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DISTRIBUTED INTELLIGENCE IN EXISTING HOUSING STOCK: SMART THERM MESH, SOLARHOMEHUB, AND ECOFLIPFRAME AS AN INTEGRATED FRAMEWORK FOR ADAPTIVE RETROFIT ENGINEERING

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Abstract

Residential buildings constructed before 1980 represent over one third of global housing stock and account for a disproportionate share of total energy use relative to their population density. Yet retrofit practice remains fragmented across thermal, electrical, and structural disciplines. This paper reports empirical results from field deployments of three coordinated technical systems, a distributed zone-level HVAC control architecture (SmartThermMesh), a cluster-based residential micro-grid (SolarHomeHub), and a factory-assembled interior renovation system (EcoFlipFrame), whose design principles and preliminary field results have been described in prior work (Rakhimov, 2025 a; Rakhimov, 2025 b; Rakhimov, 2025 c). A six-week controlled monitoring campaign demonstrated a 37.6% reduction in HDD-normalised heating energy ($p < 0.001$) relative to a single-thermostat baseline, with a concurrent 45% improvement in the predicted mean vote comfort index. Prefabricated module installation across five sites yielded a mean renovation timeline of 5.1 working days per 100 m² (SD = 0.6), an 86.6% reduction against a regional conventional benchmark of 37.8 days, with zero occupant displacement at all sites.

Keywords: *distributed HVAC control, residential retrofit, cluster micro-grid, adaptive building systems, prefabricated renovation, energy efficiency, reinforcement learning, thermal comfort*

Introduction

Roughly one third of global housing was built before 1980 and was never designed for the thermal, electrical, or digital standards that climate and energy policy now demand (European Commission, 2023). The residential sector consumes approximately 40% of

total final energy and generates over 25% of global CO₂ emissions (IEA, 2024). The bulk of emission reductions must come from modernising buildings that are already occupied and structurally constrained, not from new construction, which addresses only a marginal share of the total stock.

No published study evaluates the combined deployment of adaptive HVAC control, cluster micro-grid energy management, and prefabricated MEP-integrated renovation panels within a single operational framework. A systematic search of Scopus and Web of Science conducted in February 2026 using the terms (“micro-grid” OR “HVAC control”) AND (“prefabricated retrofit”) AND (“residential” OR “apartment”) returned no studies combining all three domains. This paper fills that gap by reporting unified empirical data from controlled field trials. Four questions structure the analysis: whether zone-level machine learning control reduces heating energy without comfort degradation; whether cluster micro-grid architecture is technically and economically viable in legacy multi-unit buildings; whether factory-assembled panels can simultaneously meet thermal, acoustic, airtightness, and digital integration requirements; and whether joint deployment of all three systems produces synergistic effects beyond individual contributions.

The integrated framework reported in this paper was conceived and designed by Farrukhzhon Rakhimov, an independent researcher specialising in adaptive building systems for legacy residential stock. Rakhimov identified the integration gap as a structural problem in retrofit engineering and formulated the architectural logic connecting thermal control, distributed energy storage, and prefabricated construction within a single operational layer. The three systems – SmartThermMesh, SolarHomeHub, and EcoFlipFrame – represent original technical contributions developed by Rakhimov across a sustained programme of applied research (Rakhimov, 2025 a; 2025 b; 2025 c).

Methods

Three technical systems were deployed and monitored across nine cold-climate residential sites in western Ukraine. Nine sites were monitored across western Ukraine: S1 (single-family, 160 m², Smart Therm Mesh only), S2 (three 1970s blocks, 90 apartments, Solar Home Hub only), S3–S7 (single-family and apartment interiors, Eco Flip Frame only), and S8–S9 (apartment interiors, 88–101 m², all three systems combined).

At site S1 (160 m², two-story detached house, mean winter outdoor temperature –8

degrees C), the protocol used a sequential within-season comparison: six weeks under single-thermostat operation (baseline) followed by six weeks under full distributed adaptive control, both within the same heating season. Meteorological comparability was verified using heating degree days (HDD, base 18 degrees C) from a Metro Ukraine station 1.2 km from the site: baseline mean 312 HDD (SD = 18), experimental mean 308 HDD (SD = 21); $t = 0.43$, $p = 0.67$, confirming no significant difference. Energy consumption was recorded by DIN-rail meters at 15-minute resolution. Thermal comfort was assessed hourly via predicted mean vote (PMV), evaluated against the ASHRAE 55 acceptable band (–0.5 to +0.5).

The pilot site (S2) comprised three five-story reinforced concrete blocks from the 1970s in western Ukraine, totalling 90 apartments across nine clusters. Pre-installation baseline data (12 months of grid import records and outage logs) were obtained from utility billing and the regional distribution network operator (OBLENERGO). The monitoring period recorded solar irradiance within 3% of the 30-year Lviv regional climatological mean (1991–2020, Ukrainian Hydrometeorological Center, 2023). Post-installation monitoring ran for 18 months at 1-minute resolution.

The prefabricated module system (EcoFlipFrame) uses factory-assembled wall and ceiling panels with pre-integrated insulation, HVAC duct chases, electrical wiring harnesses, and IoT conduit. Structural connection is via mechanical quick-connects; MEP interfaces are plug-and-play standardised. Panels arrive dimensionally complete without on-site cutting or MEP rough-in, eliminating the sequential trade coordination that dominates conventional renovation timelines (Rakhimov, 2025 a).

Field deployment covered sites S3–S7 in the same western Ukrainian region. The conventional renovation benchmark of 37.8 working days per 100 m² (SD = 4.3 days, range: 29–46 days) was derived from 22 documented renovation contracts drawn from the Lviv Regional Construction Industry Association database (2023). Occupant displacement was recorded as a binary outcome per site.

Sites S8 and S9 were two residential apartment interiors of 88 m² and 101 m² located in a separate building in the same district as S2, with comparable construction era (1970s), building envelope characteristics, household size, and tariff zone. All three systems were commissioned simultaneously at S8 and S9 during autumn 2024. Cross-system energy data were logged at 15-minute resolution for 90 days through winter 2024–2025. Morning peak demand (06:00–09:00) at S8 and S9 was compared against three micro-grid-only clusters at S2 serving apartments of equivalent area (85–105 m²), using a paired daily comparison over 90 observations.

Results

At site S1, HDD-normalised daily heating consumption fell by 37.6% (68.4 kWh/day baseline vs. 42.7 kWh/day experimental; SD = 4.1 and 3.8 respectively; paired t-test: $t = 18.4$, $df = 41$, $p < 0.001$). The proportion of hourly PMV readings within the ASHRAE 55 acceptable range rose from 58% to 84%, a 45% relative improvement in comfort stability. Zone-level analysis showed the largest energy reductions in south-facing rooms (mean 43.2%) and intermittently occupied bedrooms (41.8%), consistent with the RL policy exploiting predictable occupancy cycles. The RL policy converged within eight commissioning days. During two internet outage events totalling 31 hours, all zone control continued without interruption.

Over 18 months at S2, annual per-apartment grid imports fell by 35% (4,820 kWh/year pre-installation vs. 3,133 kWh/year monitored; 95% CI: 3,041–3,225 kWh). System self-consumption reached 71%; self-sufficiency 48%; mean battery round-trip efficiency 93.2% (SD = 0.8%) across nine clusters. SAIDI fell by 76%: from 4.8 hours/household/year (OBLENERGO pre-installation records, Lviv distribution zone) to 1.15 hours (95% CI: 1.02–1.28 hours). A sensitivity run incorporating LiFePO₄ battery replacement at year 12 (EUR27,000) yields a simple payback of 7.9 years and IRR of 9.4%. Resident satisfaction composite score rose from 33.4 (SD = 5.1) at month 1 to 48.2 (SD = 3.9) at month 18 (paired t-test: $t = 9.8$, $p < 0.001$; $n = 74$ matched respondents).

All configurations satisfy EPBD minimum requirements; R-30 meets Passivhaus airtightness criteria. Mean field renovation time across S3–S7 was 5.1 working days per 100 m² (SD = 0.6; 95% CI: 4.5–5.7 days), against the regional conventional benchmark of 37.8 days, an 86.6% reduction (independent samples t-test: $t = 29.1$, $p < 0.001$). No site required occupant displacement, against an 80–100% displacement rate in the regional conventional dataset (Lviv Regional Construction Industry Association, 2023).

At S8 and S9, joint operation of SmartThermMesh and SolarHomeHub reduced morning peak demand by 23% relative to micro-grid-only reference clusters (mean peak: 4.82 kW reference vs. 3.71 kW integrated; paired t-test over 90 daily observations: $t = 11.3$, $p < 0.001$). SmartThermMesh shifted pre-conditioning load to the 04:00–05:30 window when battery SOC exceeded 70%, reducing battery draw during the morning peak tariff period. This interaction effect was absent when either system operated independently at the S2 reference site.

Discussion

Zone-level resolution explains why the observed heating energy reduction exceeds the 20–25% range reported for model-free RL controllers in comparable residential settings (Biemann et al., 2021). A single thermostat cannot distinguish between a sun-heated south room and a shaded north bedroom simultaneously, whereas the mesh architecture manages each as an independent thermal subsystem. RL convergence within eight days is faster than commercial building benchmarks (Biemann et al., 2021), likely because the lower thermal mass variability of a single-family house reduces the policy search space. The on-device inference architecture resolves a reliability problem documented by Rakhimov (2025c), who reported that cloud-dependent residential HVAC controllers generated occupant dissatisfaction during outage events, a failure mode absent in the present deployment.

The 23% morning peak demand reduction at S8–S9 is statistically robust within its dataset but contingent on a specific alignment of thermal mass, battery capacity, and tariff structure. Whether it generalises to

buildings with lower thermal mass, smaller batteries, or flat-rate tariffs requires purposefully varied multi-site studies. This finding is reported as a system-level interaction effect that becomes visible only when all three layers operate in coordination, not as a claim generalisable from two sites.

Three limitations bound the scope of the findings. All sites are cold-climate western Ukrainian buildings from a specific construction era; performance in warmer climates or post-1990 buildings cannot be inferred. The economic analysis covers a single tariff environment and one battery replacement scenario. EcoFlipFrame joint integrity and MEP interface reliability data beyond three years are not yet available.

Conclusion

Aligning thermal control, electrical autonomy, and structural renovation within a shared operational logic produces outcomes that no single-system intervention matches, and the three sets of field data reported here make that case empirically.

The core intellectual contribution of this work belongs to Rakhimov's recognition that the retrofit integration gap cannot be closed

by optimising individual systems in sequence. The architectural decision to design Smart-Therm Mesh, Solar Home Hub, and Eco Flip-Frame as co-dependent layers – sharing sensor data, load schedules, and commissioning timelines – was made at the design stage, not discovered post-hoc. No published framework prior to Rakhimov's applied research programme combined adaptive HVAC control, cluster micro-grid management, and MEP-integrated prefabrication within a unified operational logic for legacy residential buildings.

Future work should prioritise multi-site replication of integrated deployment across diverse building typologies and climatic zones, full lifecycle cost modelling over 20–25 year horizons incorporating tariff uncertainty, long-term EcoFlipFrame durability monitoring, and investigation of neighbourhood-scale demand aggregation across multiple SolarHomeHub clusters. The methodology developed by Farrukhzhon Rakhimov is replicable with commercially available components and standard communication protocols; the primary remaining barriers are institutional, specifically the absence of integrated subsidy frameworks that incentivise cross-layer retrofit.

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