아주대학교 AJOU UNIVERSITY

히트펌프 전환을 위한 자연냉매 R290 적용 기술과 과제

2026.11.23

Presenter: **Yongseok Jeon**

Dept. of Mechanical Engineering

Ajou University

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01 Profile

Personal Background and Research Achievements



EDUCATION & PROFESSIONAL EXPERIENCE:

2007-2011 BS, Korea University, Mechanical engineering

2011-2017 Ph. D, Korea University, Mechanical engineering (R.A. Yongchan Kim)

2017-2019 Research professor, Korea University, Mechanical engineering, Seoul, Korea

2019-2021 Assistant professor, Chonnam National University, Yeosu, Korea

2021-2024 Associate professor, Korea Maritime & Ocean University, Busan, Korea

2024-Present Associate professor, Ajou University, Suwon, Korea

RESEARCH ACHIEVEMENTS:

Journal Paper : SCI(E) 49 (29 as first or corresponding author)

Patent : 11 (International 4, Domestic 7)

Research project : 8 (3: Main researcher, 5: Co-researcher)

PROFESSIONAL ACTIVITIES:

대한기계학회 열공학부문 편집이사, **한국유체기계학회 전자장비열관리부문** 총무이사

대한설비공학회 (냉동, 히트펌프, 콜드체인, 열저장 등) 부문이사, **한국지열수열에너지학회** 총무이사

한국산업기술기획평가원(KEIT) 에너지기계 분야 **기획위원 (2024~)**

한국에너지기술평가원(KETEP) 에너지인력양성 로드맵 **분과위원 (2026~)**

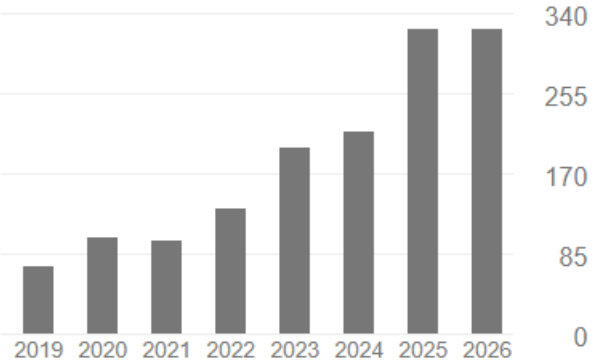
국토교통부(MOLIT) 데이터센터 설비 모듈화 기술개발 **기획위원 (2026~)**

한국환경산업기술원(KEITI) 데이터센터 수열 활용 냉각 기술(DLC) **기획위원(2026~)**

한국환경산업기술원(KEITI) 국제협약 대응형 불소계 온실가스 저감 기술개발사업 **기획위원(2026완)**

인용 모두 보기

	전체	2021년 이후
서지정보	1570	1313
h-index	24	23
i10-index	33	32



01 Profile

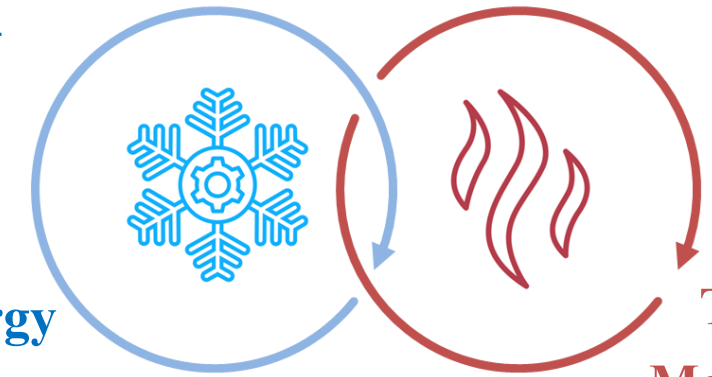
Research Projects and Thermal Energy & Refrigeration Lab.

RESEARCH PROJECTS:

과제명	전문기관(사업명)	연구기간	역할	연구비 (Lab Share)
상변화 멀티노즐 제트충돌 액침냉각 기반 Zero-TR/TP 지향 배터리 열관리 기술 개발	**한국연구재단** (우수신진연구 유형B)	2026.03 – 2030.02	연구책임자	**7.5 억**
폐플라스틱 탄소중립 자원순환 기초연구실 (with KU)	**한국연구재단** (기초연구실, BRL)	2025.03 – 2028.02	공동연구원	**15억 (3 억)**
고발열 데이터센터 열관리를 위한 고열유속 콜드플레이트 성능 분석 연구	**해양수산부, K-HVAC** (위탁연구)	2026.07 – 2028.12	연구책임자	**6 억**
Low GWP 냉매적용 히트펌프식 고효율 항공기 PCA 시스템 개발	**한국산업기술평가원** (제조기반생산시스템)	2024.07 – 2028.03	공동연구원	**43억 (4 억)**
배터리 팩 단위 열폭주 화재 가능성 분석 모델 개발 용역	**철도기술연구원** (연구용역)	2026.02 – 2026.10	연구책임자	**0.3 억**
공동주택 지열히트펌프시스템 실측데이터 기반의 성능 모니터링 연구용역	**LH한국토지주택공사** (연구용역)	2025.09 – 2026.12	공동연구원	**1.2억 (0.3 억)**
흡수식냉동기 열교환기 세관 후 에너지 절감 효과 분석 연구	**한국지역난방공사** (연구용역)	2026.04 – 2026.10	공동연구원	**0.8억 (0.2억)**
스마트 에너지-AI 열유체기기 시스템 인력양성	**한국에너지기술평가원** (교육훈련)	2026.04 – 2030.02	참여교수	**23.9억 (약 3.5억)**

Thermal Energy & Refrigeration Lab.: (열에너지 및 냉동공조 연구실)

Research Areas:



Thermal Energy System
(Refrigeration & Heatpump)

Thermal Management System

Research Team:



Postdoctoral Researcher	1
Ph.D. Student	4
M.S. Student	7
Undergraduate researcher	6
Total	18

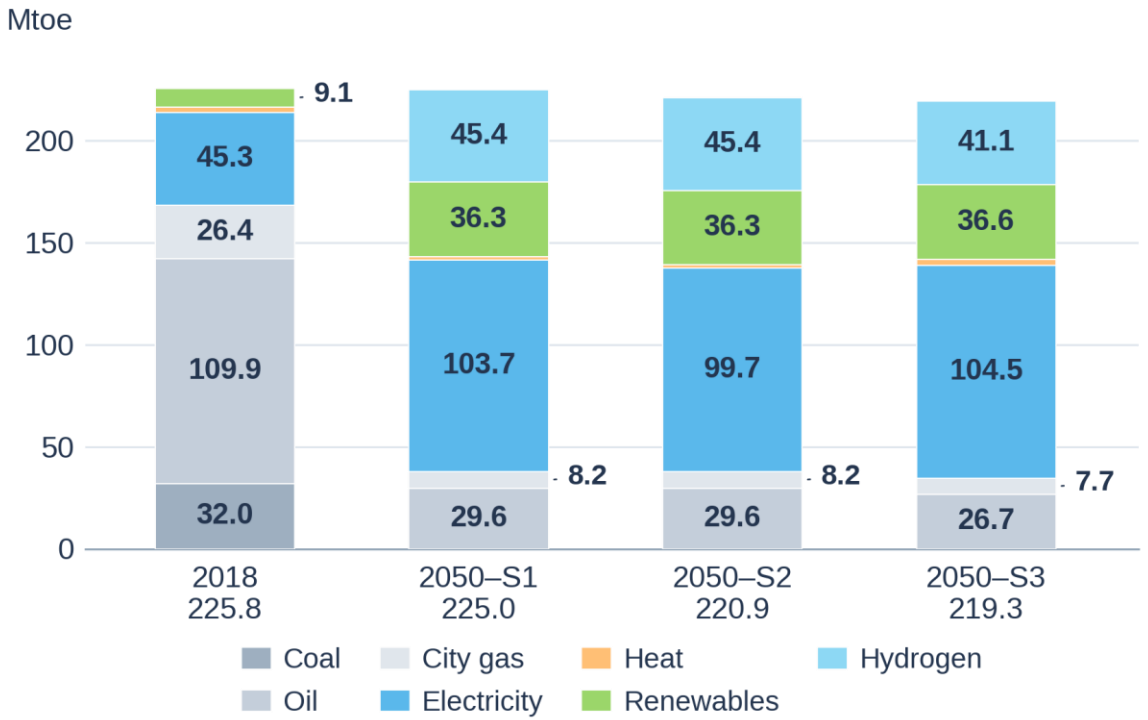
01 Introduction

Buildings Account for 34% of Global Final Energy Demand

Carbon Neutrality and Energy Use in Buildings

Korea's 2050 energy scenarios

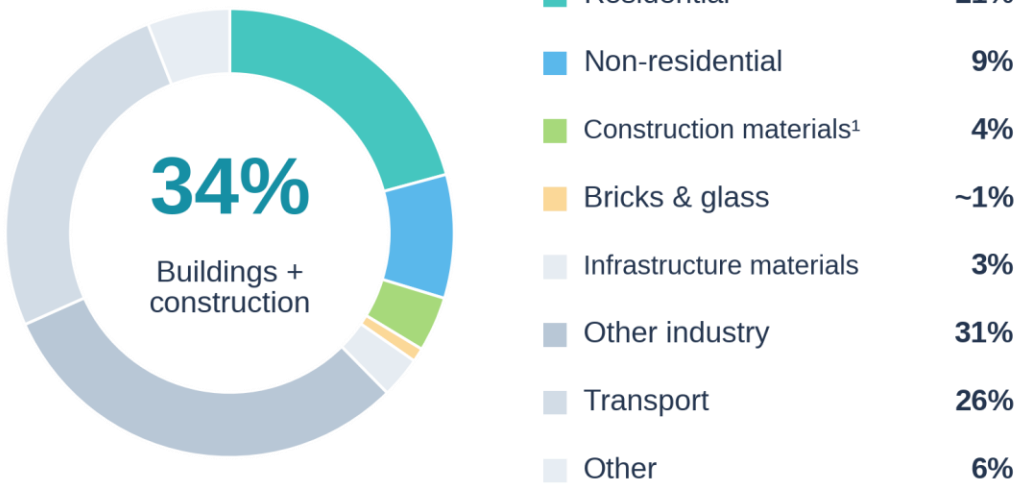
2021 draft scenarios, final energy demand (Mtoe)



Reported totals below bars; source sums differ slightly

Global final energy demand

2021 data, GlobalABC 2022 report



Building operation 30% + construction 4%

[1] Concrete, steel and aluminium for buildings

Reported shares are rounded and sum to 101%

Electrification and building efficiency are central to the energy transition

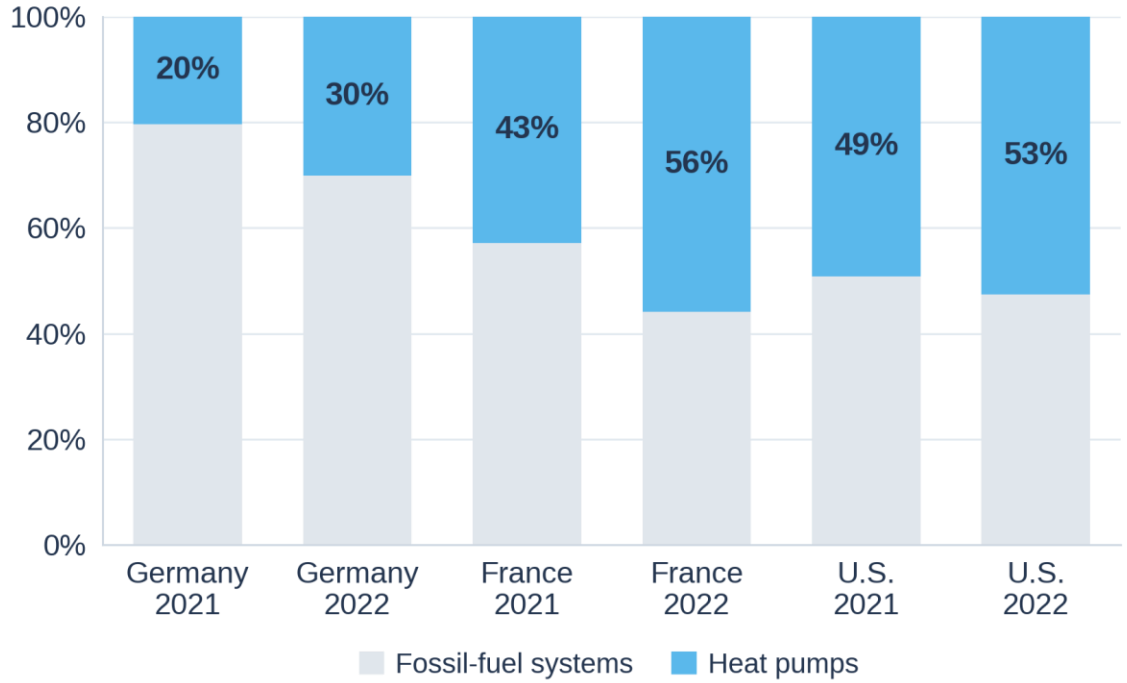
Sources: Korea 2050 carbon-neutrality scenarios (2021 draft); UNEP / GlobalABC, Global Status Report 2022.

Heat Pump Sales Growth in Major Markets, 2021–2022

Heat Pump Market Trends

Heat pump share of heating-system sales

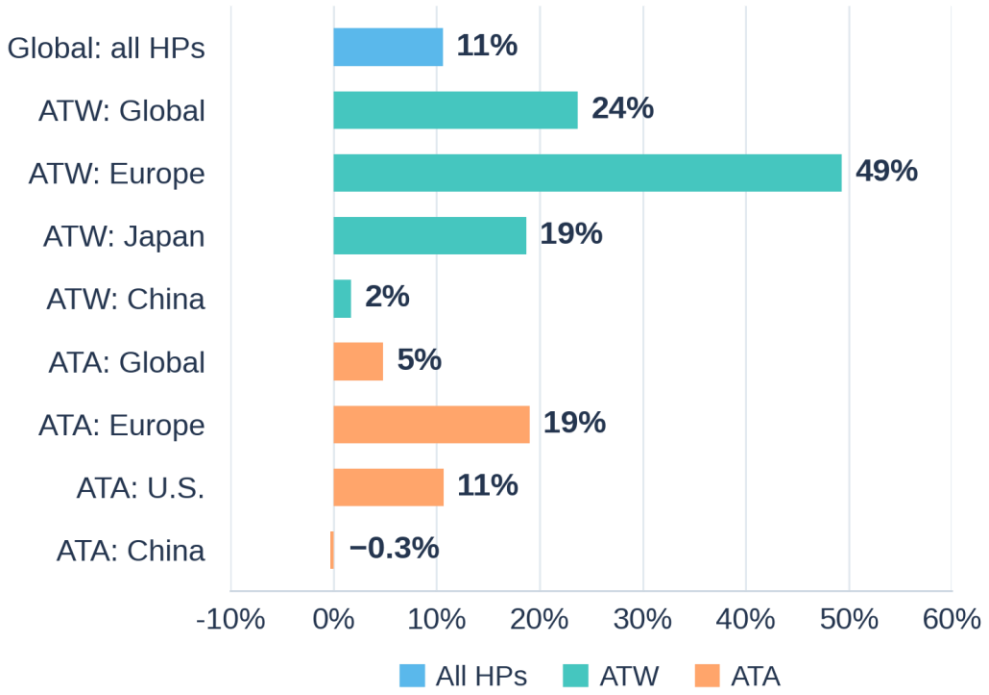
Selected countries, 2021–2022



Share among heat pumps and fossil-fuel heating systems

Annual growth in heat pump sales

2022 compared with 2021



ATW: air-to-water ATA: air-to-air

Heat pumps gained sales share, with faster growth in air-to-water systems

Source: IEA (2023), heating-system sales in 2021–2022. Values rounded except China ATA (−0.3%).

Heat Pumps as a Core Pathway to Net-Zero Heating

Heat Pumps in the Electrification of Heating

Technology pathways

Options shown in the reference framework

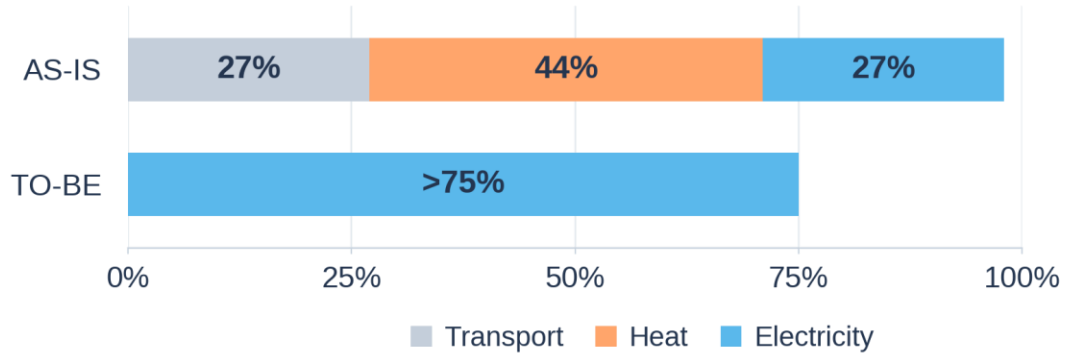
Transport	Electric vehicles Hydrogen vehicles
High-temperature heating	Hydrogen combustion
Low-temperature heating	**Heat pumps**

Heat pumps provide low-temperature heat using electricity

RACHP: refrigeration, air conditioning and heat pumps

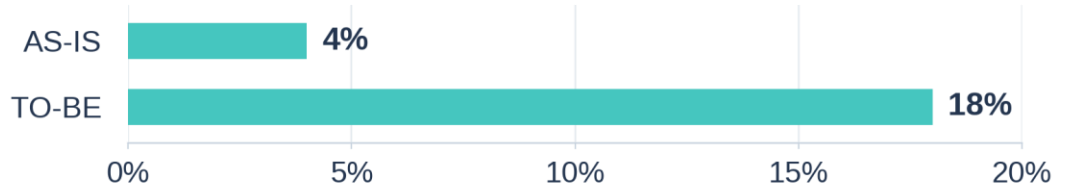
Illustrative net-zero transition

Reported shares from the reference scenario



TO-BE shows the electricity lower bound only

RACHP share in the reference illustration



RACHP percentage basis is not specified in the supplied slide

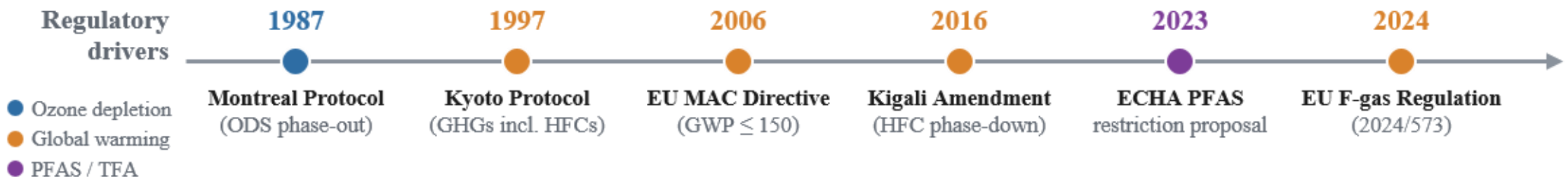
Electrification increases the role of heat pumps in low-temperature heating

Source: supplied reference slide; Kuijpers, ICR 2023, paper 1160, DOI: 10.18462/iir.icr.2023.1160.

01 Introduction

Regulatory Timeline from CFCs to Natural Refrigerants

Environmental Regulations and the Transition to Natural Refrigerants



Refrigerant class	CFCs	HCFCs	HFCs	HFOs	Natural refrigerants
Examples	R11, R12, R115	R22, R123, R124	R32, R134a, R407C, R410A	R1234yf, R1234ze(E)	R290, R600a, R1270, R744, R717
ODP	0.6–1	0.02–0.055	0	0	0
GWP_{100}	4,750–10,900	77–1,810	675–2,088	< 10	0–3
Safety class	A1	A1, B1	A1 (R32: A2L)	A2L	A3 (HCs)*

*GWP_{100}: IPCC AR4 100-year values. Safety class: ASHRAE Standard 34. *R744: A1, R717: B2L.*

Favorable Moderate Unfavorable

01 Introduction

HFC Phase-Down, F-gas Regulation and PFAS Restrictions

Global Environmental Regulations on Refrigerants

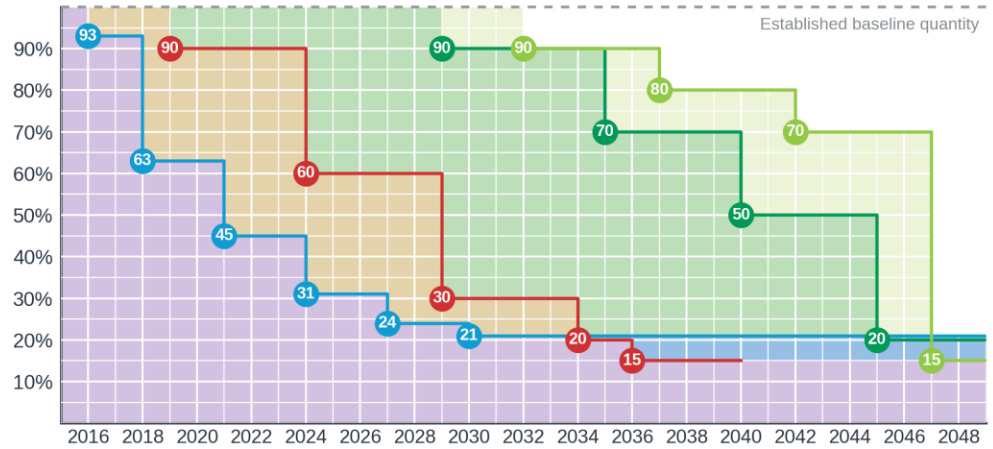
HFC phase-down & low-GWP transition

EU F-gas and the US AIM Act accelerate the transition to low-GWP refrigerants

몬트리올 의정서 HFC 감축 계획

- EU F-gas (2015 rules)
- Non-A5 · US, Japan
- A5 Group 1 · Korea, China
- A5 Group 2 · India, Middle East

Remaining HFCs (% of baseline)



한국: 2024년 동결 → 2029년 10% 감축
2035년 30% · 2040년 50% · 2045년 80% 감축

Source: Trane, HVAC Industry Update (2020)

PFAS restriction discussions



Application-specific alternatives and validation are required

HFO-1234yf · HFO-1234ze(E)/(Z) · HCFO-1233zd(E)

EU restriction proposal under evaluation

Refrigerant options by GWP and density

GWP	Vacuum	Low	Medium	Medium	High	Other
>2500			R422B/D	R404A		
<2500			R438A R22	R452A R407A/F/H	R410A	
<1500		R134a		R449A R449B R448A		
<750		R450A R513A R513B R515A R515B		R454A	R32/R452B R454B	
<150	R123 R1336mzz(Z) R514A R1233zd(E)	R516A R1270 R600a R1234ze/yf	R444B	R454C R455A R290	No LGWP option; move to low density	R744/CO_2 R717/NH_3

Flammability line

Density →

Source: Danfoss, Refrigerant applications (2024), p. 5

Growing demand for low-GWP refrigerants and validated alternatives

Sources: Trane, Korean government, GeneralGas, Danfoss. Original sources and regulatory context in slide notes.

01 Introduction

EU F-gas Regulation and Refrigerant Phase-Out Dates

EU refrigerant restrictions for existing and new systems

Servicing existing equipment

Limits on virgin F-gases for maintenance

2025 Refrigeration equipment
GWP ≥2,500

2026 Air conditioners and heat pumps
GWP ≥2,500

2032 Stationary refrigeration, except chillers
GWP ≥750

Reclaimed and recycled F-gases

Conditional exemptions for GWP ≥2,500

Refrigeration: until 1 January 2030

AC and heat pumps: until 1 January 2032

Placing new equipment on the EU market

Selected restrictions by equipment type and rated capacity

New System	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Closed Refrigeration Systems	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150
Refrigeration Systems	GWP 2500	GWP 2500	GWP 2500	GWP 2500	GWP 2500	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150
Cooler < 12kW	GWP 2500 and More	GWP 2500 and More	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	No F-Gases	No F-Gases	No F-Gases	No F-Gases	No F-Gases
Cooler > 12kW	GWP 2500 and More	GWP 2500 and More	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750
Air Conditioning Systems and Heat Pumps < 12kW	GWP 2500 and More	GWP 2500 and More	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	No F-Gases	No F-Gases	No F-Gases	No F-Gases	No F-Gases
Air Conditioning Systems and Heat Pumps > 12kW	GWP 2500 and More	GWP 2500 and More	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750	GWP 750
Split Air Conditioning Systems and Split Heat Pumps < 12kW	GWP 2500 and More	GWP 2500 and More	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	GWP 150	No F-Gases	No F-Gases
Split Air Conditioning Systems and Split Heat Pumps > 12kW	GWP 2500 and More	GWP 2500 and More	GWP 2500 and More	GWP 2500 and More	GWP 750	GWP 750	GWP 750	GWP 750	GWP 150	GWP 150	GWP 150	GWP 150

Growing demand for low-GWP refrigerants and validated alternatives

Sources: Trane, Korean government, GeneralGas, Danfoss. Original sources and regulatory context in slide notes.

02 Low-Charge R290 Heat Pump Design

Reducing R290 Charge to Manage Flammability Risk

Flammability and Safety Consideration

BACKGROUND AND OBJECTIVE

1 **Problem:** R290 is flammable; high charge increases the potential release inventory.

2 **Objective:** Reducing Refrigerant Charge through Liquid-Line Design

Why R290 for heat pumps?

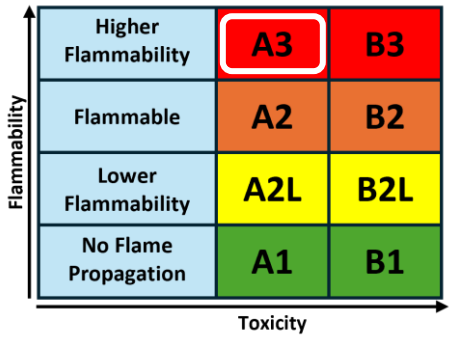
Drivers of refrigerant transition

01 **HFC phase-down**
Kigali Amendment accelerates the shift to low-GWP alternatives.

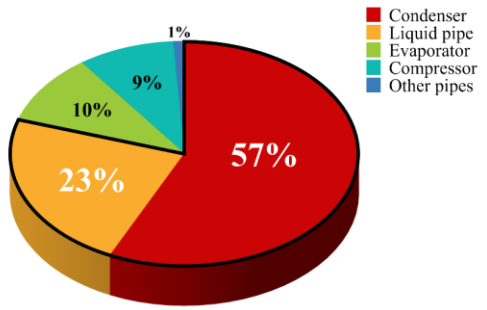
02 **Ultra-low GWP**
R290 is a natural refrigerant with GWP = 3 and no Ozone depletion.

03 **Heating performance**
Favorable thermodynamic characteristics for heating operation.

Why reduce the total charge?



R290: A3 safety class



Refrigerant distribution by component

- R290's A3 flammability highlights the need for refrigerant charge reduction.
- The condenser (57%) and liquid line (23%) account for most of the refrigerant inventory.
- Liquid-line downsizing offers a practical approach to reducing charge without major system modifications.

Target: Lower optimum charge while maintaining heating COP

02 Low-Charge R290 Heat Pump Design

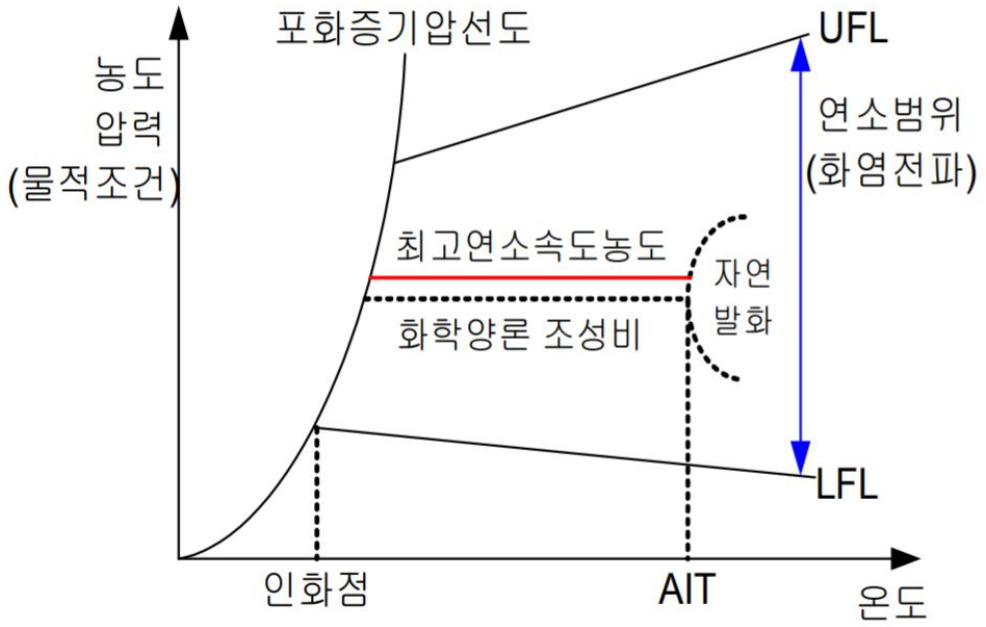
Flammability Limits and Charge Thresholds for R290

R290 for Low-GWP Heat Pumps

R290 flammability characteristics

R290 (propane): an A3 refrigerant

Very low GWP · Zero ODP · Fluorine-free



Conceptual diagram; R290 limits in air shown below

LFL ≈ 2.1 vol% **UFL ≈ 9.5 vol%**

Refrigerant charge thresholds

Selected A2/A3 refrigerants

Refrigerant	Class	m_1 [kg]	m_2 [kg]	m_3 [kg]
R50	A3	0.128	0.832	4.16
R152a	A2	0.520	3.380	16.90
R170	A3	0.152	0.988	4.94
R290	**A3**	**0.152**	**0.988**	**4.94**
R600	A3	0.152	0.988	4.94
R600a	A3	0.172	1.118	5.59
R1150	A3	0.144	0.936	4.68
R1270	A3	0.184	1.196	5.98
RE170	A3	0.256	1.664	8.32

R290 charge ranges (m: refrigerant charge)

$m \le m_1 = 0.152$ kg	밀폐 공간에서도 사용가능
$m_1 < m \le m_2 = 0.988$ kg	사용공간의 면적, 환기조건 달성 시 사용가능
$m_2 < m \le m_3 = 4.94$ kg	사용 불가

*Earlier IEC framework. Applicable KC edition and installation conditions govern.

R290 heat pumps: low climate impact with dedicated flammability management

03 Integrated Heat Pumps for Residential Buildings

Apartment Buildings: Key Sector for Heat Pump Deployment

Need for Heat Pump Deployment and Key Challenges

Ministry of Climate, Energy and Environment

- ✓ **Deployment 3.5M heat pump over 10 years (Boiler Replacement)**
- ✓ Air-source heat recognized as renewable energy source

➔ **Apartment buildings: a key sector for large-scale heat pump deployment**



Key barriers to scale-up

Economic

- High upfront investment
- Progressive residential electricity tariff risk

Space / Infrastructure

- Limited installation for outdoor-unit & TES tank
- Noise, electrical, piping constraints
- Proven application in high-rise apartments limited

Centralized-Distributed cooperative heat pump system with thermal storage and predictive control

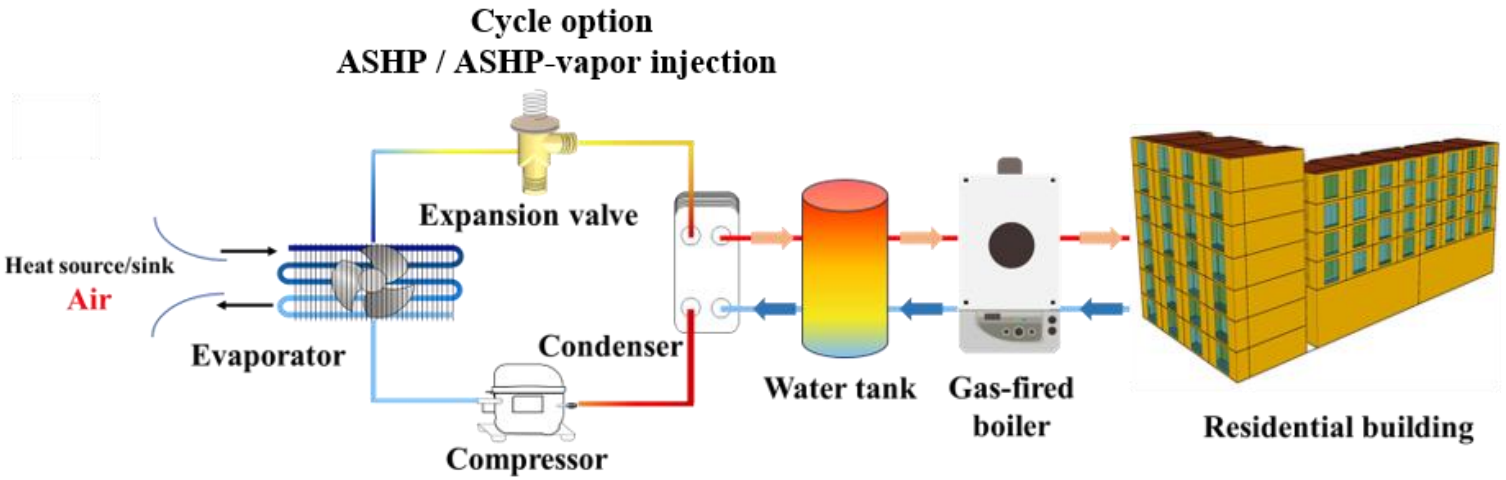
03 Integrated Heat Pumps for Residential Buildings

Building Load and Combined ASHP System Models

3E Analysis of Replacing Individual Gas Boilers with Air-Source Heat Pumps

Combined ASHP system

ASHP or ASHP-VI coupled with an auxiliary gas boiler

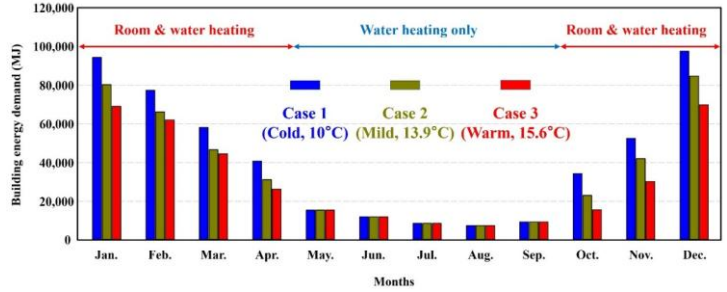


Boiler-assisted operation

Compressor discharge temperature > 110°C

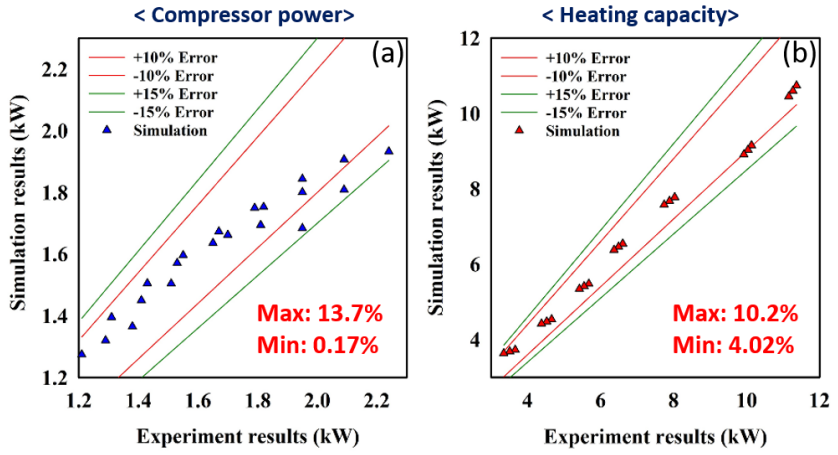
HP outlet set to 50°C with boiler boosting to 60°C

Building load model



Thermodynamic model

Maximum deviations: power 13.7%, heating capacity 10.2%, COP 9.8%



Model-based comparison of energy use, cost and environmental impact

03 Integrated Heat Pumps for Residential Buildings

Research Objectives of the Cooperative Heat Pump System

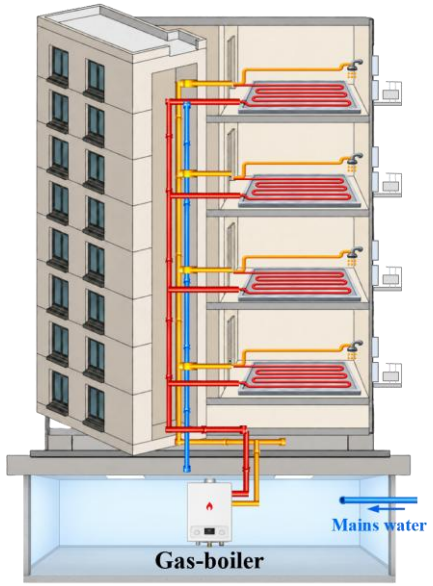
Low-Charge R290 Heat Pumps and AI-Based Cooperative Control

RESEARCH OBJECTIVES

1 **Develop a low-charge cooperative heat-pump system**
Central R32 HP preheating reduces the **required capacity** of each household R290 HP, allowing a **lower refrigerant** charge.

2 **Minimize carbon emissions through AI-based cooperative control**
Predictive control optimizes load sharing, storage temperature, and operating schedules based on heating demand

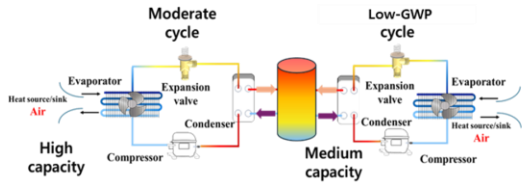
Central Gas-fired boilers



Fossil fuel-heated building

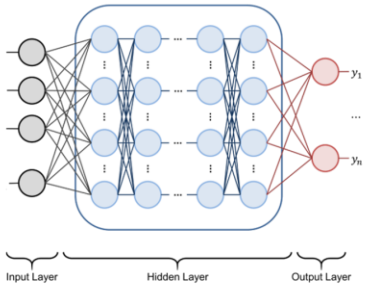
Key technology 1

Refrigerant	T_{eva} [°C]	P_{eva} [kPa]	T_{con} [°C]	P_{con} [kPa]	P_{ratio}[-]	GWP	ODP	Class.
R290	-23	219	50	1713	7.8	3	0	A3
R410A	-23	356	50	3063	8.6	2088	0	A1
R1234yf	-23	134	50	1302	9.7	4	0	A2L
R32	-23	362	50	3141	8.7	675	0	A2L
R290	-23	219	50	1713	7.8	3	0	A3
R744(CO_2)	-23	1714	50	12320	7.2	1	0	A1



Low-GWP Centralized–Distributed Integrated Heat Pump System

Key technology 2

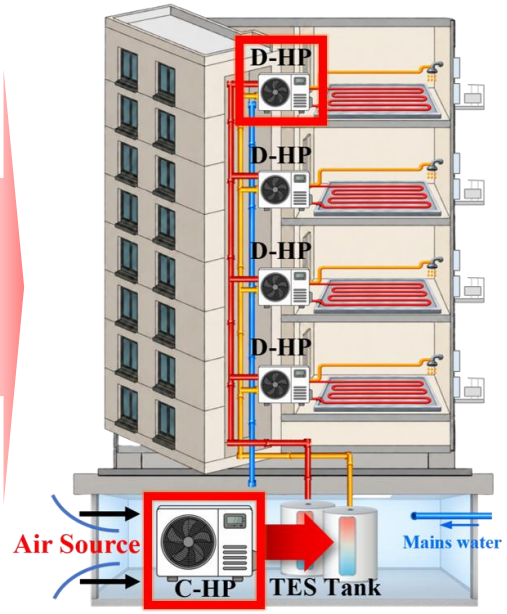


Objective Function
- Energy consumptions
- Carbon emissions
- Energy costs

Optimization variable
- Boosting Temp
- Operating schedule
- Heat pump load

AI-Based Cooperative Control

Centralized HP + Distributed HP



Electrified building

Central HP preheating enables low-charge R290 HPs while AI-based control coordinates the entire system

03 Integrated Heat Pumps for Residential Buildings

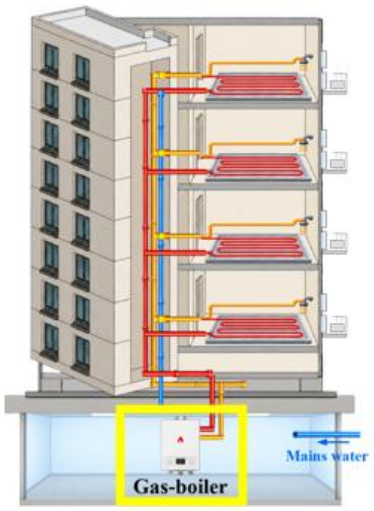
Conventional, Transitional and Proposed Systems Compared

System Configurations and Operating Modes

Comparison systems

현재 보편적 시스템

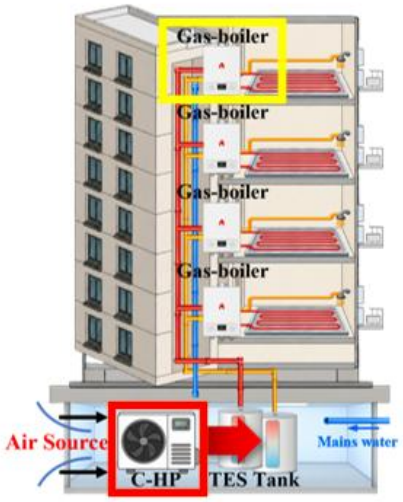
01 중앙 가스보일러



- 기계실에 가스보일러 설치
- 중앙 보일러로 난방·급탕 독립 공급

전환기 현실적 대안

02 중앙HP + 보조 보일러

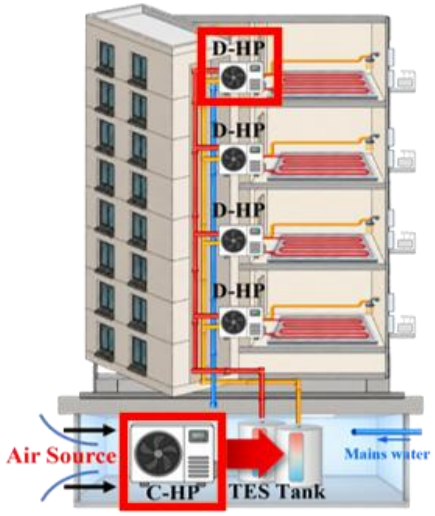


- 기계실에 중앙HP · 축열조 설치
- 각 세대에 보조 가스보일러 설치
- 중앙HP 우선 공급, 부족분 세대보일러 보충
- 중앙 HP 압축기 토출온도 ≤ 110 °C

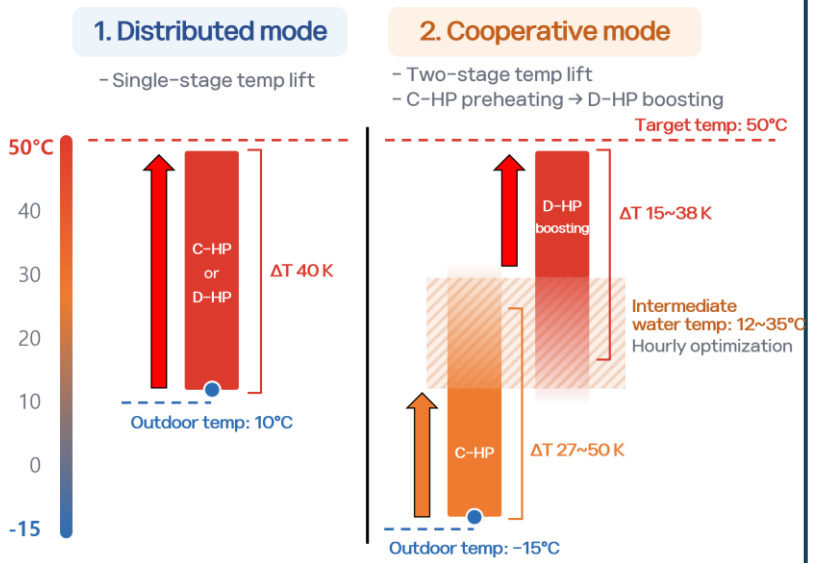
Proposed system

전기화 건물

03 중앙-분산 통합형 HP



- 기계실에 중앙HP · 축열조 설치
- 각 세대에 소용량 히트펌프 설치
- 분산 · 협조 모드 전환 운전
- 보일러 없이 난방·급탕 공급



< Distributed mode >

- Higher outdoor temperatures or lower heat demand
- Single-stage heating by a central or distributed HP

< Cooperative mode >

- Lower outdoor temperatures or higher heat demand
- Central HP preheating followed by distributed HP

The proposed system will be evaluated for energy efficiency, economic feasibility, and environmental impact (3E)

03 Integrated Heat Pumps for Residential Buildings

Reinforcement Learning Improves Annual System COP

Reinforcement Learning-Based Operational Optimization

강화학습 기반 최적운전 제어구조

상태 입력 (9개) 외기온도 (1), 난방·급탕부하 (2), 축열조 온도 (2), 일중·연중 주기 변수 (4)

목표: 보상 합 Q 최대
= 연간 총 전력 최소 · 매시간 반복

실행 가능 운전 후보 평가 (후보 수는 매 시간 가변)

후보·보상·상태 계산 | Q 최대 후보 선택·실행 | 미래 가치 평가 → 행동 선택

Environment
중앙-분산 통합형
선택한 행동을 1시간 적용

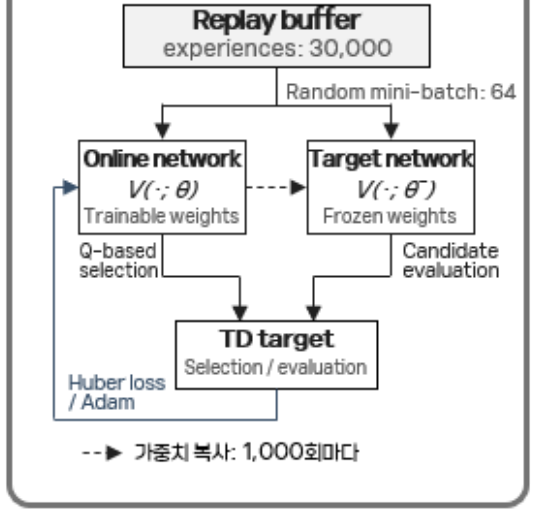
Action a_t
공급수온
열공급 경로
축열조 운전 방식

Agent
후보별 가치 평가
$Q = r + 0.98V$

Updated state and reward
$r_t = -(E_t - 7) / 10$

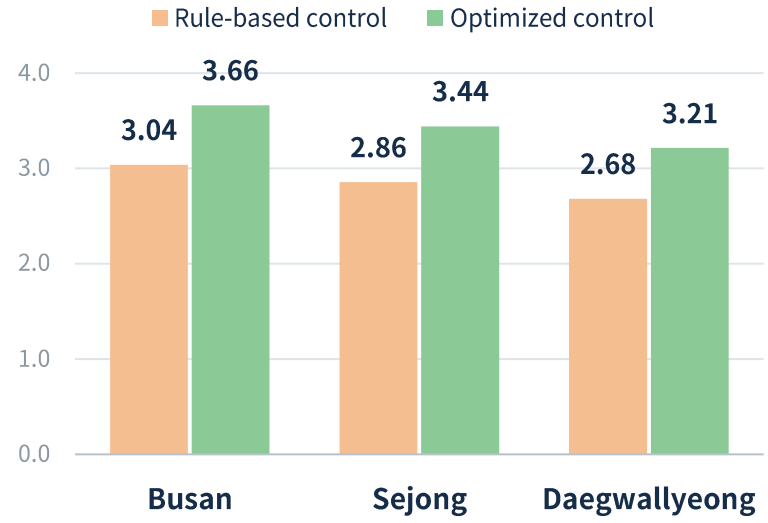
E_t: 해당 시간의 전력소비량

Agent > 사후상태 가치 신경망 V
학습 방식 · Experience Replay and Value Learning



지역별 연간 시스템 COP

System COP based on compressor work and pumps



Central + distributed HPs with R290 distributed units

COP increases by 19.8–20.6% with optimized control

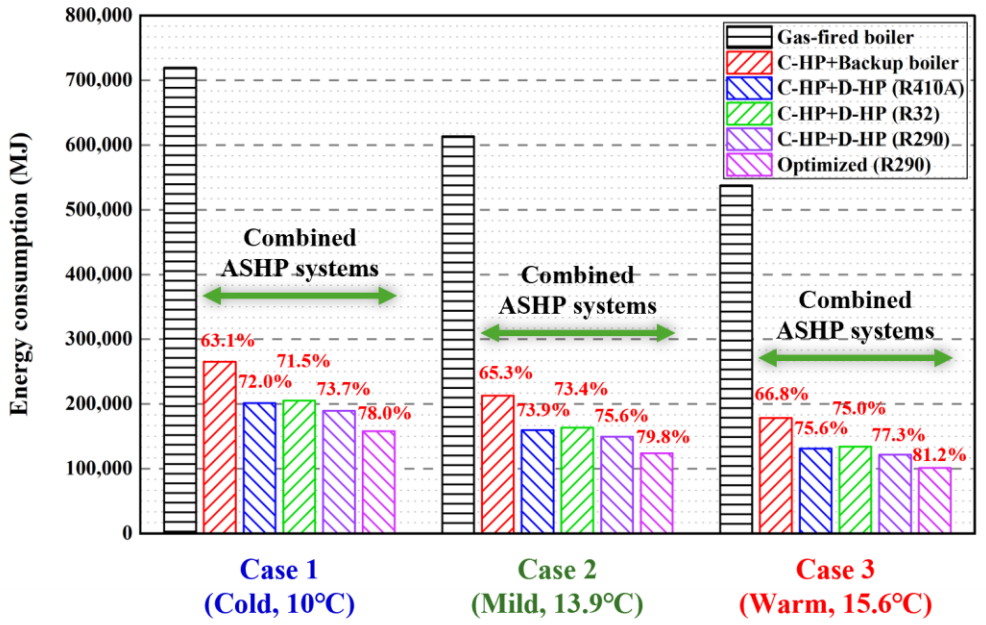
Hourly control combines immediate electricity use with learned future value

03 Integrated Heat Pumps for Residential Buildings

Annual Energy Use by Region and System

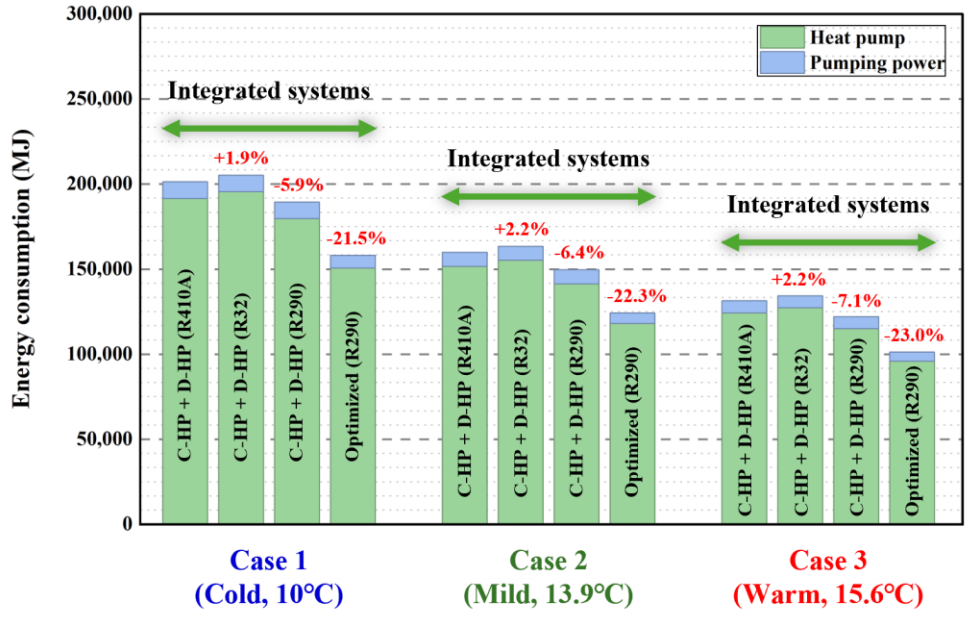
Energy Use by Region and Operating Strategy

Energy consumption by region and system



- ✓ Optimized R290 reduced annual energy use by **78.0–81.2%** relative to the gas boiler across all three regions.

Energy consumption by distributed HP refrigerant



- ✓ Relative to rule-based R410A, R290 saved 5.9–7.1% under rule-based control and **21.5–23.0%** with optimization.

R290 and optimized control reduce annual energy use across all three climates

03 Integrated Heat Pumps for Residential Buildings

Life-Cycle Cost and Operating Cost Comparison

Cost Assessment Across the Three Regions

Life-cycle cost model

LCC

- Initial investment
- Operating cost
- Maintenance cost
- Replacement cost

Calculation

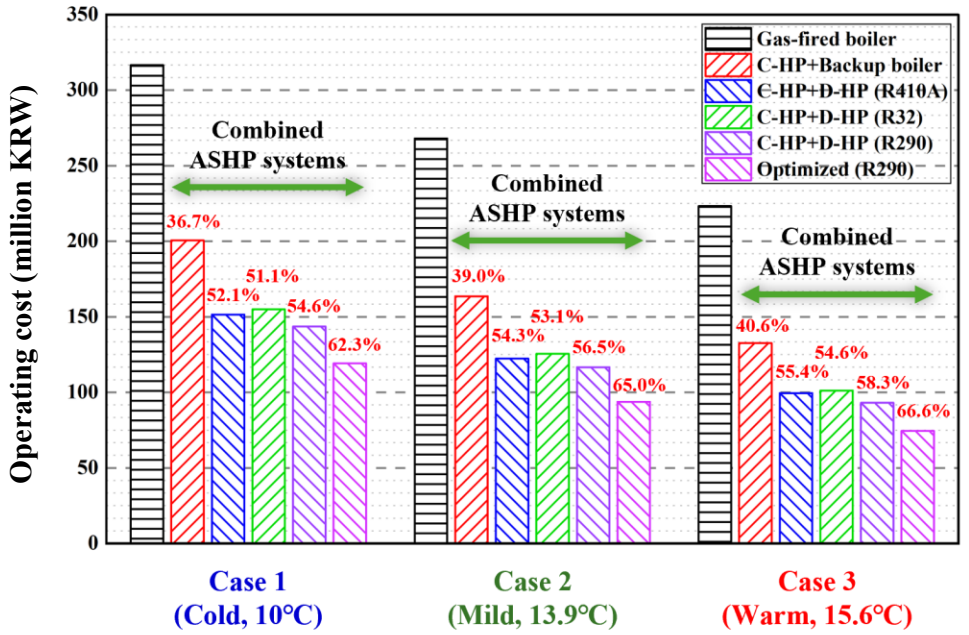
LCC = Initial investment
+ (Operating cost + Maintenance cost)×APVF
+ Replacement×PVF

Discount factors

- Annuity present value factor (APVF) $= \frac{(1+i)^n - 1}{i(1+i)^n}$
- Present value factor (PVF) $= \frac{1}{(1+i)^{RP}}$

✓ LCC combines initial investment with discounted operating, maintenance and replacement costs.

Operating cost by region and system



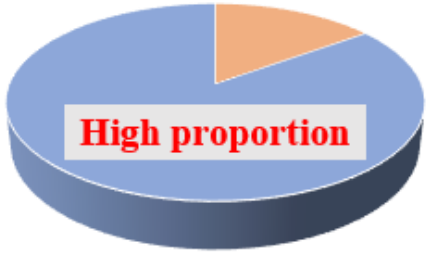
✓ Optimized R290 has the lowest operating cost in all three regions, followed by rule-based R290.

R290 and optimized control reduce operating costs across all three climates

03 Integrated Heat Pumps for Residential Buildings

Heat Pump Electrification on a Decarbonizing Grid

Life Cycle Climate Performance (LCCP)



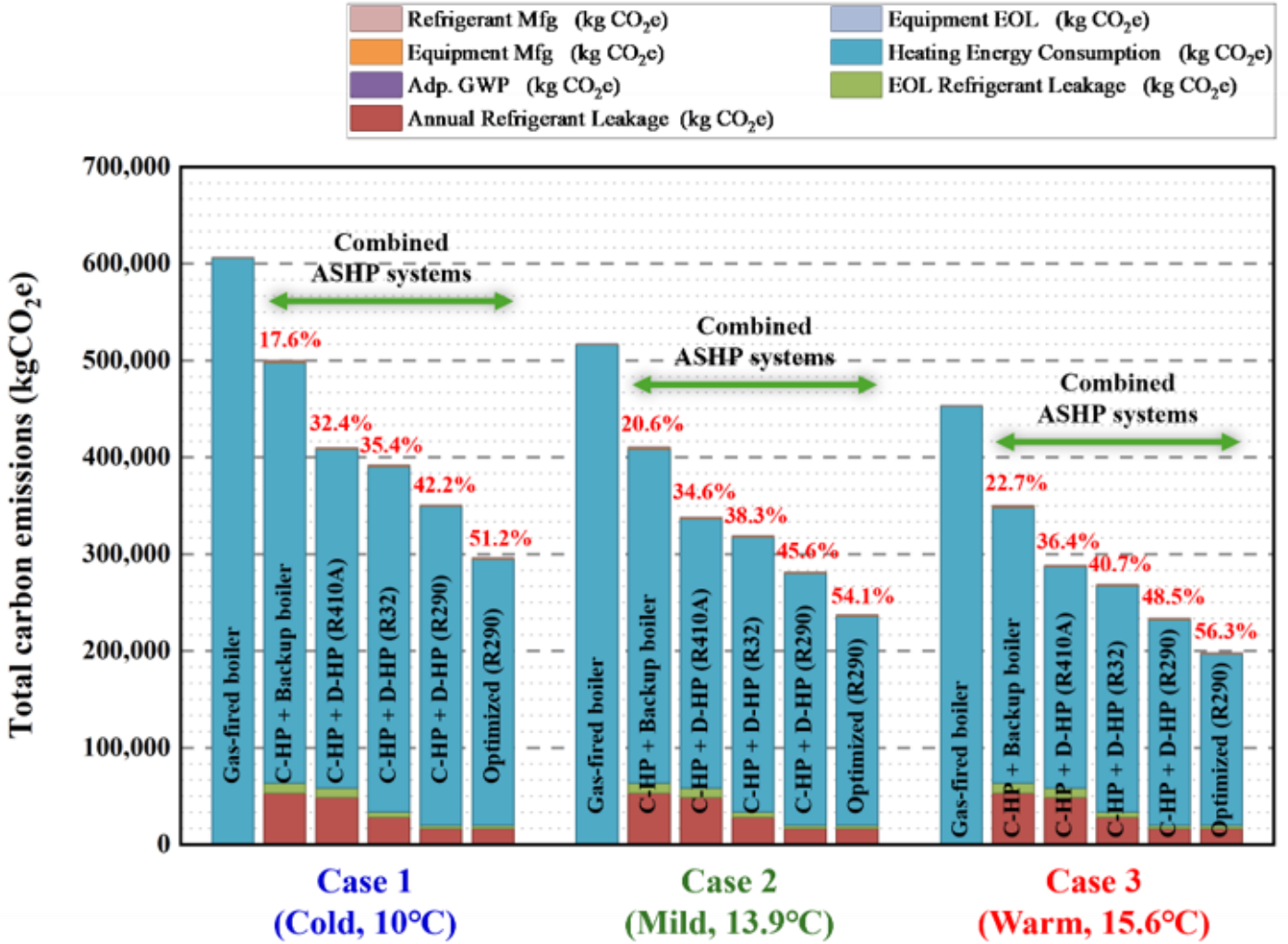
- Indirect emission
- Direct emission

LCCP

Direct emission
- Refrigerant leakage
- End-of-life leakage

Indirect emission
- Energy consumption
- Material & refrigerant manufacturing
- Recycling

Refrigerant (D-HP)	GWP
R410A	2,088
R32	675
R290	< 3



03 Integrated Heat Pumps for Residential Buildings

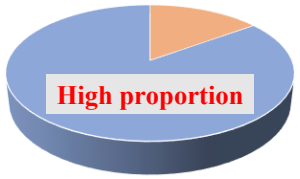
Heat Pump Electrification on a Decarbonizing Grid

Life Cycle Climate Performance (LCCP)

LCCP calculation method

Unit	System	Heat pump Gas-fired boiler
Refrigerant	HFC-R410A /HFC-32 / R-290	
Charge (kg)	36.594 (C-HP, one stage) /	
	11.515 (C-HP, two stage)	
	22.16 (D-HP, two stage)	
Annual Refrigerant Leakage	5.00%	Per year
EOL Leakage	15.00%	
Lifetime	15	Years
Manufacturing Emissions Type	Virgin	

Electricity Generation Region	Average Emission Rate ($kgCO_{2e}$/kWh)	LNG Emission Rate ($kgCO_{2e}$/kWh)
Korea	0.4173	0.201



Indirect emission

Direct emission

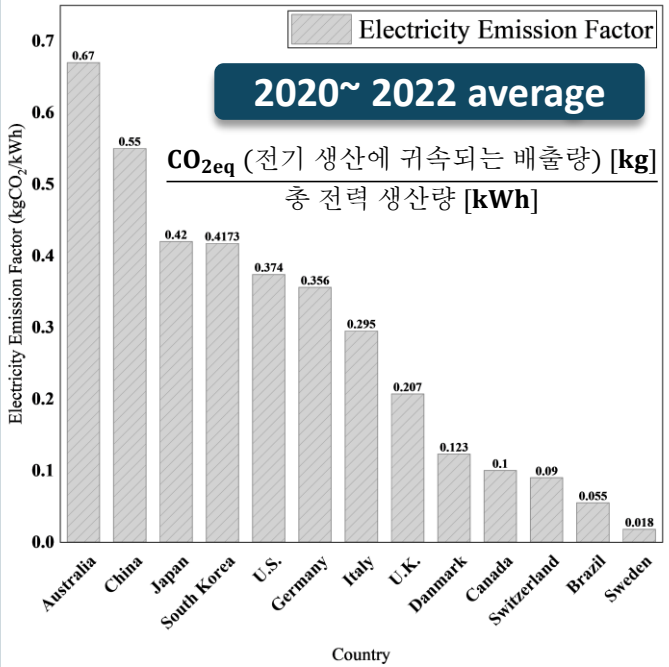
LCCP

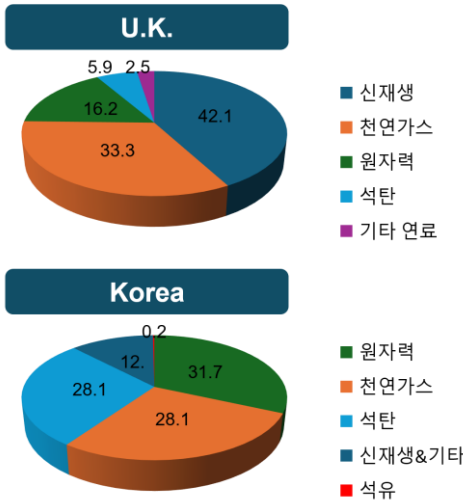
Direct emission
- Refrigerant leakage
- End-of-life leakage

Indirect emission
- Energy consumption
- Material & refrigerant manufacturing
- Recycling

✓ Over the 15-year system lifetime, energy use accounts for most emissions, while refrigerant leakage contributes to direct emissions.

Electricity Emission Factor by country





✓ The U.K. grid emission factor is about half Korea's (0.207 vs. 0.4173 kg CO_2e/kWh), reflecting differences in the generation mix.

As the grid decarbonizes, the same heat pump delivers heat with lower life-cycle emissions.

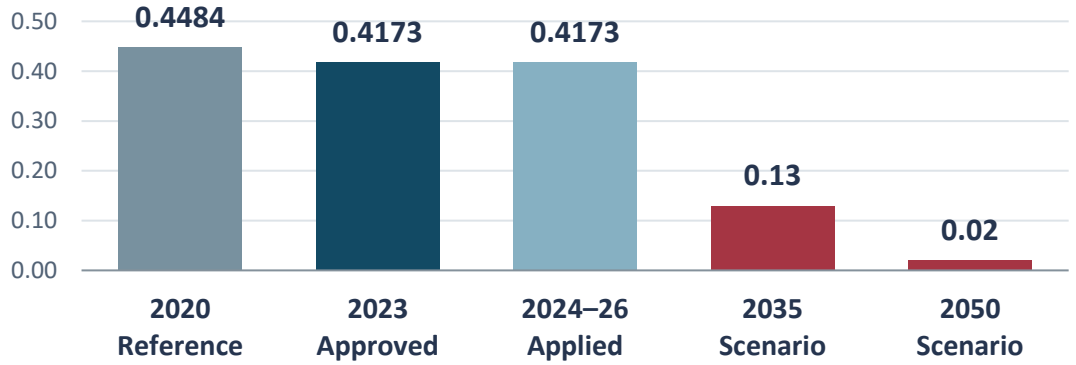
03 Integrated Heat Pumps for Residential Buildings

Heat Pump Electrification on a Decarbonizing Grid

Life Cycle Climate Performance (LCCP)

Grid emission factors

kg CO_2e per kWh of electricity consumed



For 2024–26, the study holds the 2023 factor constant.

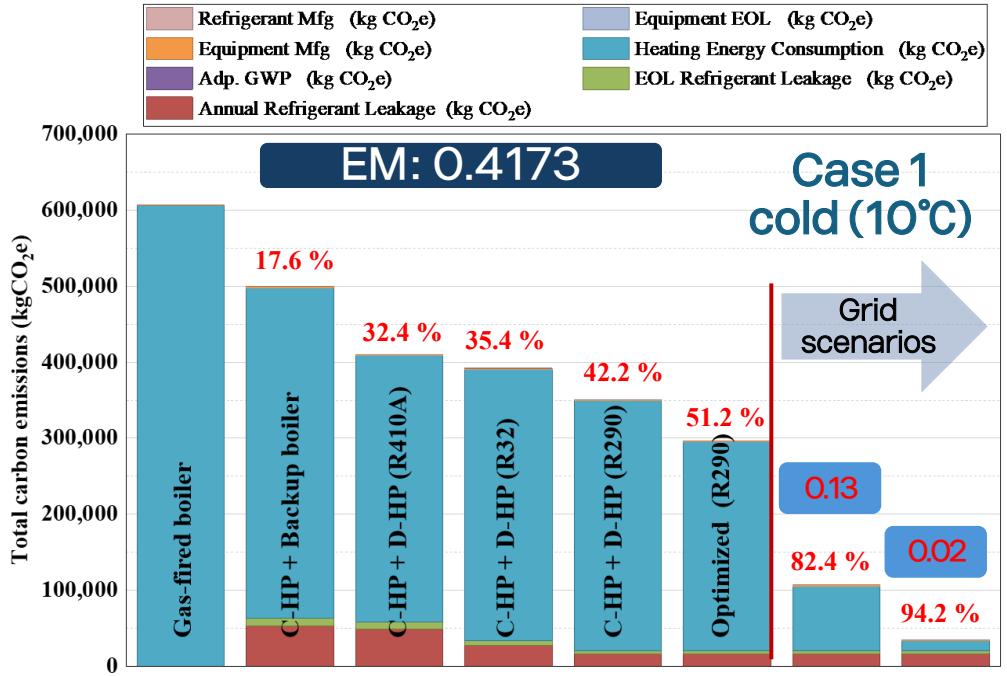
2035 Lower-emission grid scenario

Assumed emission factor of 0.13 kg CO_2e/kWh

2050 Near-zero-emission grid scenario

Assumed emission factor of 0.02 kg CO_2e/kWh

LCCP calculation results



✓ Optimized R290 cuts LCCP by **51.2%** versus the gas boiler. The reductions reach **82.4%** in 2035 and **94.2%** in 2050 under the assumed grid scenarios.

Optimized R290 and cleaner electricity reduce life-cycle carbon emissions

04 Low-Charge R290 Heat Pump Design

Liquid-Line Diameter Reduction from 3/8″ to 1/4″

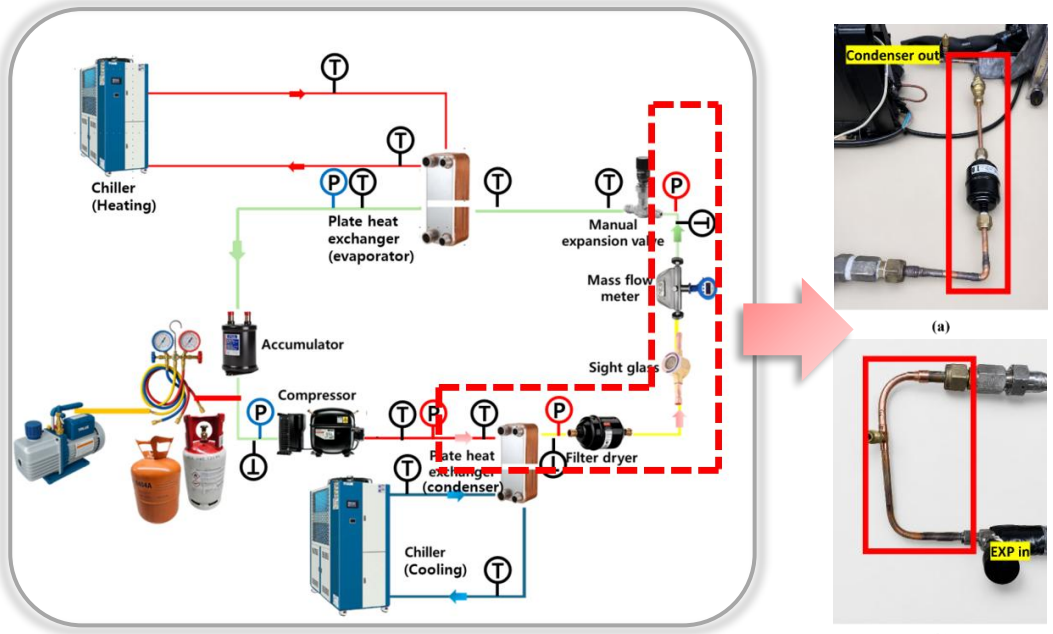
Heat pump cycle optimization

Ongoing

Heat pump cycle and modification

3/8″ (9.52 mm) → 1/4″ (6.35 mm) **−66% Vol.**

Same 0.8 m liquid line | Fixed operating conditions | 5 g charge increments



- The liquid line between the condenser outlet and expansion-valve inlet was downsized.
- The same test bench and measurement system were retained for direct comparison.

Procedure and test matrix

Charge R290 → Stabilize cycle → Evaluate performances → Select optimum

Parameter	Baseline	Reduced
Outer diameter	9.52 mm	6.35 mm
Refrigerant	R290	
Comp. RPM	3200	
$T_{\text{eva},sat}$	-15 ℃	
$T_{cond\ \text{water,out}}$	45 ℃	
Charging amount	175 g - 195 g	140 g – 165 g

- Refrigerant charge was varied in 5 g increments under identical operating conditions.
- Pressure, temperature, mass flow rate, and power were recorded after operating stabilization.
- The optimal refrigerant charge was determined based on the maximum heating COP.

Goal: efficient, eco-friendly cold energy with a low refrigerant charge

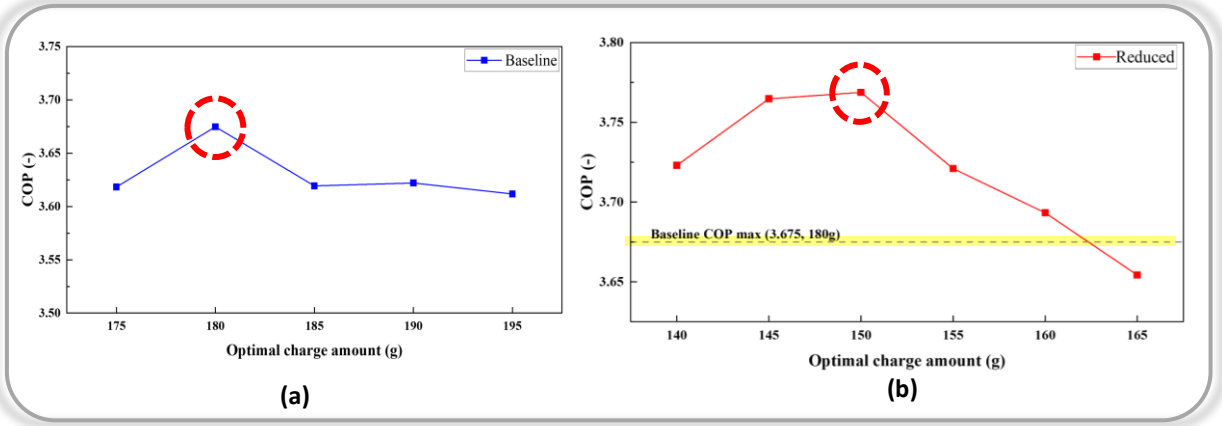
04 Low-Charge R290 Heat Pump Design

Charge Sweep: Baseline vs. Reduced Liquid-Line System

Heat pump cycle optimization

Ongoing

Charge-sweep analysis

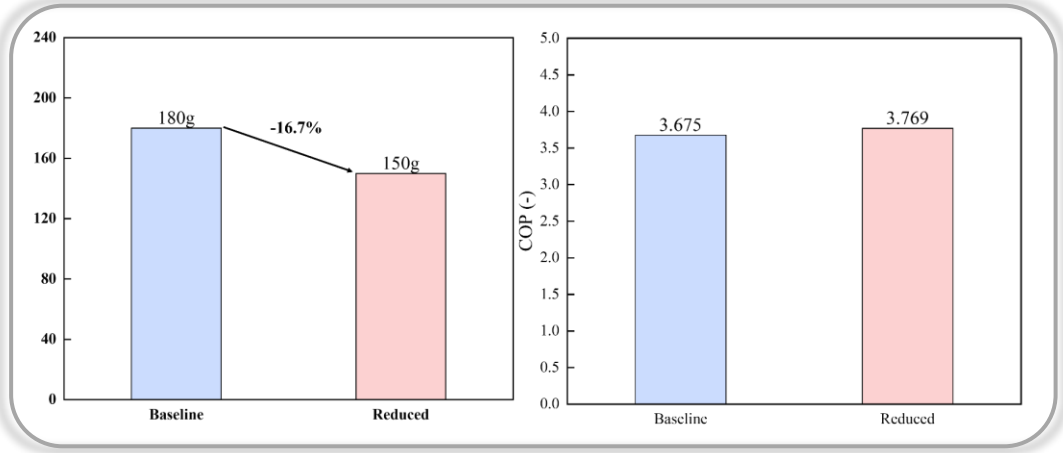


Comparison of baseline system and liquid-line reduced system

Baseline: 3.675 at 180 g → Reduced: 3.769 at 150 g

- The baseline system achieved a maximum COP of 3.675 at 180 g, with lower COP at other charge levels.
- Liquid-line downsizing reduced the optimum charge from 180 to 150 g (−16.7%).
- The maximum heating COP increased to 3.769 (+2.6%), despite the lower charge.

Optimal-charge performance comparison



Comparison of optimum refrigerant charge and heating COP at the optimum charge

Parameter	Baseline	Reduced	Change
Charge amount (g)	180	150	-16.7%
Q_{cond} (kW)	0.664	0.679	+2.3%
Comp. work (kW)	0.181	0.180	-0.2%
COP_H	3.675	3.769	+2.6%
Subcooling at $Cond_{out}$ (K)	3.7	5.8	+2.1K

Low-charge cycle design can contribute to efficient R290 systems with reduced flammability concerns

04 Low-Charge R290 Heat Pump Design

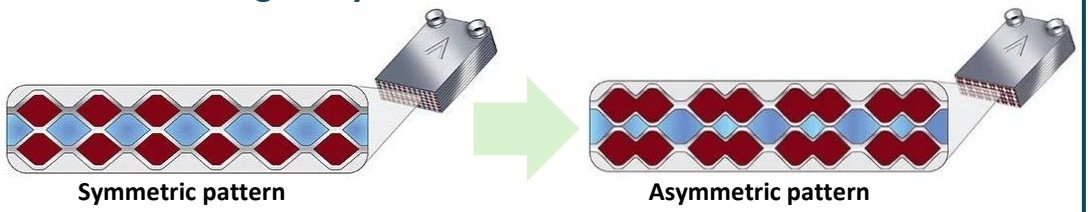
Condenser Redesign to Cut Refrigerant Hold-Up

Heat pump cycle optimization

Ongoing

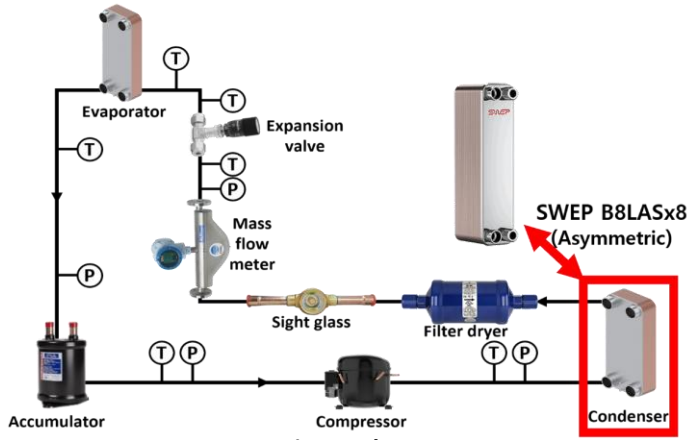
Condenser re-design concept

Condenser design & system modification



Symmetric pattern

Asymmetric pattern



Experimental setup

Expected Design Benefits

- Refrigerant-side volume reduced by 61% (155 → 60 mL), with a 21% increase in heat transfer area.
- Low design pressure drop (1.04 kPa) and approximately 15 g additional charge reduction expected.

Design comparison & validation

Parameter	DIC 193-11F (Current)	SWEP B8LASx8 (Modifying)
Type	Symmetric	Asymmetric
Number of plates	11	8
Channels (Ref. / Water)	5 / 5	3 / 4
Heat transfer area (m^2)	0.126	0.152
Ref.-side hold-up volume (mL)	155	60
Water-side hold-up volume (mL)	155	100

Experimental validation plan

- Replace the existing condenser with an asymmetric BPHE in the same R290 heat pump test bench.
- Conduct refrigerant charge-sweep tests under identical operating conditions.
- Compare optimal refrigerant charge, heating COP, and heating capacity between the two condenser configurations.

Goal: Further refrigerant charge reduction through asymmetric condenser design.

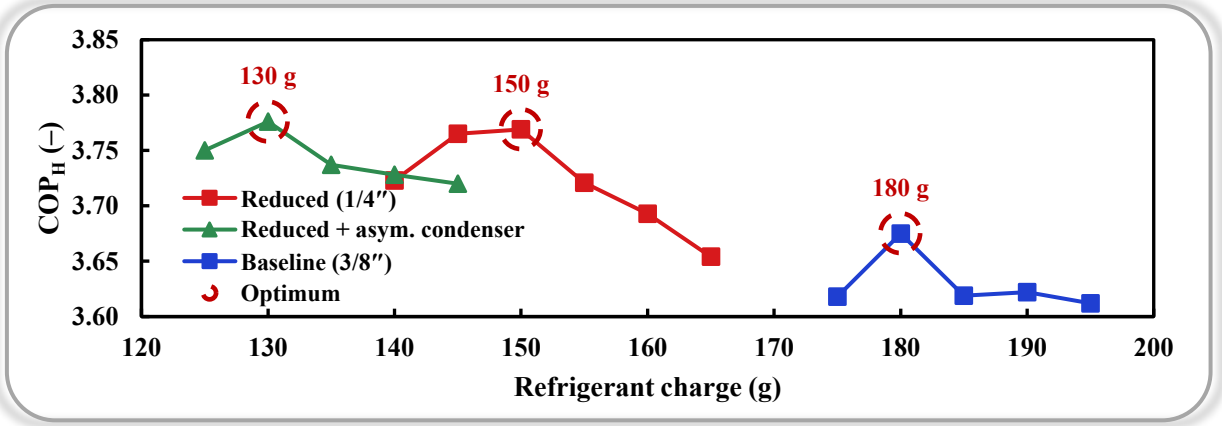
04 Low-Charge R290 Heat Pump Design

Charge Sweep: Reduced Liquid Line vs. Asymmetric Condenser

Heat pump cycle optimization

Ongoing

Charge-sweep analysis

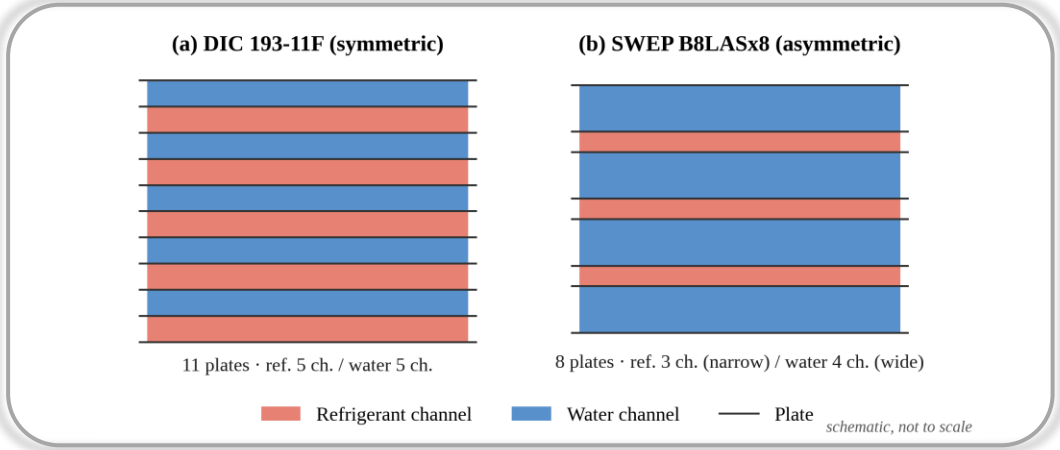


Heating COP versus refrigerant charge for the three system configurations

Reduced: 3.769 at 150 g → Asymmetric: 3.776 at 130 g

- The asymmetric condenser reduced the optimum charge from 150 to 130 g (−13.3%).
- The maximum heating COP was maintained at 3.776 (+0.2%), within test repeatability.
- Overall: 180 → 130 g (−27.8%), 22 g below the IEC 60335-2-40 m_1 (152 g).

Optimal-charge performance comparison



Optimum refrigerant charge and heating COP of the three configurations

Parameter	Reduced	Asymmetric	Change
Charge amount (g)	150	130	**−13.3%**
Q_{cond} (kW)	0.679	0.672	−1.0%
Comp. work (kW)	0.180	0.178	−1.1%
COP_H	3.769	3.776	+0.2%
P_{dis} (kPa)	1642.9	1589.0	−53.9 kPa

Two-step design cut the R290 charge by 27.8% while maintaining heating COP

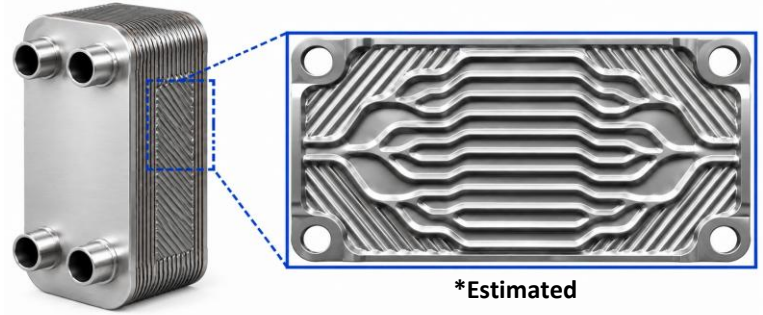
04 Research Extensions and New Directions

CFD-Based Multi-Objective Optimization of PHE Channels

Topology-based channel design for low-charge R290 heat pumps

Planned

Research concept



*Estimated

Conceptual design of a plate heat exchanger with an optimized refrigerant-side flow channel

Design variables (Refrigerant side)



Channel height (h)



Channel width (w)



Channel layout

Optimization Metrics

- Refrigerant hold-up volume
- Heat transfer performance
- Pressure drop

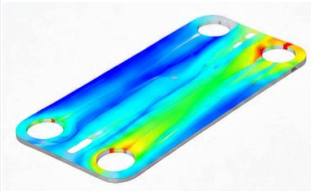
Final Objective

- COP_{max}
- Refrigerant charge (m_{ref})

Goal: Optimize the plate heat exchanger channel topology to maximize COP and determine the optimal refrigerant drop

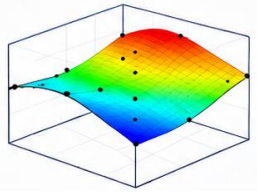
Optimization framework

CFD
(Data generation)



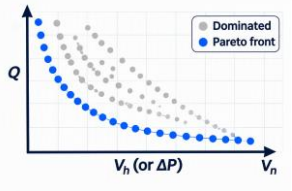
- $Q, \Delta P, V_n$
- Design of experiments

RSM*
(Surrogate model)



- Response Surface Methodology
- Regression model
- Performance prediction

NSGA-II**
(Multi-objective optimization)

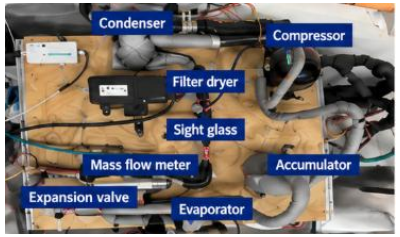


- Non-dominated Sorting Genetic Algorithm II
- Multi-objective search
- Optimal channel topology

*Estimated

Iterative design & refinement

Experimental test
(Data generation)



Performance Evaluation

- CFD re-analysis of selected Pareto-optimal designs
- Refrigerant charge-sweep tests to determine the optimal charge
- Comparison of COP, heating capacity, and refrigerant charge with the baseline

RSM*: A statistical method that predicts performance using mathematical models based on CFD results.
NSGA-II**: A genetic algorithm that identifies Pareto-optimal solutions by balancing multiple conflicting objectives.

04 Research Extensions and New Directions

Blending and AI-Driven Discovery of New Refrigerants

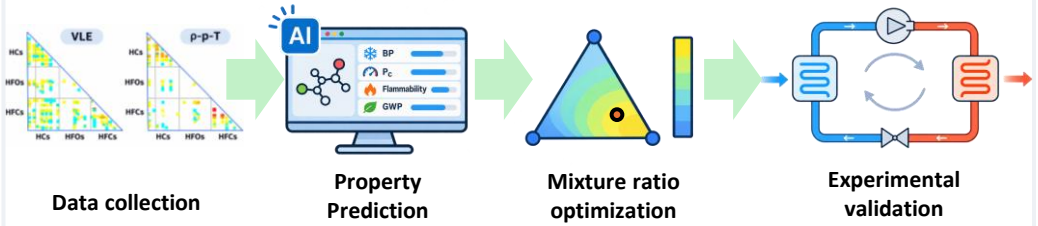
Refrigerant Mixtures and Novel Refrigerant Development

Planned

Refrigerant mixture

Concept: Develop refrigerant blends by mixing two or more refrigerants at specific ratios to optimize performance, safety, and environmental impact.

AI-Assisted development process



Data collection → Property Prediction → Mixture ratio optimization → Experimental validation

Key input variables

- Refrigerant Components and Mixing Ratios
- Thermodynamic Properties (GWP, Flammability)
- Operating Conditions (Temp., Pressure, Load)
- System Performance Requirements (COP, Capacity etc.)

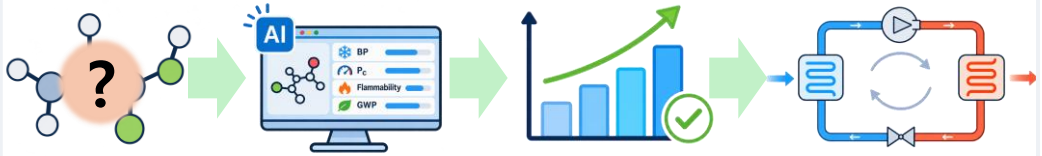
Expected benefits

- High Energy Efficiency and Performance
- Low-GWP
- Improved Safety & Operational Reliability

Novel refrigerant discovery

Concept: AI-driven molecular design and screening of high-performance, low-GWP, safe refrigerants, followed by synthesis and validation.

AI-Based Development Process

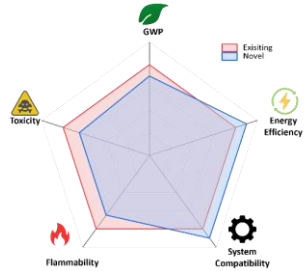


Designated candidates → Property Prediction → Performance evaluation → Experimental validation

AI applications

- Large-Scale Molecular Screening and Generation
- Property Prediction (Thermodynamic Properties and Safety)
- System Performance Simulation
- Prioritization of Promising Candidates

Target Refrigerant Characteristics



Thank you

