"Energy, economic and environmental(3E) assessment of low-GWP combined ASHP systems for residential building heating decarbonization"

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Abstract

This study conducted a comprehensive energy, economic, and environmental (3E) evaluation that considers energy performance, economic feasibility, and environmental impact in residential heating and domestic hot-water systems. The assessment incorporated ASHP and ASHP-VI cycles as well as low-global-warming-potential refrigerants, with the overarching goal of supporting decarbonization in the residential sector. Previous studies have often been limited by narrow climate conditions, restricted refrigerant options, simplified system configurations, or evaluations based on a single performance metric. To overcome these constraints, the present study developed a simulation-based framework that integrates multiple climates and system arrangements, thereby providing a broader and more holistic perspective on 3E performance. In addition, a hybrid combined ASHP strategy was introduced to address the operational instability and performance degradation commonly observed in ASHP systems during winter operation. In this configuration, the supply-water temperature is controlled based on the compressor discharge temperature, and an auxiliary boiler is incorporated to supplement the heating demand when necessary. The results indicate that the application of ASHPs reduced energy consumption by an average of 57.7% across all regions compared with the conventional gas-boiler system. The ASHP-VI system using R290 achieved the highest overall performance, with an average reduction in energy consumption of 72.4%. This configuration also demonstrated the most favorable economic and environmental outcomes, achieving carbon-emission reductions of up to 36.2% compared with the gas boiler. These findings provide meaningful insights that can support the wider adoption of safe, efficient, and environmentally responsible heating technologies in the residential sector, particularly as national policies increasingly emphasize the transition toward carbon neutrality.

Keywords: Air-source heat pump; Building Energy; 3E performance assessment; Life cycle cost; Life cycle climate performance

1. Introduction

Global efforts to mitigate greenhouse gas (GHG) emissions have intensified under international agreements such as the Paris Climate Accord, and many countries have established ambitious Nationally Determined Contributions (NDCs) targeting a 45% reduction in emissions by 2030 and carbon neutrality by 2050 [1,2]. Achieving these targets necessitates significant reductions in energy consumption across key sectors, including industry, transport, and buildings. Within IEA member countries, the residential building sector accounts for approximately 22% of total energy use, of which space heating represents nearly 69% [3]. Consequently, numerous European countries are accelerating the adoption of heat pump technologies powered by renewable energy sources to transition toward low-carbon heating. In Korea, where multi-family residential buildings dominate, the deployment of geothermal or water-source heat pumps is often constrained by limited installation

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space, complex infrastructure requirements, and high capital costs. As a result, air-source heat pumps (ASHPs), which require neither auxiliary heat-source facilities nor extensive structural modifications, have emerged as a highly promising alternative.

Previous research on ASHP integration in buildings has largely concentrated on isolated assessments of energy performance, economic feasibility, or environmental impact, with only a limited number of studies addressing these aspects in combination [4]. Even in studies adopting broader evaluation frameworks, analyses were typically restricted to specific climatic conditions or focused predominantly on detached houses [5]. However, multi-family residential applications require a more holistic assessment that simultaneously considers operational performance across diverse outdoor conditions, lifecycle economic outcomes, and long-term environmental implications—an aspect insufficiently explored in existing literature.

To address these research gaps, this study presents a comprehensive 3E (energy, economic, and environmental) evaluation of an advanced ASHP system incorporating a vapor-injection (VI) cycle (ASHP-VI). The analysis is conducted under multiple representative Korean climate conditions and includes various low-GWP refrigerants to quantify climate- and refrigerant-dependent performance variations. In addition, a combined ASHP configuration is proposed to enhance operational stability and reliability during severe winter conditions by dynamically adjusting key operating parameters. The outcomes of this study provide valuable insights for the large-scale deployment of ASHPs in multi-family residential buildings and support policy development aimed at achieving national carbon-neutrality goals.

2. Model development

2.1. Residential building model

A 60-unit multi-family residential building currently under construction in Sejong, Korea, was selected as the representative model [6]. The space-heating load was evaluated using TRNSYS 18, incorporating the outdoor temperature profiles of three climatic regions: Busan (warm, case 3), Sejong (mild, case 2), and Daegwallyeong (cold, case 1). Domestic hot-water loads were calculated using a modified BIN method. In addition, the time step for the TRNSYS and modified BIN-method analyses used to calculate the space-heating and domestic hot water loads was set to 1 hour. The building model adopted in the simulation, along with the corresponding regional weather conditions and the total building energy demand derived from the simulations, is illustrated in Fig. 1. These load profiles served as the basis for a comprehensive 3E (energy, economic, and environmental) comparison between a conventional gas-boiler system and an air-source heat pump (ASHP).

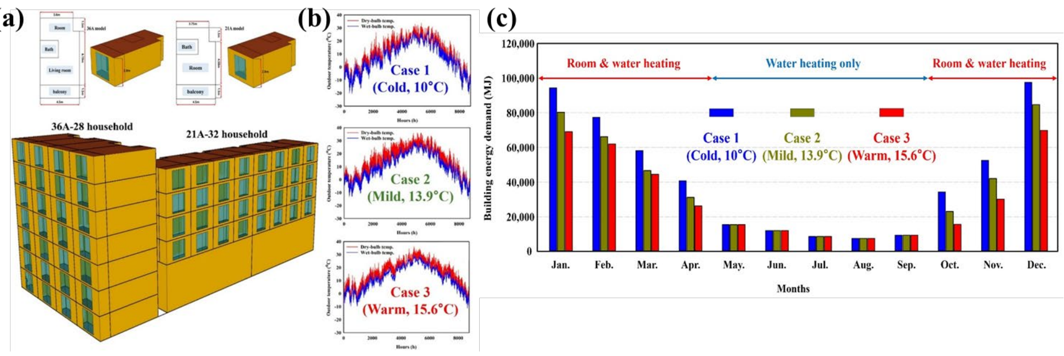

Figure 1. Residential building model. (a) Building geometry and 3D building model. (b) Outdoor temperature according to region. (c) Total building energy demand for different regions.

2.2. Air-source heat pump

The heat pump cycle was analyzed using Engineering Equation Solver (EES) [7]. Model validation was conducted based on the manufacturer's performance catalogue (Company C), and the predicted compressor power consumption, heating capacity, and coefficient of performance (COP) showed maximum deviations of 13.7%, 10.22%, and 9.78%, respectively. To address the degradation of air-source heat pump (ASHP) performance under low ambient temperature conditions and to ensure stable supply-water temperatures during winter operation, a vapor-injection (VI) cycle was incorporated into the system model. The VI cycle operates by diverting a portion of the condensed refrigerant and expanding it to an intermediate pressure through an auxiliary expansion valve. The resulting two-phase refrigerant is separated in a flash tank, where the saturated vapor is injected into the intermediate port of the compressor, while the remaining liquid refrigerant continues to the main expansion valve and evaporator. This injection process increases the effective refrigerant mass flow rate through the evaporator, reduces the overall compression ratio, and alleviates excessive compressor discharge temperatures, thereby enhancing heating capacity and operational stability under cold-climate conditions.

In this study, R410A was selected as a baseline refrigerant and simulated both with and without the vapor-injection cycle to explicitly isolate and quantify the performance impact of VI relative to a conventional single-stage ASHP configuration. For low-GWP alternatives, namely R32 and R290, only vapor-injection configurations were considered, as VI operation is generally required to mitigate discharge temperature limitations and performance degradation associated with high pressure ratios during low-temperature heating operation. In addition to the standalone ASHP configurations, a combined ASHP system incorporating a backup boiler was introduced. This combined configuration reduces the ASHP outlet temperature while providing auxiliary heating through the boiler when required, thereby ensuring stable supply-water temperatures under severe operating conditions. Fig. 2 presents a schematic of the combined ASHP system and compares the monthly heating COP of the ASHP and ASHP-VI systems across the three regions.

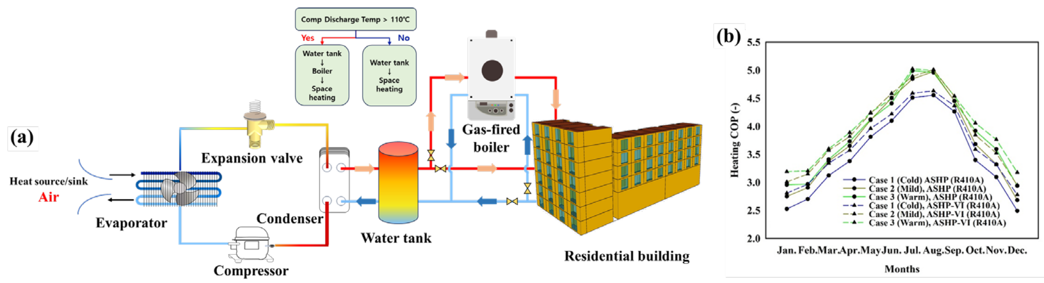

Figure 2. ASHP system. (a) Schematic of combined ASHP system. (b) Comparison between ASHP and ASHP-VI in terms of monthly heating COP

The baseline heating and domestic hot-water system for the multifamily building was assumed to be a gas boiler, which operates on LNG rather than electricity, unlike the heat pump. For comparison with the ASHP system, the gas-boiler energy consumption was calculated by dividing the building's total thermal load by the boiler efficiency. The boiler efficiency was set to 92%, corresponding to the average performance of major condensing-boiler manufacturers in the Korean market.

3. Results and discussions

3.1. Energy analysis

Based on the annual thermal load of the multifamily building and the operating performance of the combined ASHP system calculated in the previous sections, the annual energy consumption was evaluated for each region and refrigerant option. The resulting annual energy use and primary energy consumption for the different regions and system configurations are presented in Fig. 3(a) and Fig. 3(b), respectively.

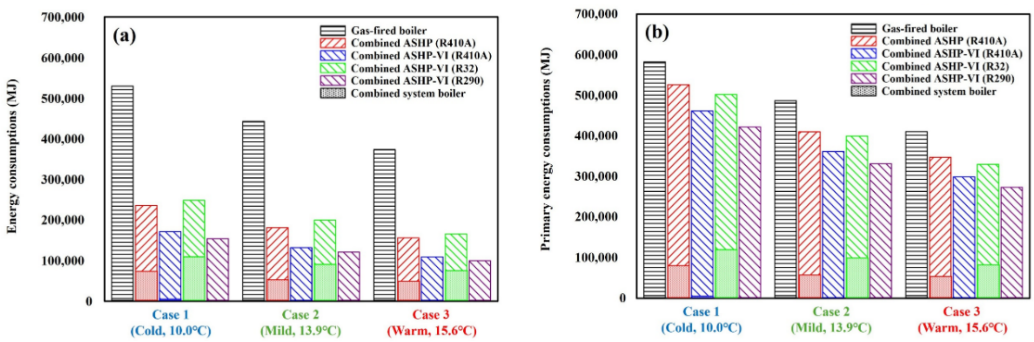

Figure 3. Annual (a) energy consumption and (b) PEC for combined heating systems across different regions.

To enable an equivalent comparison between the gas boiler and the heat pump—which utilize different energy sources—the primary energy consumption was determined using the primary energy conversion factors for gas and electricity, as expressed in Eq. (1). A conversion factor of 1.1 was applied for gas and 2.75 for electricity [8].

$$E_{PEC} = E \times Primary\ energy\ coefficient \quad (1)$$

In the R410A and R32 cases, the compressor discharge temperature exceeded 110 °C at low outdoor temperatures in winter, which increased the operating share of the gas boiler. In contrast, for the R290-based ASHP-VI cycle, the compressor discharge temperature remained stable even under low outdoor-temperature winter conditions, and the gas boiler did not operate.

When the baseline R410A ASHP was applied, the annual energy consumption decreased by an average of 57.7% across all regions compared with the conventional gas-boiler system. The ASHP-VI (R410A) configuration further enhanced performance, achieving up to a 30.2% reduction relative to the standard ASHP (case 3). Among the refrigerants evaluated, R290 exhibited the most favorable thermophysical characteristics, resulting in an average 34.7% decrease in energy consumption compared with the basic ASHP. In contrast, the application of R32 led to an increased reliance on the auxiliary boiler within the combined ASHP system due to its inherently high compressor discharge temperature, ultimately causing higher overall energy consumption than R410A. When converted to primary energy to ensure an equivalent comparison between electricity- and gas-based systems, the combined ASHP consistently showed lower primary energy use than the existing gas-boiler system across all regions. These results demonstrate that the combined ASHP configuration not only ensures stable winter operation but also provides substantial energy-saving potential relative to conventional heating systems.

3.2. Economic analysis

The economic assessment was conducted using the Life Cycle Cost (LCC) methodology to evaluate the long-term cost performance of residential heating and cooling systems. The LCC includes all costs incurred over the system lifetime, such as initial investment, operation and maintenance, and end-of-life disposal. Based on the simulated annual energy consumption, the operating cost of each system was calculated, and a 30-year LCC was determined considering capital, operating, and maintenance costs as well as the expected service life of the installed equipment.

The 30-year LCC evaluation showed that construction cost accounted for the largest share of total life-cycle expenditures. As a result, most alternative systems exhibited higher total LCC values than the baseline gas boiler system (USD 693,943), despite reductions in operating cost. The only exception was the ASHP-VI (R290) configuration, which achieved approximately 53% lower operating costs compared with the gas boiler system, with 30-year operating costs of USD 49,505 and USD 110,587, respectively. Among all climate cases, the lowest 30-year LCC of USD 679,292 was obtained for the ASHP-VI (R290) system in Case 3, where the heating demand is relatively low. Although ASHP systems generally demonstrated substantial operating cost savings, these were largely offset by higher initial investment, resulting in limited economic benefit in terms of total LCC, except for the ASHP-VI (R290) system.

3.3. Environment analysis

The environmental impact assessment was conducted using the Life Cycle Climate Performance (LCCP) methodology developed by the International Institute of Refrigeration (IIR, 2006) [9]. LCCP is calculated as the sum of direct and indirect emissions. Direct emissions include annual refrigerant leakage and end-of-life losses during system disposal, while indirect emissions account for CO_2 released due to electricity consumption during system operation, as well as emissions associated with raw material extraction, component manufacturing, refrigerant production, and recycling processes. The calculation variables were set based on the LCCP guidelines and the ASHP product catalog [10], as detailed in Table 1.

Table. l Input values for LCCP calculations

Item	Value
C (kg)	14.7
L (years)	15

ALR (%)	4
EOL (%)	15
EM ($kgCO_{2e}$/kWh)	0.4598 (Electricity), 0.201 (LNG)
RM ($kgCO_{2e}$/kg)	0.07 (Meatal), 0.01 (Plastics)
RFM ($kgCO_{2e}$/kg)	10.7 (R410A)
	7.2 (R32)
	0.05 (R290)

The LCCP results show that the conventional gas-boiler system exhibited higher carbon emissions than all ASHP configurations across every climate condition due to its reliance on fossil fuels. Although carbon emissions increased in Case 1, where the heating load is highest, the ASHP systems demonstrated improved performance in milder climates. Among all systems, the ASHP-VI (R290) configuration showed the greatest reduction, achieving up to 31.7% and 36.2% lower total emissions compared with the gas boiler in Case 1 and Case 3, respectively, thereby exhibiting the most effective environmental performance.

4. Conclusions

Most existing studies on ASHPs have focused on basic system performance using standard refrigerants such as R410A, typically evaluated for single-family homes or under a single climatic condition. To address these limitations, this study conducted an integrated 3E (energy, economic, and environmental) assessment of a combined ASHP system aimed at decarbonizing heating and domestic hot-water supply in multifamily residential buildings. The simulation results demonstrated that the ASHP-VI (R290) configuration outperformed all other systems across every evaluation metric. Compared with the conventional gas-boiler system, the proposed configuration achieved reductions of up to 72.4% in energy consumption and 36.1% in carbon emissions, while also delivering favorable LCC outcomes despite its higher initial investment cost. Overall, this study provides meaningful insights into building-sector decarbonization by presenting comprehensive performance evaluations across multiple refrigerants and climate conditions for a real multifamily residential building.

Acknowledgements

This work was supported by the Basic Research Program through the National Research Foundation of Korea (NRF) funded by the MSIT (No. RS-2025-00512709), and supported by the Korea Evaluation Institute of Industrial Technology (KEIT) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea) (Grant No. RS-2024-00442911).

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