on energy savings, with a median of 18 years [3]. When health benefits and reduced healthcare expenditures were considered, payback periods decreased to 8-15 years, there-by enhancing the attractiveness of such investments [4].

Renovation quality emerged as a primary factor explaining the discrepancies between the projected and actual outcomes. Post-renovation monitoring studies have identified an average gap of 23% between the predicted and realized energy savings, frequently attributable to overlooked thermal bridges, substandard workmanship, and insufficient quality control measures [55,55]. This gap is even more pronounced in projects that prioritize cost reduction over quality assurance [38].

3.4. Energy Poverty Alleviation and Socioeconomic Impacts

Renovations have multifaceted effects on energy poverty. Among households that undertook renovations, studies reported substantial reductions in the proportion of in-come allocated to energy expenses, with an average decrease of 5.2 percentage points (95% CI: 4.1-6.3) among low-income groups [56,57]. Additional indicators of energy poverty, such as the inability to maintain adequate indoor warmth or arrears on utility bills also improved. Two years post-renovation, 42% of households previously classified as energy poor no longer met the criteria [58].

However, these positive outcomes were substantially mediated by household socio-economic characteristics and financing arrangements for renovations. However, these positive results depend heavily on household income and how renovations are financed. Households that received grants saw larger reductions in energy poverty than those who took out loans because loan payments sometimes cancelled out savings and led to new financial problems [9,59].

The most vulnerable groups, such as elderly pensioners, single parents, and unemployed people, often face barriers to accessing renovations; therefore, the benefits mostly go to moderate-income households instead of the poorest [32,60].

The rebound effect, defined as the loss of energy savings due to increased heating for comfort, was observed in 65% of the renovations studied. The average rebound was 28%, ranging from 10% to 45% [30,55]. While this rebound reduces absolute energy savings, it improves thermal comfort and health for previously underheated households, suggesting that the rebound should be interpreted as a positive outcome rather than an implementation failure in the context of energy poverty [31].

3.5. Housing Comfort and Indoor Environmental Quality

Multiple studies have consistently reported improvements in thermal comfort following renovations. On average, winter indoor temperatures increased by 3.2°C in living rooms and 2.7°C in bedrooms impacts [63,26]. Consequently, a greater proportion of homes achieved the WHO-recommended minimum of 18°C, with 78% of renovated homes meeting this standard compared to 34% prior to renovation [19,61].

The findings regarding indoor air quality were mixed. Some studies have identified improved ventilation and reduced indoor pollutants following renovations that incorporated mechanical ventilation systems [24,25]. In contrast, other studies have observed deteriorated air quality when increased airtightness is not accompanied by adequate ventilation [26,27]. In 45% of renovations, the relative humidity increased by an average of 8%, and the indoor CO_2 concentrations increased by 180 ppm, prompting concerns about potential health impacts [28,62].

The outcomes related to mold and dampness varied throughout the studies. Renovations that included vapor barriers and mechanical ventilation reduced the proportion of homes with mold from 38% to 12% [63]. Conversely, poorly designed renovations that increase airtightness without enhancing ventilation or moisture control led to higher mold prevalence, with rates rising from 35% to 47% in some cases [27]. These findings underscore the importance of renovation strategies that simultaneously address thermal comfort and in-door air quality [64].

Summer overheating is an increasing concern, particularly in the context of climate change. Post-renovation, 32% of the buildings experienced more hours of excessive indoor temperatures during summer.

This outcome is frequently attributed to improved insulation without sufficient attention to solar shading, thermal mass, or natural ventilation [36,65]. These results indicate that renovation efforts should address both winter heating and summer cooling requirements [65,66].

3.6. Health Outcomes and Well-being Impacts

The direct assessment of health outcomes in Romanian renovation contexts remains limited, with only three studies incorporating health indicators. These studies reported improvements in self-rated health: 34% of residents reported better health status 1 year after the renovation, compared with 8% who reported worse health [3,10]. The prevalence of respiratory symptoms among residents with pre-existing conditions declined from 42% to 28%, although definitive causality could not be established because of study design limitations [3].

Evidence from Europe provides further insights into the potential health effects. A meta-analysis of 18 studies found that energy efficiency improvements in homes were as-sociated with reduced respiratory symptoms (OR=0.72, 95% CI: 0.61-0.85), fewer cardio-vascular events among older adults (OR=0.78, 95% CI: 0.65-0.94), and improved mental health, as measured by standard depression and anxiety scales (standardized mean difference = -0.31, 95% CI: -0.45 to -0.17) [4,61,67].

Healthcare utilization studies from comparable contexts documented a reduction in general practitioner visits (mean reduction of 1.8 visits per year, 95% CI: 1.3-2.3), fewer hospital admissions for respiratory conditions (rate ratio = 0.83, 95% CI: 0.74-0.93), and lower medication expenditures (€127 less per year, 95% CI: €89-€165) among residents of renovated homes compared to those in unrenovated dwellings [11,22]. These healthcare savings contribute significant economic value to renovation projects, extending beyond energy cost reduction [68]. Additionally, an increased sense of control over the home environment is associated with measurable improvements in quality-of-life indicators [21]. Social benefits, such as reduced isolation, enhanced ability to host visitors, and improved neighborhood cohesion in collectively renovated buildings, represent important but frequently overlooked co-benefits of renovation interventions [58].

3.7. Methodological Quality and Risk of Bias

The methodological quality of the included studies varied considerably. Among the 22 quantitative intervention studies, 9 (41%) had a low risk of bias, 10 (45%) had a moderate risk, and 3 (14%) had a high risk of bias. Common methodological issues included the absence of control groups (15 studies, 68%), inadequate control for confounding factors (12 studies, 55%), short follow-up periods insufficient to assess long-term effects (17 studies, 77%), and potential selection bias in non-randomized studies (18 studies, 82%).

Most of the 45 observational studies were assessed as being of moderate quality. The primary limitations included the use of cross-sectional designs in 32 studies (71%), which limited the ability to establish causality; reliance on self-reported outcomes rather than objective measures in 28 studies (62%); and potential recall bias in 19 studies (42%) when retrospectively assessing past events. Assessment of publication bias using funnel plots and Egger's test indicated that studies with null or negative results, particularly regarding health outcomes, may have been underreported (Egger's test p= 0.03). Consequently, the reported effects may be somewhat overestimated impacts [70,71].

The 11 qualitative studies were generally of high quality, according to the CASP criteria. These studies demonstrated clear research aims, employed appropriate methodologies, collected and analyzed data rigorously, and considered the potential influence of the researchers on the findings. Among the 28 mixed-methods studies, 18 (64%) effectively integrated qualitative and quantitative results, whereas 10 (36%) presented findings from each method separately, with limited integration.

4. Discussion

4.1. Principal Findings and Interpretation

This systematic review synthesized evidence from 111 studies examining the im-pacts of energy renovation across technical, socioeconomic, and health dimensions in Romanian and comparable Central and Eastern European contexts to address this gap.

Energy renovation interventions demonstrate substantial technical potential for reducing energy consumption, with comprehensive retrofits achieving mean savings of 58%; however, actual implementation reveals marked spatial and socioeconomic inequalities. Renovation activity concentrates in more affluent neighborhoods and among higher-income households, leaving vulnerable populations in the greatest need of energy efficiency improvements systematically underserved [16,33,52]. This pattern reflects not only financial barriers but also the governance challenges inherent in post-socialist housing systems, where fragmented ownership, weak homeowner associations, and limited institutional capacity create formidable obstacles to equitable program access [12,51].

Energy poverty alleviation outcomes are substantial but unevenly distributed. Among households undergoing renovations, energy expenditure burdens decrease significantly, and subjective indicators of energy poverty improve markedly [58,68]. However, these benefits accrue primarily to moderate-income households that can access and navigate subsidy programs, while the most vulnerable populations, such as elderly pensioners, unemployed individuals, and marginalized communities, face persistent barriers to participation [32,60]. This creates a troubling paradox in which renovation programs, despite substantial public investment, may inadvertently widen rather than narrow energy poverty inequalities [9,59].

Housing comfort improvements are consistently documented but are accompanied by indoor air quality concerns that require careful consideration. Thermal comfort gains are substantial and represent meaningful quality-of-life improvements for previously cold homes [19,63]. However, increased airtightness without corresponding ventilation can degrade indoor air quality, potentially creating new health risks, even as cold-related hazards diminish [26,27]. This finding underscores the imperative for integrated design approaches that optimize both thermal performance and indoor air quality simultaneously, rather than prioritizing energy savings in isolation [24,64].

Health evidence, while limited to Romanian contexts, suggests substantial co-benefits that strengthen renovation investment cases beyond energy savings. Extrapolation from broader European research indicates a significant potential for improvements in respiratory health, cardiovascular risk reduction, and mental health benefits [4,61,67]. Healthcare cost savings from these health improvements, when incorporated into eco-nomic assessments, can reduce renovation payback periods by 30-50%, transforming marginally viable projects into economically attractive investments [56].

Climate adaptation considerations are absent from current renovation approaches despite the growing risk of summer overheating. The focus on winter heating reduction, while appropriate for addressing current energy poverty patterns, inadequately prepares the housing stock for the projected climate change impacts [36,37]. Integrated approaches that address both cold-weather energy poverty and warm-weather overheating vulnerability are essential for climate-resilient housing renovation strategies [65,66].

4.2. Comparison with Existing Literature

These findings align with and extend previous research on residential energy renovations in several ways. The documented spatial inequalities in renovation distribution confirm patterns identified in Western European contexts [31,32], while highlighting the distinctive features of post-socialist housing governance that amplify these inequalities [13,35]. The collective action challenges inherent to privatized multi-family buildings rep-resent a particularly salient barrier in Central and Eastern European settings, which differ from the social housing-dominated systems in Western Europe [12].

The energy poverty alleviation findings contribute important nuances to the existing literature by documenting not only positive outcomes among renovated households but also the systematic exclusion of the most vulnerable populations from program access [57,68]. This pattern of "middle-income capture" in renovation programs has been noted in other contexts [60] but receives particular emphasis in this review's focus on equity dimensions. The rebound effect findings align with previous research [30,55] while offering an important reframing: in energy poverty contexts, the rebound effect represents im-proved living conditions rather than implementation failure, suggesting that policies should embrace rather than resist comfort-driven increases in energy use among previously underheated populations [31].

The indoor air quality concerns documented in this review corroborate the findings of other European renovation studies [26,27] and reinforce calls for integrated approaches that address ventilation alongside thermal performance [24,64]. The emergence of summer overheating as a concern extends recent research on climate adaptation challenges in building renovation [36,37], highlighting the need for forward-looking approaches that address projected rather than only historical climate conditions in building renovation.

Health evidence synthesis confirms the substantial co-benefits documented in previous reviews [4,67], while highlighting critical evidence gaps specific to the Romanian and Central European contexts. The limited direct health measurement in Romanian renovation programs represents a missed opportunity to document benefits that could strengthen policy support and investment justification [56].

4.3. Implications for Policy and Practice

These findings have several important implications for the design and implementation of renovation policies.

Addressing spatial and socioeconomic inequalities requires fundamentally rethinking program delivery mechanisms. Current approaches that rely on household initiatives and co-financing systematically exclude vulnerable populations [32,60]. Alternative models, including area-based approaches with 100% grant funding for low-income households, proactive outreach and application assistance, and simplified administrative procedures could enhance equity [52,58].

Governance capacity building deserves equal priority to financial subsidies. Strengthening homeowner associations, providing technical assistance for renovation planning and procurement, and developing municipal institutional capacity for program administration are essential preconditions for successful program scaling [13,51]. Investment in these institutional foundations, while less visible than building renovations, may prove critical for achieving renovation targets and ensuring equitable outcomes [12,35].

Technical specifications and quality assurance mechanisms must address indoor air quality and thermal performance. Mandatory ventilation requirements, commissioning and verification procedures, and post-occupancy monitoring should be standard components of renovation programs [24,64]. Performance gap reduction through improved workmanship quality, attention to thermal bridges, and adherence to design specifications can enhance the actual versus predicted energy savings [38,55].

Health co-benefits should be systematically measured and incorporated into renovation investment projects in the future. Establishing health monitoring protocols, tracking changes in healthcare utilization, and conducting economic assessments that include health benefits alongside energy savings can strengthen political support and justify expanded public investment [68]. Collaboration among the housing, energy, and health sectors, which is currently limited, could unlock synergies and enhance program effectiveness [19,22].

Climate adaptation must be integrated into renovation strategies. Design specifications should address both winter heating and summer cooling by incorporating solar shading, natural ventilation, thermal mass strategies, and insulation improvements [36,66]. Forward-looking approaches that anticipate projected climate conditions rather than optimizing historical patterns are essential for long-term housing resilience [37,65].

4.4. Strengths and Limitations

The scope of this review excluded new construction and single-family housing, limiting the generalizability of the findings to these contexts. Language restrictions (English, Romanian, and major European languages) may have excluded relevant research published in other languages from this review. Finally, the rapidly evolving policy landscape means that recent developments may not be fully captured in the literature, which covers publications through 2024.

The principal strengths of this systematic review include a comprehensive search strategy across multiple databases, rigorous selection and quality assessment procedures following the PRISMA 2020 guidelines, and a multidisciplinary synthesis integrating technical, socioeconomic, and health evidence that is typically examined in isolation [40,41].

The specific focus on Romanian and comparable post-socialist contexts addresses a significant geographical gap in the existing literature, while the inclusion of both quantitative and qualitative evidence enables a nuanced understanding of complex phenomena [46].

This study had several limitations. The limited number of studies examining Romanian contexts (n = 23, 21% of the included studies) necessitated extrapolation from com-parable Central and Eastern European settings. While these contexts share important characteristics, socialistera building stock, privatization dynamics, and governance challenges, contextual differences may limit the direct transferability of the findings [3,35]. Heterogeneity in outcome measures, study designs, and intervention characteristics complicated the synthesis and limited the scope of the quantitative meta-analysis [42,69].

The predominance of cross-sectional and short-term follow-up studies limits our understanding of the long-term impact of renovations and the sustainability of the observed benefits [30,55]. Potential publication bias, suggested by funnel plot asymmetry, indicates that effect sizes may be overestimated, particularly for health outcomes, where null findings may be underreported [70,71]. The focus on published academic literature may miss important insights from grey literature, including government reports, NGO evaluations and unpublished research [43].

This review excluded new construction and single-family housing; therefore, the findings may not be generalizable to these sectors. The inclusion criteria limited studies to those published in English, Romanian, and major European languages, potentially omit-ting relevant research published in other languages. Additionally, given the rapid evolution of policies, literature published up to 2024 may not capture the most recent developments.

4.5. Future Research Directions

This review identifies several significant research gaps that warrant attention in future studies. Longitudinal research tracking participants for at least 5 years is necessary to assess the persistence of energy savings, comfort improvements, and health benefits [30,55].

Rigorous intervention studies employing control groups and adequate sample sizes are required to determine the direct impact of renovations on health outcomes in Romania [4].

Research exploring innovative approaches to organizing and managing multifamily buildings, particularly those that facilitate collective action, may generate models applicable to other programs [12,51].

Comprehensive economic assessments that incorporate energy savings, health benefits, productivity gains, and environmental impacts can provide a more complete evaluation of the value of renovation projects [72]. Given the accelerating impacts of climate change, urgent research is needed on renovation strategies that address both current energy poverty and the increasing risk of future overheating [36,37].

Equity-focused research should investigate barriers to vulnerable groups' access to renovations and evaluate interventions to enhance program inclusivity [32,60].

Further research is needed on ventilation strategies that sustain high indoor air quality while meeting heating and cooling objectives, to prevent adverse health outcomes [26,27].

Finally, applying implementation science to examine real-world program functioning, identify facilitators and barriers to success, and test quality improvement strategies could enhance the translation of research into practice [13,38].

5. Conclusions

This systematic review synthesizes multidisciplinary evidence on the impacts of energy renovation in apartment buildings across urban Romania, focusing on spatial distribution, technical performance, socioeconomic outcomes, housing comfort, and health. The findings indicate significant technical progress in energy efficiency and thermal comfort; however, persistent challenges remain in equity and governance, and the evidence on health outcomes is incomplete.

6.1. Principal Conclusions

Energy renovation interventions result in substantial reductions in energy consumption (30-70%) and notable improvements in thermal comfort (2-5°C increase in winter temperatures), demonstrating the technical viability of retrofit strategies for the Romanian building stock [53,54,63]. However, translating technical potential into widespread implementation is constrained by governance and financial barriers, leading to an uneven spatial distribution that does not adequately serve the populations most in need [16,33].

Although renovations reduce heating costs by 30-50%, approximately 40% of residents continue to experience energy poverty after renovation [57,72]. This persistence underscores the multidimensional nature of energy poverty, which is influenced by factors beyond housing efficiency, including household income, energy prices, and energy needs [73]. The tendency of lower-income households to use efficiency gains to improve thermal comfort rather than reduce expenditures highlights the prevalence of pre-renovation underheating and thermal discomfort [62].

Improvements in thermal comfort represent substantial enhancements in the quality of life of residents who previously endured cold and uncomfortable living conditions [5,6,22,74]. However, the ventilation challenges observed in some renovated buildings underscore the necessity of holistic building performance considerations [26,61]. In-creased airtightness without sufficient mechanical ventilation can introduce new indoor environmental quality issues, such as elevated CO_2 levels, increased humidity, and potential mold growth [27].

The evidence base regarding health outcomes in the Romanian context remains limited, as most findings are extrapolated from broader European research [11,61,67]. Although European studies have documented cardiovascular, respiratory, and mental health benefits associated with improved housing conditions, direct confirmation of these findings in the Romanian population is necessary. Preliminary findings of reduced respiratory symptoms among residents of renovated buildings warrant further investigation through more rigorous study designs [75].

Current renovation programs primarily benefit middle- and upper-income households, who are better positioned to meet co-financing requirements and navigate administrative processes, while the most vulnerable populations are systematically excluded [16,33,76]. This pattern illustrates the tension between environmental objectives, such as maximizing CO_2 reductions, and social objectives, including reducing energy poverty and health inequalities [77]. Achieving both objectives requires explicit attention to equity in the program's design.

6.2. Implications for Policy and Practice

The evidence synthesized in this review has several critical implications for the design and implementation of policies.

Energy renovation policies should explicitly incorporate environmental, social, and health objectives rather than focusing solely on environmental goals [78]. Achieving this integration requires cross-sectoral coordination among the energy, housing, social welfare, and health ministries, supported by mechanisms that balance potentially competing objectives [79].

To effectively reach vulnerable populations, renovation programs should offer higher subsidy rates, potentially covering up to 100% of low-income households. They should also streamline administrative procedures, engage in proactive outreach, and employ alternative financing mechanisms [69,80,81]. Additionally, safeguarding against displacement and gentrification pressures is crucial [82].

Renovation strategies should consider ventilation and moisture management as essential elements rather than secondary considerations [83,84]. This approach requires mandatory ventilation assessments, implementation of suitable technical solutions, commissioning protocols, and post-renovation monitoring of indoor environmental quality [85,86].

Given the significant yet not fully quantified health co-benefits, renovation programs should incorporate health impact assessments and outcome monitoring to document these benefits and guide program improvements. Collaboration between housing agencies and health systems can promote data sharing and integrated evaluations [87].

To tackle the challenges of collective action in multi-owner buildings, it is essential to enhance the capacity of homeowners' associations, offer facilitation services, explore alternative governance models, and establish legal frameworks that balance collective and individual rights. Investing in social processes is as crucial as investing in technical and financial mechanisms [88].

6.3. Research Priorities

Future research must address several critical knowledge gaps:

(a) direct health out-come measurement, which includes prospective longitudinal studies with control groups to assess cardiovascular, respiratory, and mental health outcomes within the Romanian renovation context [89–91];

(b) long-term sustainability, requiring extended follow-up over five to ten years to monitor the persistence of energy, comfort, and health benefits, as well as factors influencing long-term outcomes [92];

(c) equity and vulnerable populations, with research specifically examining barriers to access, differential outcomes, and strategies to enhance equity for vulnerable groups [93];

(d) ventilation and indoor air quality (IAQ) optimization, through studies that compare ventilation strategies in Romanian building types and examine IAQ outcomes, health impacts, energy implications, and res-ident acceptance [94];

(e) governance and implementation, which includes evaluating innovative governance models, financing mechanisms, and implementation strategies within the Romanian institutional context [65]; and

(f) climate adaptation integration, focusing on renovation strategies that address both cold-weather energy poverty and emerging warm-weather overheating risks [66].

6.4. Final Reflection

Renovating apartment buildings is an effective strategy for addressing climate change, energy poverty, and health inequities in Romania's urban areas. Renovation methods have demonstrated efficacy, with substantial evidence indicating improvements in occupant comfort. However, maximizing the benefits of these initiatives requires moving beyond technical solutions to incorporate comprehensive approaches that address governance challenges, promote equitable access, and systematically monitor health outcomes.

Progress in this area necessitates the development of new policies, enhanced institutional coordination, increased research funding and sustained political commitment. Given the prevalence of energy poverty, aging building stock, and persistent health dis-parities, energy renovations are an urgent priority in Romania. Ultimately, the evaluation of energy renovation programs should extend beyond energy savings and emission reductions to include their impact on equity, health, and overall quality of life, particularly for vulnerable populations. This broader perspective on success should inform the development of future policies, programs and research initiatives.

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