

Optimization of Multi-Energy Complementary Building Energy Systems

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Abstract. Under the dual impetus of the global energy crisis and carbon neutrality objectives, the construction sector, as a critical domain of energy consumption and carbon emissions, urgently requires green transformation through multi-energy complementary systems. This paper systematically reviews the coupling mechanisms, integration technologies, and synergistic optimization methodologies of multi-energy complementary building energy systems, elucidating their roles in enhancing energy efficiency, reducing lifecycle carbon emissions, and advancing net-zero energy building development. Research demonstrates that integrating renewable energy technologies, such as building-integrated photovoltaic/thermal (BIPVT) systems and hydrogen complementary systems, effectively addresses energy volatility and intermittency while balancing architectural aesthetics with economic viability. The study underscores that large-scale implementation of multi-energy complementary systems necessitates regionally adaptive design frameworks, long-term performance monitoring protocols, and multi-stakeholder collaboration, thereby offering theoretically innovative and practically actionable solutions for global low-carbon building transitions.

Keywords: Multi-energy complementary; Building energy systems; Coupling mechanisms; Synergistic optimization.

1. Introduction

Traditional fossil fuels—coal, petroleum, and natural gas—are finite and face depletion, prompting urgent global efforts to transition toward low-carbon, sustainable energy systems. This is particularly critical in the building sector, where energy consumption and emissions are significant [1]. While carbon reduction remains core goal, the broader value of energy efficiency lies in its contributions to energy security, enhanced economic productivity, and mitigated environmental degradation. Systems and controls are especially complex and dynamic design parameters, highlighting the criticality of optimized design strategies. Energy-efficient building envelope design demands rigorous adherence to multi-criteria evaluation frameworks [1].

With buildings consuming 30 – 40% of global primary resources and ranking third in fossil fuel use, energy-efficient design is now central to sustainable development. The "Asia-Link" initiative, spearheaded by the European Commission, exemplifies international efforts to promote sustainable built environments and near-zero energy building (NZEB) principles. This program systematically integrates mature renewable energy technologies into buildings for diverse applications spanning water heating, space conditioning, and power generation, reflecting the growing global emphasis on operational energy management in buildings [2]. According to Kaya et al., the Paris Climate Agreement mandates a 50% reduction in building emissions by 2030 and net-zero emissions by 2050. As the sector contributes 40% of global energy consumption and 37% of emissions, research on synergistic, multi-energy systems is essential to achieving green transformation [3]. However, high upfront investment and uncertainties in return on investment remain barriers, necessitating robust economic analyses of willingness-to-pay thresholds [4].

Despite advances, three major challenges persist: Technological limitations, with a focus on single-energy systems and insufficient research on multi-source coupling mechanisms; Lack of standardized economic evaluation, hindering lifecycle cost-benefit analysis and policy development; Insufficient empirical validation, as most models rely on theoretical assumptions without real-world testing. To address these challenges, this study employs a tripartite analytical approach: technological

synthesis, co-optimization, and scenario-specific adaptability. Methods include systematic literature review, comparative case analysis (e.g., Bullitt Center and China's rural energy transition), and evaluation of advanced tools such as AI-driven surrogate modeling and multi-objective optimization. Centered on "coupling dynamics and co-optimization," the research innovatively synergizes building-integrated photovoltaics (BIPV), hybrid multi-energy systems, and intelligent optimization algorithms. Theoretically, it develops a multi-objective optimization model reconciling energy efficiency, functional requirements, and economic constraints. Practically, digital twin simulations and empirical case studies validate system performance under real-world conditions, providing implementable data for technology deployment. The study constructs a triaxial "technology-economy-environment" evaluation framework to address technical silos and policy fragmentation in energy transitions while informing context-specific urban-rural decarbonization strategies under carbon neutrality targets.

The scholarly innovation resides in its interdisciplinary consolidation of disparate research domains into a cohesive analytical framework, offering academia a structured paradigm while delivering pragmatic solutions for industry stakeholders and policymakers. This dual contribution holds strategic significance.

2. Technological Foundations

2.1 BIPV

Building-integrated photovoltaics (BIPV) replace traditional construction materials, such as roof tiles or façades, with photovoltaic modules that serve both structural and energy-generating functions. Consequently, BIPV systems influence building functionality and are recognized as integral components of building energy systems, necessitating consideration of multifactorial design parameters [5].

BIPV modules operate by absorbing solar energy while facilitating airflow through integrated cavities or ducts. Ambient air enters at the base, absorbs thermal energy from the photovoltaic modules, and exits from the top, thereby lowering their temperature and enhancing both efficiency and durability. In specific configurations, fans and ductwork are incorporated into the system to redirect heated air into interior spaces during winter, concurrently harnessing solar energy for dual electrical and thermal applications while reducing heating demands [5].

BIPV systems are classified based on three primary criteria: solar cell technology, application type, and market nomenclature. Photovoltaic technologies are categorized into silicon-based (e.g., monocrystalline, polycrystalline) and non-silicon-based (e.g., organic, perovskite) variants, with roof and façade integrations constituting the two principal application domains. Applications focus on roofs and façades, while product types include thin-film laminates, PV tiles, modular panels, and PV glass units, each fulfilling specific architectural and functional roles [5].

2.2 BIPVT

Building-integrated photovoltaic/thermal (BIPVT) systems represent an innovative, practical, and promising technology for achieving net-zero emission buildings, demonstrating significant global market potential. Solar energy technologies are broadly categorized into two types: photovoltaic (PV) modules, which directly convert a portion of incident solar radiation into electricity, and solar thermal systems, which transform solar energy into thermal energy (heat). The latter typically requires external electrical energy to circulate working fluids. However, the integration of photovoltaic and thermal systems into a unified photovoltaic/thermal (PVT) hybrid configuration eliminates reliance on auxiliary power sources. When implemented in buildings, this hybrid system constitutes a building-integrated photovoltaic/thermal (BIPVT) system, enabling self-sufficient energy generation [6].

The system consists of PV panels for electricity and thermal absorbers for heat capture, structurally embedded into metal roofing profiles. These systems comprise a photovoltaic panel, which facilitates

electrical energy generation through the photovoltaic effect, and a thermal absorption component that captures residual heat. When such PV-T systems are structurally incorporated into buildings, they are classified as building-integrated photovoltaic/thermal systems. BIPVT technologies are applicable to both new constructions and retrofitted buildings [7].

Distinct from conventional systems, the described BIPVT configuration is directly embedded into standing seam or trapezoidal sheet metal roofing. Standing seam and trapezoidal roofs are typically fabricated from aluminum or coated steel, though copper or stainless steel may also be employed. These materials are roll-formed or pressed into profiles that enhance structural rigidity, weather resistance, and assembly efficiency. The system capitalizes on the high thermal conductivity of these roofing materials to form BIPVT collectors. During manufacturing, channels are integrated into the trapezoidal sheets to enable the circulation of heat transfer fluid. A PV cell laminate, bonded to the sheet surface, seals these channels, forming enclosed conduits for thermal energy transfer. Each channel features inlet and outlet ports at opposing ends. Furthermore, the design permits the inclusion of glass or polycarbonate glazing to create an air gap between the PV module's exterior surface and the ambient environment, thereby elevating operating temperatures to enhance thermal efficiency. When exposed to solar radiation, PV cells generate electricity while absorbing incident energy. Silicon-based PV cells primarily convert short-wavelength radiation into electricity, whereas longer wavelengths induce thermal accumulation in the laminate. In BIPVT collectors, this waste heat is transferred through the laminate to the underlying fluid medium. The heat transfer fluid, pumped through the channels via manifolds and piping, is subsequently routed to heat exchangers for energy extraction. This liquid-based cooling mechanism reduces PV cell temperatures, improving electrical efficiency under high irradiance and elevated thermals [8].

3. Integrated technology and coupling mechanisms

3.1 Integrated Technology

Multi-energy complementary systems integrating wind, solar, and hydropower have emerged as critical solutions for enhancing energy supply efficiency and stability. A recent investigation into the dynamic characteristics of multi-energy systems in the upper Yellow River basin specifically analyzed the impact of hydropower installed capacity limitations on overall system performance. Findings indicate that increasing hydropower capacity leads to reductions in both total installed capacity and maximum energy efficiency (E_{max}). These findings suggest that augmenting hydropower's regulatory capabilities can reduce reliance on other renewable energy sources while improving systemic operational efficiency [9].

Buildings increasingly adopt on-site or distributed renewable systems to meet heating, cooling, and electricity demands, which are major contributors to building energy consumption. Renewable technologies—including solar energy, heat pumps, biomass, and wind power—are gaining increasing traction in the architectural sector, positioning buildings closer to achieving sustainability benchmarks [10].

Li, Z. delineated the fundamental principles of a renewable-powered multi-energy complementary hydrogen system, composed of renewable energy generators (e.g., wind turbines, photovoltaic panels, hydro turbines), water electrolysis hydrogen production units, hydrogen storage and transportation systems, fuel cells, and power grids. Renewable electricity powers hydrogen production via electrolysis; the hydrogen is then stored, transported, or reconverted to electricity through fuel cells. This closed-loop system is clean, efficient, and adaptable across diverse energy scenarios [11].

3.2 Coupling Mechanisms

The coupling coordination degree model serves as an analytical framework to evaluate the synergistic development between interdependent systems. Coupling degree quantifies the intensity of mutual dependence and constraint among systems, while coordination degree measures the extent of

synergistic coupling within these interactions, reflecting the quality of coordinated development. The coupling degree between the digital economy and green technological innovation specifically assesses the magnitude of interaction, interdependence, and mutual constraints between these two systems while validating the strength of their synergistic effects. Zhong, X. developed a coupling coordination degree model for digital economy-green technological innovation (TG systems) in Chinese urban agglomerations, enabling systematic evaluation of their coordination status. The model is constructed as follows:

$$C = \frac{S_1' S_2'}{(S_1' + S_2')^2}$$

$$T = \alpha S_1' + \beta S_2'$$

$$D = C \times T$$

Here, S_1' and S_2' represent normalized composite scores of each subsystem (e.g., digital economy and green innovation). C ($0 \leq C \leq 1$) quantifies mutual influence; T indicates the weighted coherence of subsystems (α, β are weight coefficients); and D ($0 \leq D \leq 1$) provides an overall assessment of system synergy. Higher values of D signify stronger integration and coordination. Based on these metrics, the TG system's coupling level is classified into seven coordination stages [12].

4. Synergistic Optimization Methods

The optimal design of off-grid hybrid renewable energy systems (HRES) constitutes a critical process for ensuring reliable energy supply, cost efficiency, and pollution mitigation. Analogous to methodologies in multi-energy systems (MES) and combined heat and power (CHP) research, two-tiered (TT) modeling frameworks are widely employed for HRES design optimization. In such frameworks, the outer loop generates system configurations, while the inner loop evaluates dispatch strategies and operational costs for each configuration. Metaheuristic algorithms, such as particle swarm optimization (PSO) and genetic algorithms (GA), are commonly applied in the outer loop for system sizing. In contrast, rule-based strategies (RBS) or deterministic optimization methods manage system operations [13]. Rullo et al. advanced a TT framework integrating GA for outer-loop sizing and rolling-horizon mixed-integer linear programming (MILP) for inner-loop scheduling. Comparative analysis demonstrated that their MILP-based predictive sizing approach achieves significant cost savings over conventional RBS-driven energy management systems (EMS) [14].

Building energy modeling (BEM) has also become a key tool for advancing carbon reduction in the built environment, serving as both a practical and supportive methodology for energy-efficient design, operational management, and retrofitting. These models aim to enhance energy performance while minimizing carbon emissions [15]. Despite prolific BEM applications over the past decade, most studies focus narrowly on proposing case-specific modeling frameworks. The field is currently now shifting toward digital twins and urban-scale modeling, which demand the extrapolation of simulation methodologies to broader spatial and temporal dimensions. Synthesizing both past and emerging BEM research priorities is vital to overcome current limitations in multi-scale energy performance analysis and to meet the growing need for smart, data-driven building design and management solutions [15].

5. Application Scenarios

Quantifying the energy-saving potential attributable to occupant behavior remains a critical challenge in building energy research. Estimates vary widely—ranging from 10–20% in residential buildings and 5–30% in commercial buildings, depending on occupancy patterns and space types. Workplace behavioral interventions demonstrate more modest outcomes, typically yielding approximately 5% energy savings. Hong et al. compared operational patterns in a single-story office

building, revealing that energy-conscious workflows reduced consumption by up to 50% compared to control groups, whereas energy-profligate practices increased usage by as much as 90%. These inconsistencies point to methodological gaps in quantifying behavioral contributions, making cross-study comparisons unreliable. To address this, future research should prioritize the development of standardized behavioral energy archetypes and integrate associated uncertainties into energy impact simulations [16].

The influence of occupant behavior on energy usage is profound yet frequently overlooked in practice. Most building energy simulation tools emphasize physical design parameters—such as external weather conditions and architectural features—rather than occupant-building interactions. Conventional approaches often assume deterministic or static occupant profiles, occasionally employing limited representative patterns for performance modeling. This oversimplification results in significant disparities between simulated and actual energy consumption patterns [17].

6. Limitations

Nevertheless, the application of renewable energy technologies in the building sector remains constrained by multiple limitations. Taking rural residential buildings in China as a case study, energy utilization in these contexts confronts systemic challenges, including low energy efficiency, suboptimal energy mix composition, and prohibitive economic burdens. Current data indicate that traditional fuels such as coal and firewood still account for 32.3% of residential energy consumption and 42.8% of productive energy use in rural areas [18]. The pervasive reliance on these conventional energy sources not only results in substantial energy wastage but also generates detrimental environmental impacts. Furthermore, the economic burden of energy expenditures disproportionately affects rural households, where elevated upfront costs further impede the adoption of clean energy alternatives. These challenges not only impair rural energy security and living standards but also present significant roadblocks to national carbon neutrality and peaking goals [18].

7. Future Directions

Multi-energy complementary building energy systems have already established a robust framework and demonstrated substantial efficacy in modern architectural applications. However, significant research potential remains in advancing this field. For instance, artificial intelligence (AI) technologies may address the limitations and challenges of large-scale renewable energy integration for carbon neutrality transitions [19]. As highlighted by Liu, Z., the development of artificial neural network (ANN)-based surrogate models in large-scale energy system optimization circumvents computationally intensive physics-based models, significantly reducing computational time for optimization tasks compared to conventional engineering models. Empirical studies indicate that ANN-driven surrogate models can accelerate system optimization by over 100-fold while maintaining accuracy rates exceeding 90% [19].

Nevertheless, inherent risks in multi-energy complementary systems must be acknowledged. Multi-energy complementary integrated energy systems (MCIES) are widely recognized as effective solutions for mitigating carbon emissions and advancing carbon peaking and neutrality goals. Current MCIES capacity configurations are typically predicated on deterministic load and system model parameters. However, operational uncertainties—ranging from renewable intermittency to demand fluctuations—may compromise anticipated performance and undermine optimal capacity determination [20]. Liu, Z. further investigated the impacts of uncertainty magnitudes and scenario configurations. The findings revealed that probabilistic optimization methodologies outperform traditional deterministic approaches by holistically balancing economic viability, environmental sustainability, and thermal comfort metrics [20].

8. Conclusion

This study systematically synthesizes existing literature on coupling mechanisms and co-optimization strategies in multi-energy complementary building energy systems, elucidating their pivotal role in reducing lifecycle energy consumption, mitigating carbon emissions, and advancing net-zero energy building development. The findings demonstrate that multi-energy complementary systems, through the integration of renewable energy technologies such as solar, hydrogen, and biomass, not only enhance energy conversion efficiency and system resilience but also harmonize architectural aesthetics with economic viability, thereby offering replicable technical pathways for urban energy transitions.

However, several limitations persist in this research. First, temporal constraints in literature inclusion have resulted in limited coverage of emerging technologies such as artificial intelligence (AI) and digital twins in recent multi-energy system optimizations. Second, existing studies predominantly focus on technical dimensions, with insufficient exploration of the synergistic effects of non-technical factors, including policy frameworks, user behaviors, and social acceptance. Furthermore, the spatiotemporal scope of case analyses remains narrow, lacking comparative investigations into system adaptability across diverse climatic conditions and regional contexts.

Future research should prioritize the following directions for advancement: 1. Technological Convergence: Develop AI-driven dynamic optimization algorithms and digital twin technologies to address renewable energy intermittency and load uncertainty. 2. Interdisciplinary Integration: Formulate a holistic evaluation framework encompassing engineering, economics, and environmental science to quantify lifecycle cost-benefit ratios and socio-ecological value. 3. Policy-Market Synergy: Investigate incentive mechanisms such as carbon trading and green finance to accelerate system scalability while exploring public-private partnership models. 4. Context-Specific Adaptation: Design customized solutions for rural, urban, and extreme climate regions, validated through longitudinal monitoring of environmental and economic performance.

In conclusion, multi-energy complementary building energy systems serve as critical enablers of carbon neutrality objectives. However, their widespread implementation necessitates technological innovation, policy reinforcement, and coordinated stakeholder engagement. Future research must bridge theoretical and practical domains to deliver universally applicable and forward-thinking solutions for global low-carbon transformation in the built environment.

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