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Heat Pump Applications in Multi-Family Buildings: A Comparative Analysis of Theoretical Concepts and Real-World Installations

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Abstract

The deployment of heat pumps in multi-family houses (MFHs) is gaining strategic relevance in the context of the energy transition and increasing requirements for energy efficiency in the building sector. Historically, heat pumps have been predominantly applied in new single-family homes. However, recent technological advancements and refined system configurations now allow for economically and technically viable applications in MFHs, both in new developments and retrofit scenarios.

Despite growing evidence from numerous international case studies demonstrating successful heat pump installations in apartment buildings, widespread adoption remains limited. The barriers to broader implementation are multifaceted, involving both technical constraints and administrative challenges.

Within the framework of the HPT IEA projects Annex 50 and Annex 62, a comprehensive evaluation of possible heat pump applications in MFHs has been conducted. Various system concepts were systematically assessed across technical, economic, and operational dimensions.

This contribution presents key outcomes from the IEA studies, compares theoretical design approaches with real-world implementations, and identifies pathways for scaling heat pump adoption in the multifamily housing sector.

Keywords: multi-family buildings (MFH); heat pump systems; retrofit applications; system standardization; building energy efficiency

1. Introduction

The building sector plays a significant role in energy consumption across Europe, accounting for approximately 40% of total energy use and 36% of CO_2 emissions [1]. Multi-family buildings (MFBs) represent a particularly important segment, housing 48% of the European population [2] while presenting unique challenges for renewable energy integration compared to single-family homes.

Heat pump technology has emerged as a key solution for decarbonizing the building sector. While heat pumps have achieved significant market penetration in single-family houses—reaching 50% or more in new constructions in countries like Austria, France, and Germany—their adoption in MFBs remains limited, typically below 20% even in new buildings [3]. This disparity highlights the need for systematic analysis of heat pump applications specifically tailored to the complexities of multi-family residential buildings.

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The variety of MFBs and their characteristics necessitate diverse technical solutions based on heat pumps. However, this heterogeneity leads to individual solutions that are difficult to apply at scale, underscoring the importance for standardization and systematic classification of available options.

2. Bridging Theory and Practice

The IEA Technology Collaboration Programme on Heat Pumping Technologies has spearheaded the Annex 50 and Annex 62 projects to advance heat pump deployment in multi-family residential buildings (MFBs), which pose unique technical and organizational challenges. Annex 50 aimed to identify barriers and develop a standardized theoretical classification of heat pump solutions suitable for diverse MFB types, including new constructions and retrofits with varying heating demands. This effort produced a comprehensive "solution matrix" categorizing 13 system configurations — from fully centralized to fully decentralized — grouped into five families. Simultaneously, a rich database of European case studies was compiled, documenting practical installations to illustrate real-world application and inform stakeholders. Building on Annex 50's foundation [4], Annex 62 focuses on urban MFBs, emphasizing retrofit strategies, system optimization, and hybrid solutions tailored to high-density environments.

Both projects share the core intention to simplify the complexity of heat pump options through a theoretical classification designed to help decision-makers quickly grasp potential solutions for their specific building contexts. Alongside this framework, the continuous aggregation of real implementation examples offers empirical grounding, whereby the combined presentation of classification and case studies effectively bridges theory and practice.

3. General classification

3.1 Solutions matrix

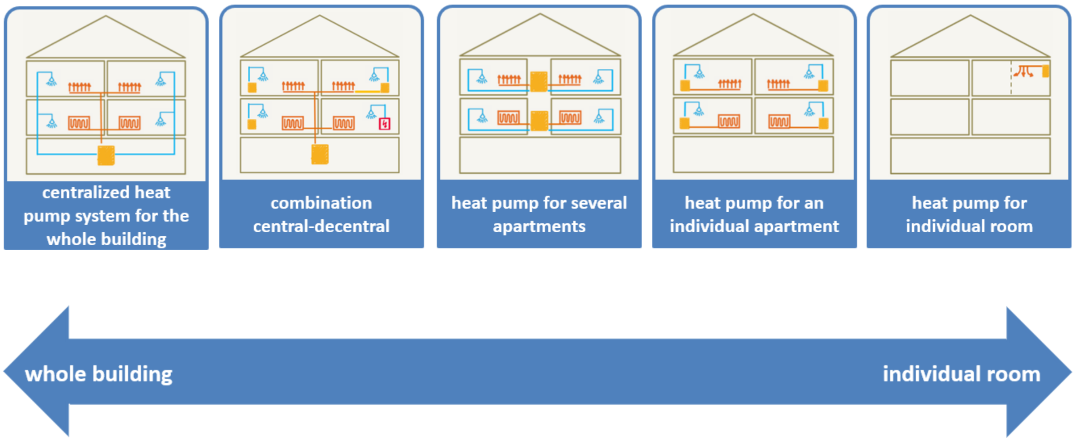

Figure 1. Solutions families.

A key aspect of classifying heat pump systems is to define the level at which the integration is realized, ranging from fully centralized to completely decentralized installations with different types of intermediate solutions. This first level of classification consists of five so-called "solutions families" (Figure 1):

- Family A: Centralized systems with single heat pump for entire building
- Family B: Centralized generation with decentralized hot water preparation
- Family C: Centralized/decentralized hybrid solutions
- Family D: Decentralized systems with apartment-level heat pumps
- Family E: Fully decentralized individual solutions

Table 1 provides a condensed overview of the 13 identified system configurations, organized by centralization level.

Table 1. Solution matrix overview

Family	Solution	Description
A. Centralized	A.1	One central heat pump system for the whole building, both for space heating and DHW.
	A.2	One heat pump system for each mode. One for space heating, separate one for DHW.
	A.3	One heat pump system for the space heating, separate heat generator (fossil, biomass, electric, …) for DHW.
	A.4	One HP system for DHW, separate heat generator (fossil, biomass, electric, …) for space heating.
	A.5	One hybrid heat pump system for space heating and DHW for the whole building.
B. Combined	B.1	One central heat pump system for one mode (for example space heating) and decentral heat pumps for the second mode (for example DHW).
	B.2	One central heat pump system for one temperature level and decentral (booster) heat pumps for reaching the needed final temperature (for example DHW).
	B.3	Central heat source and decentral heat pumps providing space heating and DHW
C. Grouped	C.1	One HP per apartment group
	C.2	Apartments grouped by generator
D. Individual	D.1	Individual solution per apartment
	D.2	One apartment - one mode
E. Room-based	E.1	HP for individual room

3.2 Parameters

Following the classification of heat pump solutions for multi-family residential buildings, a set of evaluation parameters was defined to enable comprehensive assessment of each solution's suitability and performance in different building and operational contexts. These parameters include building size suitability (small/medium/large), building insulation quality (good/average/poor), system complexity, fossil energy dependence, space requirements, heat source flexibility, and investment costs.

Note on Parameter Coverage: The current parameter framework does not systematically capture two important technical aspects: (1) type of building heating distribution system (floor heating, radiators, etc.) and (2) domestic hot water (DHW) preparation method (direct, with storage, etc.). This limitation reflects the heterogeneity of data available from case studies. Future refinements of the classification should incorporate these parameters to enable more detailed system comparisons.

4. Case studies

4.1 Case Study Collection

The Project 62 Case Studies Database currently contains close to 100 case studies from 16 participating countries, building upon the foundation established by Annex 50 (completed 2018), of which approximately 80 have sufficient data for comprehensive statistical evaluation.

Each case study is documented using a standardized template capturing building characteristics (construction year, heated area, number of apartments, insulation level), heat pump system specifications (type, capacity, heat source, operation mode), performance data (SPF/COP, heat demand, supply temperatures), and critically, "Lessons Learned" from practical implementation.

The database follows the Solution Matrix categorization system with five main solution families. The standardized documentation format enables direct comparison and statistical analysis across different system configurations, climatic zones, and building types, providing invaluable insights into the gap between theoretical design and real-world performance.

4.2 Statistical evaluation

The analysis of 78 documented case studies from the IEA HPT TCP Project 62 (Figure 2) reveals a clear dominance of centralized heat pump systems (Family A) with a total of 60 projects, representing 77% of all cases. Within this category, solution A5 (central system with multiple heat pumps) is most prevalent with 26 projects (33%), followed by A1 (central single heat pump) with 20 projects (26%).

Apartment-level solutions (Family B) account for 14 case studies, approximately 18% of the total, with variant B3 (individual heat pumps with shared heat source) leading with 6 projects. Family D cases are significantly underrepresented with only 4 documented cases (5%), while category D2 (individual exhaust air heat pumps) has not yet been implemented in practice.

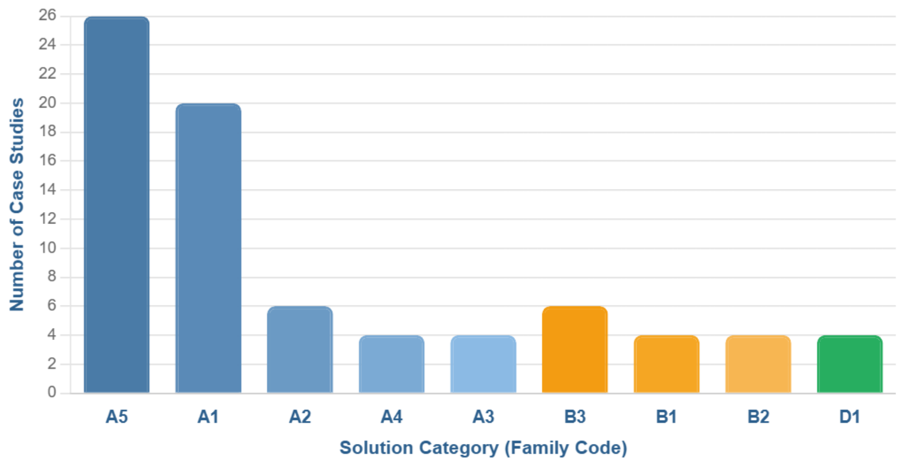

Figure 2. Distribution of Case Studies by Solution Categories (Family Codes)

This distribution reflects practical reality, where centralized solutions are preferred for larger buildings due to established infrastructure and favorable overall costs. At the same time, the various subcategories within families A and B demonstrate that there is no "one-size-fits-all" approach, and system selection strongly depends on building-specific framework conditions.

4.3 Limitations of the Statistical Analysis

While the case study database represents valuable documentation of real-world installations, the quality and completeness of master data varies significantly across projects. Critical parameters such as precise energy consumption figures, detailed operating conditions, economic data, and standardized performance metrics were not systematically collected for all cases. This heterogeneity in data quality prevents comprehensive statistical analysis and quantitative comparisons across the full dataset. The following analysis therefore focuses on qualitative patterns and representative examples rather than statistical aggregations. Future database development should prioritize standardized data collection protocols to enable more rigorous quantitative evaluation.

4.4 Additional Considerations

The case studies span approximately 20 years (from Annex 50 to current Annex 62), during which technology, regulations, and installation practices have evolved significantly. Direct comparisons between older and newer projects may not fully account for these technological advances. Furthermore, the dominance of certain solution types may reflect country-specific regulations, subsidy structures, and market preferences rather than universal technical superiority. Results should therefore be interpreted within their specific market contexts.

4.5 Selected Case Studies

Rather than presenting exhaustive descriptions, this section highlights selected representative case studies that illustrate the diversity of implemented solutions and demonstrate key technical success factors and challenges. Table 2 presents these examples in structured format, organized by solution family and key technical parameters.

Table 2. Selected Representative Case Studies

Solution A.1: Centralized Air-Source System for Retrofit **Example: St. Julien, Geneva, Switzerland** The St. Julien project demonstrates successful heat pump retrofit of poorly insulated buildings without major envelope renovations. This 1972 building with 53 apartments (4,049 m^2) was retrofitted with two 156 kW air-source heat pumps operating monovalently with existing radiators unchanged. Despite poor insulation requiring supply temperatures up to 65°C, the system achieved SPF 2.3, with DHW accounting for 42% of total demand. The initial 300 kW oil boiler backup proved unnecessary and was removed after two years. Key lessons include the importance of proper pump regulation, attention to DHW circulation losses, measuring actual building demand to avoid oversizing, and implementing noise-reduction measures for industrial heat pumps in residential settings.
Solution A.5: Centralized Bivalent System with PVT Collectors **Example: Smart Quarter Karlsruhe-Durlach, Germany** The Smart Quarter project demonstrates innovative technology integration in a 1963/1995 building serving 30 apartments (2,112 m^2). The system features a 55.4 kW high-temperature heat pump capable of 75°C supply temperatures, combined with 202 m^2 PVT collectors that provide both photovoltaic electricity and thermal heat collection. Operating bivalently with gas boiler backup, the system includes SG-ready interface for optimizing PV and CHP self-consumption. The Low-Ex distribution approach enabled retention of 137 of 150 original radiators after reducing temperatures to 55/45°C. A pilot ultrafiltration system enables DHW temperature reduction from 62°C to 55°C while maintaining hygiene standards, demonstrating that efficiency and safety requirements need not conflict.
Solution B.2: Individual Mini Heat Pumps Fed by Central Loop **Example: The Fennerstrasse project in Innsbruck** The Fennerstrasse project demonstrates an innovative hybrid approach where 48 apartments switched from individual boilers to combined centralized-decentralized heat pump technology. A large central rooftop heat pump distributes energy through stairwells at an extremely low flow temperature of only 20°C, while individual 3 kW mini heat pumps in each apartment increase temperature to meet heating and DHW needs. This system achieves SCOP 4.0 with exceptional quietness (38 dB), housed in wall-mounted units barely larger than gas boilers. The ultra-low central loop temperature (20°C vs. conventional 80°C district heating) dramatically reduces circulation losses. The mini heat pumps work directly with existing radiators, allowing installation without tenant relocation—a critical advantage for retrofit projects. Stakeholders agree this represents a valuable blueprint for future renovations in existing buildings.
Solution B.3: Collective Heat Source with Individual Heat Pumps **Example: Kensa & Thurrock Council, Chadwell St Mary, UK** The Chadwell St Mary project represents a groundbreaking retrofit of three high-rise tower blocks where 273 storage heaters are being replaced with individual 3-6 kW ground source heat pumps connected to a Shared Ground Loop Array (SGLA). Ground borehole clusters transfer ambient temperatures (-5°C to 20°C) to a communal fifth-generation district heating loop, which feeds each individual heat pump that independently provides heating (up to 65°C) and hot water. The system achieves COP 3.84 per unit and projects 40-50% fuel bill reductions—crucial as over half of recipients face fuel poverty—with expected 70%+ carbon emission reduction and lifetime savings of 7,080 tons CO_2. The project demonstrates that shared ground loop technology can decarbonize multiple properties rapidly and affordably at scale, particularly valuable for high-rise developments.

Solution D.1: Exhaust Air Heat Pump per Apartment
Example: Retrofit of 112 Flats, Flers, France
The Flers retrofit project demonstrates comprehensive energy renovation of 112 flats (each ~60 m²) in a 1963 building, improving the energy label from D to A for consumption and F to A for emissions, reducing tenant costs and carbon footprint by 50%. The collective boiler room and individual bath heaters were replaced with NIBE F730 exhaust air heat pumps in each flat—compact all-in-one units with no outdoor units that integrate mechanical ventilation, space heating (55°C radiators), and DHW (180-liter tank) achieving SPF 3.38. The heat pumps recycle warm ventilation air to produce heating and hot water, with load shedding capability via current sensors if needed. Combined with comprehensive envelope renovation (external insulation, new windows, renovated roofs), the project proves that compact exhaust air solutions are ideal for replacing individual boilers in retrofits with minimal installation complexity.

5. Key Findings Across All Examples

The following key findings emerge from systematic analysis of the case study database and comparative evaluation against the theoretical classification framework. Each finding is grounded in empirical observations from implemented projects.

5.1 Technical Success Factors

Continuous monitoring and optimization prove essential across all case studies. Real-world performance often deviates from design calculations (as demonstrated by the Vienna and Paris projects), necessitating ongoing stakeholder cooperation for system tuning. Projects achieving SPF values above 3.5 consistently employed active monitoring and adjustment protocols during the first operational year.

Lower distribution temperatures consistently improve efficiency across all solution families. The Zurich retrofit project achieved SPF 3.2 despite existing building stock by reducing system temperatures to 45/35°C, while the Amsterdam ambient loop installation demonstrated that even radiator systems can operate efficiently when properly dimensioned. Buffer tanks enable better optimization of heat pump operation, particularly evident in the Paris case where storage integration improved load management and reduced cycling.

Smart control strategies balancing space heating and DHW demands prove crucial for overall performance. The Berlin and Stockholm projects both implemented predictive controls that reduced DHW-related efficiency losses by 8-12% compared to conventional time-based controls.

5.2 Innovation Trends

Heat source diversification represents a major innovation trend. The Vienna wastewater project achieved exceptional performance (SPF 3.8) through consistent source temperatures, while the Amsterdam ambient loop demonstrates viability of low-temperature networks for district-scale implementation. The industry shows a clear shift toward natural refrigerants, with R290 (propane) increasingly deployed in decentralized solutions as exemplified by the Berlin installation.

Retrofit capability is enhanced by solutions that work with existing radiator systems, as demonstrated in Amsterdam and Zurich, enabling faster adoption in existing building stock without extensive distribution system replacement. Hybrid approaches (Family C solutions) prove particularly valuable for challenging retrofit scenarios where complete system replacement is economically or technically prohibitive.

5.3 Consistent Challenges

DHW demand consistently exceeds design predictions across multiple projects. The Paris and Berlin installations both reported actual DHW consumption 15-25% higher than norm-based calculations, directly impacting overall system efficiency. This systematic discrepancy suggests that standard design assumptions underestimate real-world domestic hot water use in multi-family contexts.

User behavior differs from norm assumptions regarding indoor temperatures and ventilation patterns. Several case studies reported thermostat settings 1-2°C above design assumptions, with corresponding efficiency impacts. Projects must balance competing priorities such as DHW temperature requirements for Legionella prevention (minimum 60°C) versus efficiency optimization (which favors lower temperatures), while addressing acoustic and visual integration requirements in urban settings.

5.4 Documented Performance

Documented performance across the case studies demonstrates that SPF values of 2.7 to 4.0 are achievable across different system types and building contexts. High renewable energy shares of 80% or more have been successfully demonstrated in multiple projects (Vienna, Berlin, Stockholm). Systems have proven successful operation in various climate conditions from Nordic (Stockholm) to Central European (Vienna, Zurich, Paris) and maritime (Amsterdam) climates. Retrofit solutions have been validated as viable alternatives for existing buildings, with the Zurich, Amsterdam, and Paris projects showing that proper system design can overcome building stock limitations.

6. Discussion

The results presented from Annex 50 and Annex 62 represent the best of our current knowledge and understanding. Nevertheless, some limitations should be acknowledged.

The description of the proposed "solution matrix" should be seen as a framework prepared for further elaboration rather than an accomplished task. Each description represents a compromise between various views of the involved Annex partners. In some cases, specific national perspectives result in different views on the topic. Opening this discussion to the broader research and practitioner community is recommended to refine these concepts further.

With the simplified approach chosen to classify and describe the solutions, the planned tool "solution finder"—suggesting particular solutions for certain types of buildings—should not be regarded as a "pre-planning" tool. Rather, it serves, and will continue to serve even with improvements, as a decision-support aid to identify suitable solutions and explore available options.

The case studies database serves as a valuable tool with significant potential for expansion. The collected cases demonstrate the successful applicability of heat pumps in multi-family buildings. Despite significant efforts, ensuring uniform detail and completeness across all case descriptions was not fully achievable with the available information, as discussed in Section 4.1. The database should be further developed with more case studies and standardized data collection protocols to reach its full analytical potential.

Overall, it is highly recommended that the work continues and builds upon the results already achieved.

7. Conclusions

This comparative analysis of theoretical concepts and real-world installations demonstrates that heat pump systems in multi-family buildings are technically feasible and increasingly practiced across Europe and other regions. The classification framework provides valuable structure for understanding the diversity of possible solutions, while case study analysis reveals the complexity and innovation occurring in practice.

Key findings indicate that successful implementation requires careful matching of technical solutions to building characteristics, with centralized systems (Family A) dominating in larger buildings and hybrid approaches (Family C) proving valuable for challenging retrofits. The significant variation between theoretical concepts and practical applications underscores the importance of flexibility in system design and the need for continued innovation in addressing MFB-specific challenges.

While technical solutions exist for virtually all MFB contexts, broader deployment requires addressing non-technical barriers including standardization, capacity building, and financial mechanisms. The transition to heat pump systems in MFBs represents not merely a technical challenge but a complex socio-technical transformation requiring coordinated efforts across the building sector.

Future research should focus on long-term performance monitoring of implemented solutions, development of standardized design tools with systematic data collection protocols, and investigation of novel business models addressing the unique challenges of multi-family residential buildings. As Europe advances toward climate neutrality, the systematic deployment of heat pumps in MFBs will play an increasingly critical role in achieving decarbonization goals while ensuring comfortable and affordable housing for all residents.

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