Efficient Appliances for People & the Planet

Technology Options for Doubling the Energy Efficiency of Room Air Conditioners

Perspectives From China

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Executive Summary

This report explores pathways to double the global rate of energy efficiency improvement, focusing on room air conditioner (RAC) technologies that deliver substantial efficiency gains. It analyzes the technical potential of ultra-efficient RACs in China, showing efficiency could improve by up to 40%[i] within a decade with only a 10% increase in cost. The report also examines market implications and estimates the associated carbon-reduction benefits from reduced energy consumption.

KEY RESULTS

- To improve RAC efficiency, manufacturers are deploying advanced compressor technologies, inverter drives, optimized electronic controls, larger heat exchangers, and low global warming potential (GWP) refrigerants, achieving significant performance improvements.
- Efficiency gains in RACs have evolved from single-component optimization to integrated system design and intelligent controls. RAC efficiency improvements follow a systematic synergistic approach that integrates thermodynamic cycles, component optimization, and smart control. Key pathways focus on optimized core components, inverter-based system integration, and intelligent multi-energy coupling applications.
- Different technologies vary in maturity and energy-saving potential. High-efficiency motors and inverters are well established, typically delivering 15% to 25% efficiency gains. Deep structural optimization remains at a development stage, with contributions estimated at 5% to 15%. At the system level, efficiency potential may reach up to 30%, though coordinated application has not yet been widely adopted. Intelligent control represents the most promising frontier, with theoretical contributions exceeding 40%. Together, these evolving technologies form a robust technical foundation for higher RAC efficiency.

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[i] The 40% is estimated over the averaged energy efficiency level of most popular RACs available in Chinese market.

- Optimization strategies should be refrigerant-specific: R32 systems benefit most from compressor efficiency improvements to mitigate high pressure-ratio power losses, whereas R290 systems should prioritize evaporator efficiency to exploit their superior phase-change heat transfer properties. Aligning tailored component strategies with refrigerant characteristics can deliver meaningful system-level efficiency gains with better economic benefits.
- RACs are expected to achieve an annual performance factor (APF) of 6.25, which is equivalent to 9.15 in ISO CSPF[ii], within the next decade, while limiting overall cost increases to approximately 10%. The associated cumulative carbon dioxide (CO_2) emission reduction potential is projected to reach 1.75 gigatons (Gt) by 2040, 2.89 Gt by 2050, and 3.71 Gt by 2060. These estimates demonstrate the significant long-term climate mitigation impact of efficiency improvements.
- Efficiency improvements show a dynamic cost-benefit relationship. While technological progress and innovation deliver stronger marginal returns at higher efficiency levels to some extent, a balanced development pathway is essential to avoid “high-efficiency, high-cost” outcomes and to mitigate the risk of an “efficiency trap.”

RECOMMENDATIONS

- Comprehensive policy support for high-efficiency RAC development

Governments should provide comprehensive policy support for high-efficiency RACs, including fiscal subsidies, tax incentives, and consumer rebates. Policies should prioritize the adoption of low-GWP refrigerants, inverter compressors, and intelligent controls, while also promoting green manufacturing practices to ensure long term efficiency gains.

- MEPS as a driver of technological upgrading

Policymakers must strengthen and raise minimum energy performance standards (MEPS), ensuring they reflect real operating conditions. Countries should benchmark new standards against the world’s best MEPS, while leading economies must aim for Best Available Technology (BAT) levels, balancing efficiency improvements with cost-effectiveness and affordability considerations.

- Global collaboration and knowledge sharing

All stakeholders across government, industry, and research institutions must deepen global collaboration and knowledge sharing. This includes joint research, demonstration projects, and harmonized standards to accelerate the diffusion of green innovations, reduce costs, and unlock greater efficiency and emission-reduction potential worldwide.

[ii] The expedited conversion from APF to ISO CSPF is based on parameters of sample RACs and theoretical calculations.

Designing policies that drive market transformation and maximize the technical potential of RACs is essential. Well-designed policies can accelerate the adoption of high-efficiency appliances and equipment at the lowest cost, reduce consumer electricity bills, save energy, lower peak demand, and significantly cut greenhouse gas emissions.

This study aims to support the revision of China's MEPS for RACs and the promotion of high-efficiency products, while offering guidance for industry stakeholders to advance the development of efficient RACs.

The report highlights key efficiency-enhancing technologies for RACs, covering solutions already commercialized and those with strong near-term deployment potential. It evaluates their technical feasibility and energy-saving performance across different usage scenarios, providing reliable technical references for industry stakeholders and policymakers.

To assess feasible RAC efficiency improvement targets, this study integrates theoretical analysis, technical modeling, and empirical validation. By linking research insights with manufacturing realities, it ensures that proposed efficiency goals are technically achievable and economically viable.

Background

1. International Progress on Doubling Energy Efficiency

DOUBLING ENERGY EFFICIENCY: POLICY AND PROGRESS

At the 28th United Nations Climate Change Conference (COP28) in 2023, more than 110 countries pledged to double the rate of energy efficiency measures by 2030[1]—an initiative known as "doubling energy efficiency". This means increasing the global annual energy efficiency improvement rate from about 2% to over 4%[2]. The goal is to accelerate the deployment of energy-saving technologies and policies so that each unit of energy delivers greater economic and social benefits. Energy efficiency strengthens energy security, lowers costs, and reduces greenhouse gas emissions. Alongside the expansion of renewable energy, it is widely recognized as one of the two main pillars of the global energy transition.

Improving energy efficiency means delivering more output from the same level of energy input. This leads to reduced waste, higher productivity, competitiveness, and energy system resilience. According to the International Energy Agency (IEA), energy efficiency improvements globally could deliver greater emission reductions by 2030 than any other single mitigation measure.[3]

Beyond its role in climate mitigation, energy efficiency is a fundamental driver of economic growth and social well-being. It lowers energy costs for households and businesses, supports job creation, improves air quality, and helps alleviate energy poverty. As a result, it is central to building energy systems that are fair, affordable, and inclusive. Energy efficiency has evolved from a narrowly defined technical issue into a multidimensional proposition involving economic, environmental, and social governance. It is now widely recognized as a strategic priority for the global community.

Despite widespread political support for the doubling energy efficiency pledge, progress has been insufficient. According to the IEA[4], in 2024, one year after COP28, the global annual rate of efficiency improvement is projected to be approximately 1%, far below the target. Many countries still lack comprehensive policies, and regulatory stringency, investment levels, and technology deployment remain inadequate. This delay shows that faster policy action and stronger cross-sector cooperation are needed to avoid losing a critical window of opportunity. Achieving the 2030 target will require major improvements in end-use sectors such as buildings, transport, industry, and appliances.[5]

WHY APPLIANCE EFFICIENCY MATTERS

As household incomes grow and electricity access expands, the global stock of appliances keeps increasing, driving up energy use. In 2021, appliances—including those used in residential and commercial buildings, as well as industrial motor systems—accounted for 35% of global final energy consumption and nearly 40% of energy-related carbon emissions. Household appliances represented roughly 46% of electricity demand in buildings, making them one of the largest contributors to building energy consumption.[6]

Appliances are replaced more frequently and upgraded more rapidly than building envelopes or heating and cooling systems, creating a significant opportunity for energy-saving before 2030. Meeting the doubling energy efficiency target will require appliance efficiency to increase by 30%–40%[7]. CLASP research shows that improving appliance efficiency can reduce energy demand by about 20%[8], underscoring its importance as a critical technology pathway for achieving COP28 climate commitments.

Early action and strong policy measures are essential to doubling appliance efficiency. MEPS help phase out inefficient products and shift markets toward efficient alternatives. CLASP calls on countries to set clear, measurable appliance efficiency targets within their national climate plans and to track progress with consistent indicators. Standards should align with the most advanced technologies to ensure the doubling efficiency goal is met. At the same time, stakeholders must expand international and cross-sector cooperation to speed up global improvements in appliance efficiency.[9]

AIR CONDITIONER ENERGY CONSUMPTION

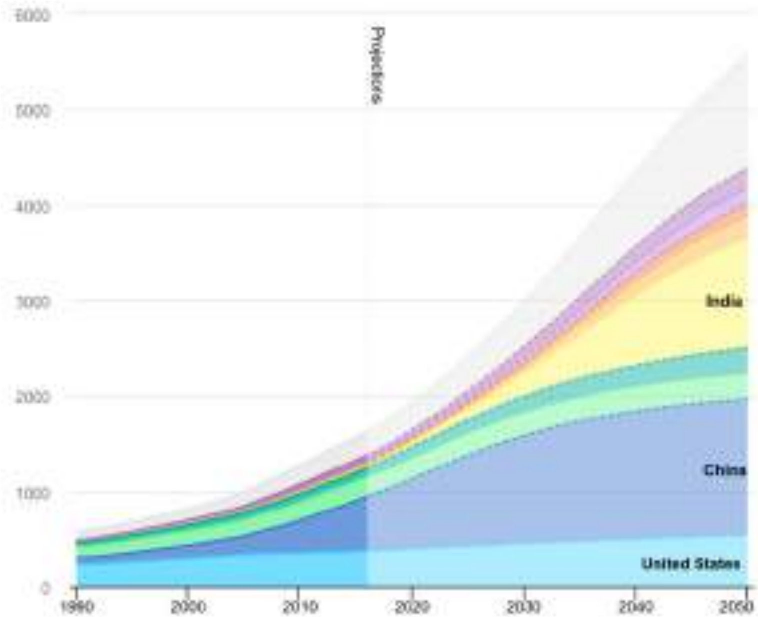
As global warming intensifies and extreme heat events become more frequent, air conditioning has become essential for protecting health and quality of life. Air conditioners (ACs) and fans account for approximately one-fifth of global building electricity use, or around 10% of total global electricity consumption.[10] This rising demand is straining energy systems.

In 2024, unprecedented heat waves hit many regions, with temperatures above 50 °C in some areas and record highs recorded in several countries. Surging air conditioning use drove electricity demand to new peaks. More than 40 countries, including Brazil, China, India, Mexico, and the United States, which together account for nearly 70% of global demand, experienced record peak loads during the heat waves. Some countries faced widespread blackouts and rolling outages, as heavily stressed grids struggled to meet demand, particularly in hot-climate nations with high appliance ownership.[11] AC demand has become a critical factor for grid stability and energy security.

Many countries have implemented appliance efficiency standards[iii,12], yet inefficient ACs are still widely available in the market. Data show that the average efficiency of air conditioners sold today is less than half the efficiency of models typically available on the shelves—and only one-third the efficiency of the best available technology. The IEA projects that sales will keep rising, with two-thirds of the world's population expected to own ACs by 2050. China, India, and Indonesia alone will account for half of the new units. Air conditioning is set to become a major driver of global electricity demand. Without stronger efficiency measures, energy use for cooling could more than triple.[13] According to Mepsy, CLASP's policy tool, projected emissions from room air conditioners in 2030 could reach approximately 800 megatons (Mt)—roughly equivalent to the annual emissions of 186 million gasoline-powered cars.[14]

[iii] By 2024, MEPS covered roughly 89% of air conditioners globally.

FIGURE 1 GLOBAL AIR CONDITIONER STOCK WITH PROJECTION, 1990-2050



Source: IEA, Global air conditioner stock, 1990-2050, IEA, Paris, Licence: CC BY 4.0 Last updated 15 May 2018, https://www.iea.org/data-and-statistics/charts/global-air-conditioner-stock-1990-2050.

> *"Growing demand for air conditioners is one of the most critical blind spots in today's energy debate. Setting higher efficiency standards for cooling is one of the easiest steps governments can take to reduce the need for new power plants, cut emissions and reduce costs at the same time." --Fatih Birol, IEA Executive Director*

RACs are major energy-consuming products, but with great potential for efficiency improvements, making them central to cutting emissions and managing energy demand. High-efficiency cooling technologies are not necessarily more expensive, as lower operating energy costs provide better lifecycle economics. In a doubling energy efficiency scenario, the IEA estimates that appliances such as ACs and refrigerators could cut energy use per service by 30% to 40%[15], easing the pressure from rising appliance ownership on electricity demand. To realize this potential, countries should adopt and enforce stricter MEPS, phase out inefficient products, and accelerate the development, production, and uptake of efficient cooling technologies. Efficient air conditioners represent a key opportunity for achieving the doubling energy efficiency goal.

2. RAC Energy Efficiency: A Priority for China

STATUS OF RAC USAGE AND EFFICIENCY IN CHINA

China is the largest producer and consumer of RACs worldwide, accounting for over 80% of global production and selling approximately 100 million units annually in its domestic market[iv]. As air conditioning becomes increasingly widespread, cooling now makes up for more than 15% of national electricity use[16], and RACs account for over 20% of household consumption. During summer heatwaves, air conditioning can drive over 40% of peak demand in some regions, and up to 60% in major cities, posing challenges for grid operations and energy system stability.[17]

The country's air conditioner market has seen major gains in energy efficiency, driven by technology advances and supportive policies. For heat pump inverter RACs with a cooling capacity of 3,500-4,500W, efficiency rose sharply between 2008 and 2020[v]. The adoption of high-efficiency inverter compressors, improved fins and heat exchange tubes, and advanced refrigerants boosted performance, with registered inverter RACs achieving nearly a 33% increase in efficiency. By 2022, inverter models dominated the market, and the average APF[vi] of RACs reached 4.2.[18] Widespread deployment of high-efficiency inverter technology has cut energy use per unit while improving user comfort, positioning China at the forefront of global RAC efficiency improvements.

China's latest MEPS for RACs have been central to these product improvements, with efficiency levels playing a key role in market competition. Companies continue to invest in developing high-efficiency technologies, and RAC efficiency has continued to increase as new innovations are introduced.

KEY TECHNOLOGIES DRIVING MEPS UPGRADES

- **Inverter technology** improves RAC efficiency by 30% at part load, as a foundation for APF metrics.
- **DC inverters** optimize motor efficiency, enabling APF 5.0+.
- **Dual-rotor compressors** boost large-capacity efficiency by 20%, expanding cooling capacities up to 14,000W.
- **Microchannel heat exchangers** replace copper tube-fins, with a 15% increase in heat transfer.
- **Graphene-coated fins** enhance conductivity and wettability, reducing defrost energy consumption and improving heating capacity in low ambient temperatures.

Note: The data are aggregated from information shared through industry technical exchanges.

[iv] According to AVC PSI monitoring data, in the 2025 cooling year China produced 200 million RACs, with total sales reaching 196 million units. Of these, 102 million units were sold domestically, and 93.96 million units were exported. https://mp.weixin.qq.com/s/62dvn_X006ZAbRe_La0F-A

[v] In 2008, China introduced the energy label system for RACs, and the updated RAC MEPS GB 21455-2019 entered into force in 2020. Products with cooling capacity below 4500W occupy market share of 84%; Heat pump RACs, which provide both cooling and heating, now dominate the market with a 97% share.

[vi] China's RAC MEPS standard GB 21455-2019 requires the Annual Performance Factor (APF) as the main metric for assessing RAC efficiency. APF is calculated by measuring performance under several standard conditions and combining the results through weighted averaging, and it reflects annual energy efficiency by accounting for seasonal temperature changes.

In recent years, policymakers have launched a package of measures to steer the air conditioning industry toward efficiency, sustainability, and smart innovation. Key actions include raising efficiency levels, replacing refrigerants with low-GWP alternatives, and reducing product weight. Financial subsidies and incentives for green products also encourage consumers to purchase efficient products, accelerating the market shift to high-performance RACs. In 2024 and 2025, the Chinese government launched a trade-in program offering consumers a 15% to 20% subsidy on new appliances that meet Grade 2 or Grade 1 energy efficiency standards. All these measures have helped reduce energy consumption and advance climate targets.

Air conditioners have become one of the main drivers of load growth in China's power system. Improving RAC efficiency reduces household electricity costs and pressure on the power system, serving as a key lever for achieving China's energy conservation and emission reduction goals.

The report, *China Room Air Conditioner Industry Technology Roadmap*[19], released in November 2024, sets targets for improving RAC efficiency over the next 5-10 years. Based on current MEPS efficiency levels, the metrics of Grade 1 are expected to increase by up to 10% by 2030 and by 15% by 2035. Industries are encouraged to raise overall efficiency by 10% between 2024 and 2030, and by a further 10% from 2030 to 2035. The roadmap also outlines directions for technology upgrades, product innovation, and policy development in the air conditioning industry.

In the context of global efforts to double energy efficiency, CLASP supported Professor Wang Ruixiang's team at Beijing University of Civil Engineering and Architecture in developing a technology roadmap for promoting ultra-high efficiency room air conditioners in China to support the global doubling energy efficiency goal by 2030. The study explores feasible pathways and key challenges for improving RAC efficiency, drawing on advances across multiple disciplines. It also analyzes new technologies with higher energy-saving potential, to drive innovation in the RAC industry and provide evidence-based references for policymakers seeking to strengthen efficiency standards.

Research Methods and Theoretical Basis

1. Research Methods

This study explores the energy efficiency improvement potential of RACs by combining theoretical analysis with manufacturing research and development (R&D). Using a methodology that integrates technical modeling and empirical validation, it balances technical feasibility with economic affordability to identify pathways for efficiency gains.

Starting with an analysis of RAC energy use, the research maps consumption patterns, identifies high-demand components and potential savings, and explores matching technical solutions. By identifying key factors affecting performance and their mechanisms, the study builds a technical framework covering core components, system integration, and control strategies. With assessments of technological maturity and cost effectiveness, the research evaluates production costs and energy-saving potential, ultimately outlining a feasible pathway for efficiency improvements.

Key tasks included setting APF baselines, estimating the contributions of core components (compressor, condenser, evaporator) to overall RAC performance, reviewing ultra-efficient technologies with cost analysis, and assessing the current market status and growth potential for high-efficiency RACs. Collectively, these efforts provide both theoretical and practical insights for developing technical options and policy recommendations.

Using the GA3300 model[vii] as a case study, the research team designed an efficiency retrofit. They quantified the impact of specific measures and technology combinations under RAC operating conditions, identified critical processes and integration strategies, and projected their contributions to efficiency gains. Design parameters were subsequently refined, and improvements validated with real-world data, resulting in a practical product optimization plan.

Moving beyond a single product to a broader technical system, and validated through prototype retrofits, this study establishes a practical framework for high-efficiency RACs that is both technically robust and economically viable. It offers industry a reference to support the doubling energy efficiency goal. Alongside market research and analysis of emission reduction potential, the study evaluates the environmental impacts of scaling up high-efficiency RACs, providing evidence-based references to support the transition toward a green, low-carbon future.

[vii] GA3300 is a representative efficient product with a baseline APF of 5.20, which was manufactured by a top Chinese RAC brand and sold in 2024.

2. Theoretical Basis

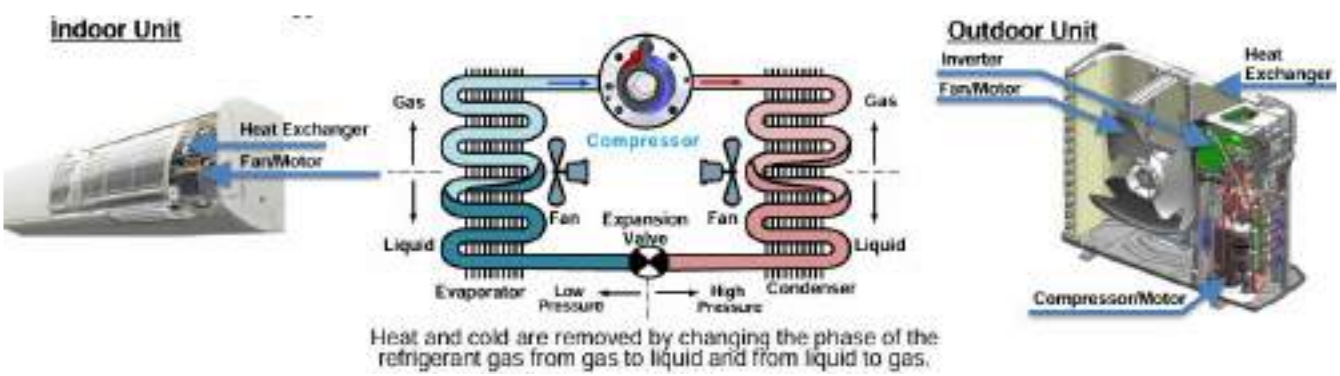
OVERVIEW OF RAC CORE COMPONENTS

RACs regulate indoor thermal environments through a vapor compression- refrigeration cycle. The cycle system mainly consists of a compressor, condenser, expansion valve, and evaporator, forming a closed loop charged with refrigerant for heat transfer between indoor and outdoor environments, as shown in Figure 2.

In cooling mode, the compressor raises the pressure and temperature of the gaseous refrigerant into a high-temperature, high-pressure gas. The refrigerant then enters the condenser, where it releases heat to the outdoor environment and condenses into a high-pressure liquid. After passing through the expansion valve, the refrigerant undergoes a pressure drop and temperature reduction before entering the evaporator. In the evaporator, it absorbs heat from the indoor air and evaporates back into a low-pressure gas, reducing the room temperature.

Indoor centrifugal or tangential fans improve heat exchange, while outdoor axial fans aid heat release. The control system, guided by temperature and humidity sensors, dynamically adjusts compressor speed and damper positions to balance efficiency with comfort factors such as airflow and temperature, ensuring effective indoor climate regulation. By switching the refrigerant flow direction with a four-way reversing valve, both cooling and heating modes can be achieved with heat pump RACs.

FIGURE 2 HOW RACS WORK AND CORE COMPONENTS



Source: Kota Miyazumi and Masahito Yoshizawa, Promoting Inverter Air Conditioning and the Realization of a Decarbonized Society (Daikin Industries, Ltd., 2025)[20]

The RAC system is composed of several core components: the compressor, condenser, evaporator, control devices, and fans. During the cooling cycle, these components operate in coordination to circulate refrigerant, releasing and absorbing heat through phase transitions, thereby lowering indoor temperature. The functions of the main components are described below:

- **Compressor**: Acting as the “heart” of the RAC system, the compressor provides the driving force for refrigerant circulation and plays a vital role in the entire cooling cycle. It compresses low temperature, low-pressure refrigerant to a high temperature, high-pressure state, enabling the refrigerant to release heat in the condenser and condense into liquid, thus ensuring heat transfer. Powered by an electric motor, the compressor operates with variable frequency control to adjust speed according to different load conditions, enhancing system efficiency. As the primary energy-consuming component, compressor performance determines RAC efficiency. In China, most RACs currently employ rotary (also called rolling rotor) compressors.

- **Condenser**: Serving as the heat-releasing component of the RAC system, the condenser cools the high-temperature, high-pressure refrigerant gas discharged from the compressor. As the refrigerant flows through, it transfers heat to the outdoor environment and condenses into liquid. Most condensers adopt fin-and-tube coil designs. During production, aluminum fins are shaped into specialized forms to enlarge the surface area and enhance heat-exchange efficiency.
- **Expansion Device**: The expansion device controls the refrigerant flow to maintain the pressure conditions required for evaporation and condensation. It lowers the pressure of the liquid refrigerant leaving the condenser, and converts it into a low-temperature, low-pressure mixture that can vaporize in the evaporator and absorb indoor heat. In RACs, two types of expansion devices are commonly used: capillary tubes and electronic expansion valves (EEVs).
- **Evaporator**: The evaporator is another key heat exchanger, serving as the “cooling-provider”. Once the refrigerant passes through the expansion device, its pressure and temperature drop, allowing it to become vapor inside the evaporator and absorb heat from the surrounding air. This process lowers the ambient air temperature and delivers the cooling effect. In RACs, evaporator fins are typically treated with hydrophilic coatings, which reduces the surface tension of condensate and improves airflow by enlarging the effective passage area.
- **Fan/Motor**: The fan/motor in RAC drives air circulation, ensuring cooled air from the evaporator or heated air from the condenser is delivered into the surrounding space to establish a continuous airflow loop. This circulation enables dynamic regulation of indoor comfort and outdoor heat release. Fans enhance convective heat transfer by reducing thermal resistance at the heat exchanger surface, while adjustable speeds improve the uniformity of indoor air distribution, preventing localized subcooling or superheating. Accurate fans peed control is essential for improving part-load efficiency in RACs.

ENERGY DISTRIBUTION IN RACS

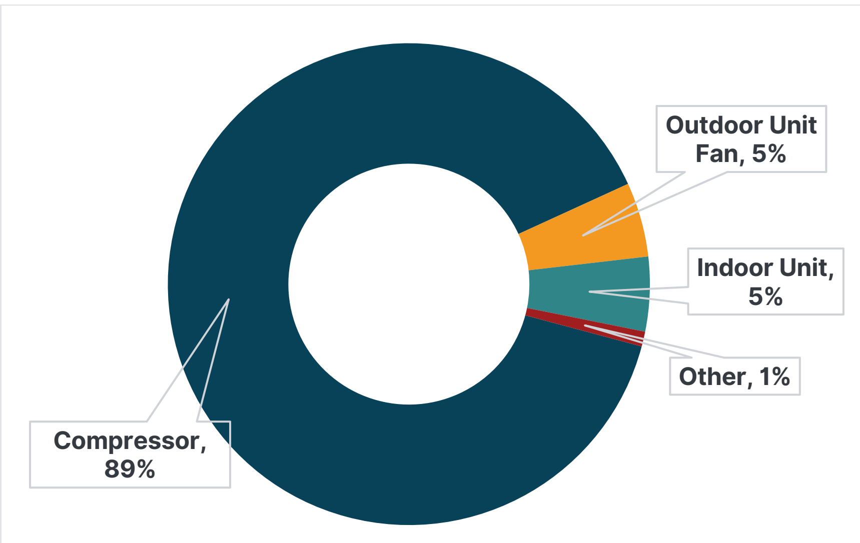
RACs regulate temperature through a continuous refrigerant cycle of compression, condensation, expansion, and evaporation, powered by electricity. Within this system, the main components consume most of the energy and their performance directly determines a RAC's overall efficiency.

For example, in a 1.5-horsepower RAC (rated cooling capacity 3500 W, rated power 1000 W) energy use is distributed as follows:

- **Compressor**: as the system's driving force, it typically operates between 150 W and 1000 W, accounting for roughly 80% of total energy use.
- **Fans/Motors**: the indoor and outdoor units together consume around 50 W, or 10%–20% of the total power use.
- **Other components**: the control devices, EEV, and display modules use roughly 10 W.

This breakdown shows that the compressor is not only RAC's "heart" but also the decisive factor in energy efficiency. Achieving energy savings requires maintaining the compressor in optimal operating condition.

FIGURE 3 POWER CONSUMPTION DURING RATED OPERATION (EXAMPLE)



Source: Kota Miyazumi and Masahito Yoshizawa, Promoting Inverter Air Conditioning and the Realization of a Decarbonized Society (Daikin Industries, Ltd., 2025)

RESEARCH STRATEGIES TO ENHANCE RAC EFFICIENCY

Today's strategies for higher efficiency focus on improving the performance of core components by applying inverters and integrating smart control technologies. Manufacturers are increasingly turning to advanced compressors, inverters, optimized electronic controls, large-sized heat exchangers, and low-GWP refrigerants to achieve higher APF ratings.

By adopting a Whole-System Approach to optimize the design and operation of core components, such as compressors and heat exchangers, RAC energy consumption can be significantly reduced. In addition, factors such as environmental conditions, user behavior, and system integration methods also impact energy performance. Enhancing adaptability and stability under diverse operating conditions has become essential for achieving high performance. In recent years, smart control technologies have emerged as a major focus in efficiency improvement.

Looking ahead, RAC efficiency improvements will emphasize system synergy and intelligent response. This represents a shift from traditional single-component optimization toward a balanced approach that combines system integration with intelligent regulation. These innovations will boost the energy-saving capability of RACs and provide support for broader sustainability and low-carbon development goals.

METHOD FOR SETTING APF TARGETS

Establishing a clear and reasonable energy efficiency baseline is the foundation for improving RAC performance. By defining standardized metrics, such as the coefficient of performance (COP) under rated conditions, partial load specifications, and energy thresholds in standby mode, researchers can create an objective framework for evaluation and reduce inconsistencies caused by experimental variability.

With a defined baseline, it becomes possible to identify limiting factors like compressor delays in variable frequency operation, uneven heat transfer in exchangers, or excessive airflow resistance. Addressing these issues enables optimization of control algorithms, component matching, and airflow design. As a result, efficiency improvements shift from isolated fixes to system upgrades, achieving a more balanced ratio of cooling or heating output to energy use.

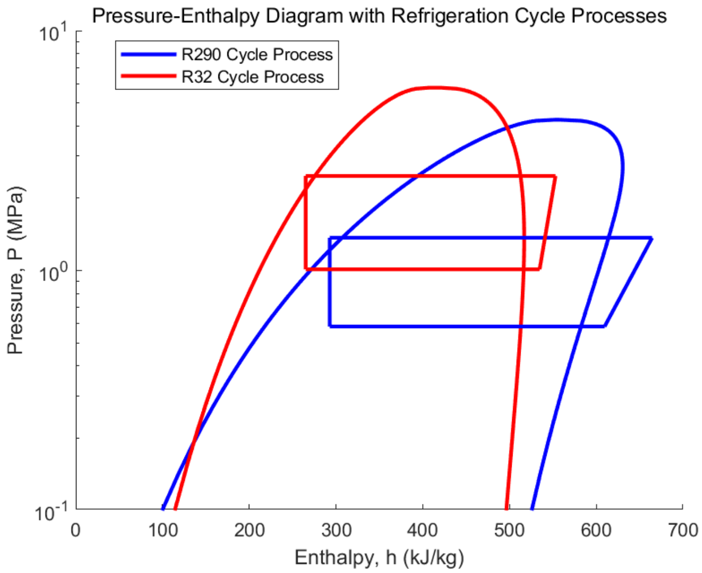
When MEPS are calibrated against a technical baseline, the techno-economic balance can be anchored at the point where marginal costs equal marginal benefits. This alignment encourages innovations such as the adoption of low-GWP refrigerants, variable driving, and enhanced heat exchange designs. It also helps overcome the “minimum compliance” trap by encouraging manufacturers to internalize the shadow price of carbon emissions while continuously improving APF. Ultimately, RAC products evolve from simply meeting regulations to setting new benchmarks for energy efficiency and sustainability.

PRESSURE ENTHALPY DIAGRAM AS A THERMODYNAMIC RESEARCH TOOL

The Pressure-Enthalpy Diagram is a widely used thermodynamic tool for analyzing refrigeration systems. It illustrates how a refrigerant’s pressure and enthalpy change throughout the cycle, making it valuable for refrigeration design, performance evaluation, and troubleshooting.

In a Pressure-Enthalpy Diagram (as a log ph- diagram), as shown in Figure 4, the refrigerant’s thermodynamic state is plotted on a rectangular coordinate system. The vertical axis represents the logarithm of pressure, while the horizontal axis shows specific enthalpy. The diagram contains families of curves, such as isothermal, isentropic, dryness fraction, and saturation lines, that provide a complete picture of refrigerant phase transitions and energy transfer processes within the refrigeration cycle. Analyzing thermodynamic relationships in the p-h diagram helps drive coordinated enhancements in RAC energy efficiency.

FIGURE 4 DIAGRAM OF AN IDEAL RAC REFRIGERATION CYCLE



Note: The pressure enthalpy diagram illustrates a refrigeration process in RACs as an example. The blue curve corresponds to the R290 system, while the red curve represents the R32 system.

Under ideal conditions, the performance of RACs can be approximated using Rankine Cycle analysis. By calculating the cooling or heating coefficient of such an ideal cycle, researchers can estimate the system's theoretical maximum efficiency. Under specific test scenarios, the contribution of different technologies to efficiency gains can be roughly assessed and then adjusted according to real operating conditions, providing a more accurate picture of their effectiveness in practice. This process establishes a thermodynamic foundation and quantitative support for defining APF baseline targets.

Building on the framework of an ideal cycle, further studies should explore thermodynamic completeness and energy quality by asking key questions:

- How is energy distributed within the system?
- Are there sources of power loss?
- Is there residual energy that could be harnessed?

Addressing these questions deepens understanding of how RACs operate and points to optimizations, such as a well-designed cycle path, efficient control logic, and effective system matching with load demands across time, space, and energy quality dimensions. These insights can uncover further strategies for improving efficiency.

Technologies, Potential, and Economics of RAC Efficiency Improvement

Technical Strategies to Enhance RAC Efficiency

Improving RAC efficiency requires a holistic approach that coordinates multiple technical aspects. Every stage, from product design and system control to circulation control and environmental adaptability, plays a critical role in determining overall performance. To achieve energy savings, manufacturers focus on both upgrading key components and optimizing system integration.

Currently, high-efficiency RACs[viii] in the market already incorporate a range of efficient technologies, typically grouped into four main strategies[21]:

- **Advanced compressors and inverters** optimized for stable low-frequency operation.
- **Larger heat exchangers** built with superior thermal materials and refined tube designs.
- **High-performance DC motors** paired with efficient fan systems.
- **Smart sensors** capable of detecting temperature and humidity, together with precise expansion devices, to fine-tune refrigerant flow in response to varying cooling demands.

Together, these innovations reduce energy use and improve operating stability and user comfort.

OPTIMIZATION OF COMPRESSORS AND DRIVE SYSTEMS

As the core component of RACs, the compressor's performance largely dictates the unit's overall efficiency. Raising compressor efficiency is therefore central to boosting system performance. Manufacturers pursue this goal by increasing displacement (measured in cubic centimeters, cc)

[viii] All subsequent discussions, unless specifically noted, focus on variable-frequency split-type RACs with rated cooling capacities of 4500 W or below.

or lowering the energy consumed per unit of cooling output, and such processes require improvements in materials, mechanical design, and control strategies.

Efficiency improvements can be approached on three levels:

- **Component level**: refinements to mechanical structure, sealing, and lubrication enhance intrinsic performance.
- **System level**: integration with motors and controllers ensures better matching and higher efficiency.
- **Intelligent control technologies**: advanced electrical topologies and algorithms, enable dynamic optimization of compressor operation.

A breakthrough comes from high-efficiency variable frequency motors. Unlike fixed frequency ones, which rely on repeated start-stop cycles to meet load changes (causing energy spikes and reduced comfort), inverters adjust compressor speed and refrigerant flow via electronic expansion valves. This smooth response minimizes energy losses, stabilizes temperature control, and improves comfort. Variable frequency compressors also run more quietly and deliver better overall performance.

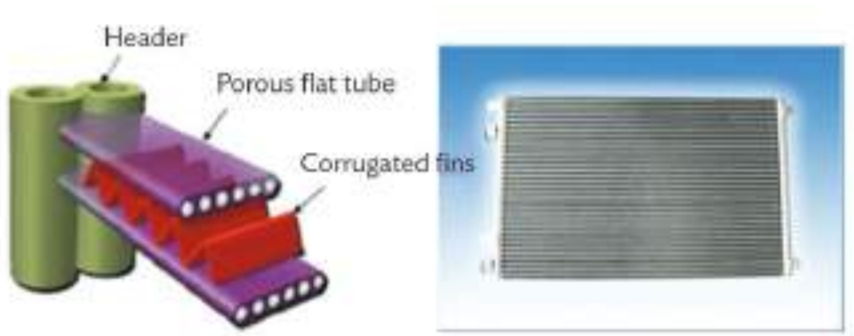
Looking ahead, compressor technology will increasingly rely on intelligent control and system-level optimization. AI algorithms and digital technologies allow compressors to accurately sense and respond to load demands, dynamically adjusting speed under partial-load conditions to cut start-stop losses. Further research will focus on how motor design and electrical topology improvements can be leveraged to achieve higher system efficiency.[22]

HEAT EXCHANGERS AND CONTROL TECHNOLOGIES

Temperature-difference losses during heat transfer represent the largest source of inefficiency in RACs. Since the condenser and the evaporator are the primary heat exchange components, their performance has a direct impact on the overall efficiency. Strengthening their heat transfer capability and minimizing temperature-related losses are critical routes to higher efficiency.

Currently, the most widely used design is the fin-and-tube heat exchanger with copper tubes and aluminum fins. For this traditional design, efficiency improvements focus on reducing tube diameter, refining fin geometry, and raising heat transfer coefficients on both the refrigerant and air sides. More recently, microchannel heat exchangers (Figure 5) have gained rapid adoption. The microchannel approach increases surface area and enhances heat transfer, which reduces refrigerant charge and delivers efficiency gains of 10% to 20%.

FIGURE 5 MICROCHANNEL HEAT EXCHANGER STRUCTURE



Source: Asian Development Bank, Sustainable Cooling: How to Cool the World Without Warming the Planet (Asian Development Bank, 2024)[23]

Beyond structural design, advances in heat exchanger performance also rely on material choices and surface treatment. Reinforcing fin and tube structures, the use of high-conductivity materials, and surface coating technologies have already demonstrated notable benefits in commercial RAC products. At the time, system-level optimization, such as improved flow path design and integration with variable frequency control, represent key avenues for efficiency gains.

Looking ahead, a more visionary approach lies in cross-disciplinary innovation. By combining smart materials, optimized structures, and AI-driven control, heat exchangers could achieve transformative improvements in efficiency. Theoretically, such integrated solutions have the potential to boost overall heat transfer efficiency by 20% to 40%.

INNOVATION IN CYCLE STRUCTURES

Traditional RACs typically operate on a single refrigeration cycle consisting of compression, condensation, expansion, and evaporation. While this design is reliable, this approach is close to the theoretical efficiency limit. Challenges such as insufficient heating capacity under variable loads and low-temperature conditions have become increasingly evident. To overcome these bottlenecks, innovation with a cycle structure offers a critical pathway to higher efficiency in RACs.

Cycle innovation moves beyond the constraints of single-stage operation to adapt to diverse scenarios. Approaches such as multi-stage cycles, vapor injections, or auxiliary heat exchangers can significantly enhance thermodynamic performance. For instance, in high-temperature cooling conditions, two-stage vapor injection technology introduces intermediate vapor during compression to reduce the compression ratio while maintaining cooling output with lower power consumption. When paired with variable-frequency control, this method can raise the energy efficiency APF by 10% to 15%[24], with especially strong gains in low-temperature heating.

Cycle structures can also be tailored to climates and operating conditions through bypass circuits, auxiliary heat exchangers, or condenser heat recovery. These designs improve adaptability and boost efficiency under partial-load operation. By dynamically regulating refrigerant flow routines and thermodynamic states, RACs can sustain high efficiency across a wide range of operating conditions.

Future innovations with cycle structures will depend on system-level integration and intelligent control. AI-driven algorithms, combined with multi-stage cycle topologies and dynamic flow optimization are expected to unlock even greater efficiency potential.

INTELLIGENT CONTROL AND OPERATION STRATEGIES

Early studies on RAC efficiency mainly focused on mechanical improvements to core components.[25] With the convergence of information and control technologies, RACs have advanced from simple mechanical execution to intelligent operation modes driven by sensing and decision-making. Intelligent control boosts energy performance and enhances adaptability to complex conditions, making it a cornerstone of innovation in air conditioning.

Today's intelligent control systems rely on three pillars: precise load matching, dynamic algorithmic optimization, and coordinated regulation across multiple variables. For instance, variable-frequency compressors working in tandem with electronic expansion valves (EEVs[ix]) can be managed through coordinated control. By responding to real-time temperature and pressure signals, the system dynamically adjusts compressor speed (with stepless variation from 10% to 100%) and valve opening, ensuring refrigerant flow aligns precisely with indoor load demands. This eliminates the inefficiencies of traditional ON/OFF cycling and can cut energy use by 30% to 50% under partial-load conditions.

Looking forward, enhancing RAC efficiency will require a stronger system-level perspective and breakthroughs in intelligent control strategies. The integration of AI algorithms, digital sensors, and edge computing promises more refined regulation and deeper efficiency gains, steering RAC products toward a future of high efficiency, intelligence, and low-carbon operation.

[ix] The electronic expansion valve, as EEV functions as the expansion device among the four key components in RAC. Compared with conventional thermal expansion valves, EEVs offer superior responsiveness, faster operation, broader adaptability to temperature variations, and easier control configuration, although these advantages come at a higher cost.

Technology Options and Potential for High-Efficiency RACs[x]

Enhancing the efficiency of RACs requires an integration of thermodynamic principles, component optimization, and intelligent control strategies. Performance improvements in key components, like compressors, evaporators, condensers, and expansion devices, help reduce energy use, while system-level coordination ensures stable and efficient operation.

On the technology front, variable-frequency control is now widely applied in both cooling and heating modes, allowing RACs to flexibly adjust to changing loads. Structural innovations are also gaining traction: liquid injection cooling boosts performance under high-temperature conditions, while vapor-injection economizers significantly improve heating in cold climates. With advances in AI algorithms and digital twin technologies, RACs can predict demand more precisely and optimize operations in real time, bringing opportunities for efficiency gains.

Different technologies vary in maturity and energy-saving potential. High-efficiency motors and inverters are well established, contributing to 15% to 25% efficiency gains. Structural optimization remains in development, with contributions of 5% to 15%. System-level coordination is not yet widely deployed but could deliver up to 30%. Intelligent control represents the most promising frontier, with theoretical contributions exceeding 40%. Together, these evolving technologies form a solid support for higher RAC efficiency.

This report presents energy-efficiency technologies for RACs, including both solutions already in commercial use and those with strong potential for near-term deployment. Emphasis is placed on the practical feasibility of these approaches and their performance across diverse operating conditions to offer robust technical insights to support policy development.

1. Optimization of Thermodynamic Cycles

TWO-STAGE AND MULTI-STAGE COMPRESSION TECHNOLOGIES

Two-stage and multi-stage compression are among the most effective strategies for optimizing thermodynamic cycle systems. They are designed to counter efficiency losses caused by high compression ratios, which often occur in high-temperature cooling or low-temperature heating scenarios, particularly in hot climates.

[x] Unless otherwise indicated, the data in this chapter are gathered from industry technical exchanges and experimental research from the R&D activities of the project team.

There are two main approaches:

- **Economizer[xi] cycle**: By injecting intermediate vapor during compression, the economizer lowers the compressor discharge temperatures and boosts cycle efficiency. In high-temperature cooling, this can raise COP[xii] by 10%–15%.
- **Twin-rotary compressors**: Through mechanical design, these achieve quasi two-stage compression, offering strong reliability and improving APF by 8%–12%.

While the energy-saving benefits are clear, these technologies also increase system costs by about 10%–15%, requiring evaluation of efficiency gains against investment.

VAPOR INJECTION CYCLE

The vapor injection cycle is an advanced approach to optimizing thermodynamic systems, designed to reduce compression power usage and enhance efficiency through structural innovation. By linking the compressor's intermediate chamber to the line after the evaporator, flash vapor is injected mid-compression, minimizing irreversible losses in compression.

Two design options are commonly used: flash tank systems and built-in channel structures. Both guide intermediate vapor flow to ease compressor load and enhance system performance. Studies indicate that RACs equipped with vapor injection deliver outstanding results in low-temperature heating, with COP gains of 20% to 30%. This makes it valuable for RAC heating in cold climates.

VARIABLE-FREQUENCY DRIVE TECHNOLOGY

Inverters regulate compressor motor speed to control refrigerant flow, allowing RACs to operate efficiently across different load conditions. Unlike fixed-speed systems that depend on frequent on/off cycling, inverters minimize energy losses during partial-load operation. Advances in inverter efficiency further enable compressors to perform well over a broad frequency range, laying the groundwork for higher overall efficiency.

Performance improvements in inverter technology are concentrated in three areas:

- **Permanent magnet synchronous motors (PMSMs)**: Their high-power density and reduced iron losses yield 15%–20% efficiency gains over induction motors.
- **High -frequency PWM[xiii] algorithms**: Precise decoupling of torque and flux adds 5% to 8% efficiency improvements.

[xi] The economizer plays a central role in two-stage compression. Acting as an intermediate heat exchanger, it introduces vapor between compression stages to improve thermodynamic performance. Beyond efficiency gains, it also protects the compressor and extends its lifespan, making it a vital element of the technology.

[xii] In RACs, the Coefficient of Performance (COP) is a measure of efficiency. It represents the ratio of useful cooling or heating output to the electrical energy input. A higher COP means the air conditioner delivers more cooling or heating for the same amount of electricity, making it more energy-efficient.

[xiii] In Electronic Engineering, Pulse Width Modulation, or PWM, is a commonly used technique for effectively controlling the power supplied to electrical devices. In order to attain a desired average voltage or power level, the principle of pulse width modulation (PWM) is used for a periodic signal, which is usually a square wave. More information is available by https://www.geeksforgeeks.org/electronics-engineering/pulse-width-modulation-pwm/.

- **Advanced optimization methods** such as model predictive control (MPC): Under partial-load conditions, these can provide an extra 5% to 10% efficiency boost.

2. Performance Upgrades of Core Components

HIGH-EFFICIENCY COMPRESSOR TECHNOLOGIES

Advances in compressor efficiency are being pursued along four main paths, and together these approaches drive the development of more efficient compressors.

- **Low-friction component design** minimizes mechanical losses.
- **Motor optimization** uses advanced design and control strategies.
- **Innovative structural layouts** improve internal flow and mechanical performance.
- **Lightweight materials** cut energy use without compromising strength.

In practice, two-stage compressors can deliver around 15% higher efficiency due to staged compression. Yet these gains come at a cost: two-stage units cost roughly 25% more than single-stage compressors due to their complexity and precision requirements. Variable-frequency compressors cost about 30% more than conventional models because of their advanced inverters and motors. High-efficiency compressor technologies thus represent a typical trade-off between efficiency gains and increased costs.

HEAT EXCHANGER ENHANCEMENT TECHNOLOGIES

Heat exchange performance can be significantly improved through structural innovations. Together, these approaches strengthen heat exchanger efficiency under demanding operating environments. Typical strategies include:

- Increasing the heat transfer area and redesigning tube geometry and arrangement to boost heat transfer on both the air side and the refrigerant side.
- Coating fins with hydrophilic-hydrophobic composites helps delay frosting and reduce condensation resistance, particularly in humid conditions, yielding 5% to 10% efficiency gains.
- Improving tube designs through three-dimensional enhanced tubes. Internally grooved or micro-ribbed designs disrupt boundary layers to intensify boiling and condensation, delivering 10% to 20% improvements.

Future developments highlight the potential of combining microchannel heat exchangers with enhanced tubes. Microchannel exchangers offer a compact structure with reduced refrigerant charge, and excellent air-side performance (though airflow resistance still requires refinement). Compared to conventional fin-and-tube exchangers, microchannel exchangers can achieve 15% to 25% higher efficiency and cut refrigerant charge by about 30%. Experimental results indicate that adopting microchannel exchangers or optimized fin designs can raise overall RAC efficiency by 4.5% to 7.2% at a cost increase of about 5%, with an additional 3% efficiency gain achievable through further interface optimization.

ALGORITHMS AND INTELLIGENT CONTROL

Algorithms and intelligent control technologies combine sensors with smart control systems, enabling air conditioners to predict loads based on historical data and weather information, and to optimize start-stop cycles and temperature settings within comfort ranges. Air conditioners can monitor indoor and outdoor environmental parameters in real time and automatically adjust operating modes to achieve precise energy savings. This dynamic adjustment improves operating efficiency and reduces unnecessary energy consumption while maintaining comfort.

Studies show that the application of intelligent control technologies in air conditioning systems can significantly improve energy efficiency. For example, AI and machine learning-based smart HVAC systems can reduce energy waste by up to 20%. In residential or commercial scenarios, the energy-saving potential is generally in the range of 10% to 20%, with specific results depending on sensor deployment, algorithm optimization, and user behavior patterns.[26]

HIGH-EFFICIENCY FAN SYSTEMS

Fan systems use 10% to 20% of RAC operating energy consumption, so boosting their efficiency is critical to overall performance. Brushless DC (BLDC) motors deliver 20% to 30% higher efficiency than conventional AC motors and operate more quietly. When paired with biomimetic blade designs that streamline airflow and reduce turbulence, power use can drop by 10% to 15%. The combination of BLDC motors and optimized blades has become a defining feature of high-efficiency RACs, underpinning system-wide energy gains.

By 2024, DC fan motors had reached around 70% market penetration, and they now dominate the domestic variable-frequency RACs.[xiv] This widespread adoption demonstrates that high-efficiency fan systems are both technically mature and commercially established.

[xiv] According to the report by ChinaIOL, the sales of DC motors for air conditioners exceeded 250 million in 2023, marking five consecutive years of growth. ChinaIOL further projected that by the end of 2024, the Chinese domestic market share of DC motors will surpass 70%. http://www.chinaiol.com/News/Content/202404/74_50640.html.

TABLE 1 ASSESSMENT OF EFFICIENCY IMPROVEMENT TECHNOLOGIES

TECHNOLOGY OPTION	EFFICIENCY IMPROVEMENT POTENTIAL WITH APF	COST INCREASE LEVEL	REMARKS
Inverter technology optimization	5%–10%	Low	Continuous iteration
Vapor injection cycle	15%–25% (heating)	Medium	In favor of heating in cold regions
High efficiency compressors	3%–8%	Low to Medium	Continuous iteration
Microchannel heat exchangers	10%–20%	Medium	Extra effect refrigerant reduction
Coordinated intelligent control	8%–15%	Medium (software development)	Sensors and algorithms
Fan system optimization	5%–10%	Low	BLDC penetration, aerodynamic blade design

3. Case Study: From Component Upgrades to System-Level Efficiency Gains

In this case study, a benchmark RAC was selected, and measured performance data were used to quantify efficiency losses during operation. The analysis assessed how different technologies influence operating conditions, considering both individual contributions and the combined effects of multiple technologies. Design parameters were further adjusted to forecast their impact on overall efficiency gains. This approach aims to provide a realistic assessment of energy-saving potential under real-world operating conditions.

TABLE 2 PARAMETERS AND ENERGY-EFFICIENCY BASELINE OF THE SAMPLE RAC[xv]

REFRIGERANT	COOLING CAPACITY (W)	COMPRESSOR POWER (W)	COP*
R32	3500	1000	3.5
R290**	3800	1000	3.8

*Note: * COP refers to the coefficient of performance and is different from APF.*

[xv] This sample RAC is equipped with a fixed-speed compressor and differs from the GA3300 prototype adopted in the later study, which has an inverter compressor with distinct data communication chips and control logic for compressor operation.

*** More than 500,000 R290 split RACs have been sold and are in use in China. Driven by international commitments and national "dual-carbon" goals, the adoption of R290 refrigerant in small-sized split units represents a development pathway. However, compared with R32 products, the cost of R290 remains relatively high. Against this background, this study undertakes a forward-looking exploration of efficiency improvements in R290 models, assessing their potential under scenarios of enhanced core component performance.*

Following the test method regulated by China's RAC MEPS (GB 21455-2019), the study selected a sample RAC operating at 50 Hz fixed-frequency conditions and defined its baseline performance parameters (see Table 2) using both R32 and R290 refrigerants. Building on this baseline, several scenarios were modeled:

- a 10% increase in compressor efficiency
- a 10% increase in condenser efficiency
- a 10% increase in evaporator efficiency
- simultaneous 10% improvements in condenser and evaporator efficiency
- simultaneous 10% improvements in compressor and condenser efficiency

These simulations were used to estimate the incremental gains in overall system efficiency. The findings, as presented in Table 3, indicate that measured improvements in condenser and evaporator efficiency closely match theoretical predictions.

TABLE 3 COMPONENT CONTRIBUTIONS TO OVERALL SAMPLE RAC EFFICIENCY ENHANCEMENT

	REFRIGERANT			
	R32		R290	
SCENARIOSWITH COMPONENT IMPROVEMENT	EFFICIENCY IMPROVEMENT (THEORETICAL)*	EFFICIENCY IMPROVEMENT (EXPERIMENTAL)	EFFICIENCY IMPROVEMENT (THEORETICAL)*	EFFICIENCY IMPROVEMENT (EXPERIMENTAL)
10% improvement in compressor efficiency	13.7%		10.0%	
10% improvement in condenser efficiency	8.0%	7.68%–8.26%	7.6%	7.62%–7.87%
10% improvement in evaporator efficiency	7.1%	7.2%–7.9%	9.5%	9.7%–10.2%
Condenser + 10% & Evaporator + 10%	15.4%		15.0%	
Compressor + 10% & Condenser + 10%	22.9%		18.2%	

Note: Theoretical efficiency improvements are based on empirical data and/or calculated estimates.

Table 3 demonstrates that while single-component efficiency upgrades can deliver notable improvements in overall RAC performance, the gains are non-linear and strongly influenced by refrigerant properties.

- **Compressor upgrades**: R32 systems show greater theoretical efficiency gains than R290 systems. This reflects R32's higher sensitivity due to its larger adiabatic index and higher discharge temperature, which amplifies the benefits of reduced compression.
- **Evaporator upgrades**: R290 systems outperform R32 and benefit from R290's higher latent heat and superior heat transfer, which translates efficiency improvements more effectively into cooling capacity gains and lower compression ratios.
- **Condenser upgrades**: Improvements yield similar benefits for both refrigerants, indicating comparable sensitivity in this component.
- **Multi-component upgrades**: Simultaneous improvements across components generate synergistic effects, however, the combined gains are less than the sum of individual improvements. This makes system-level optimization very important. For instance, simultaneous 10% improvements in compressor and condenser efficiency resulted in a 22.9% gain for R32, versus 18.2% for R290. This difference arises due to R32's advantage in compressor-driven ("power-side") optimization, while R290 has more potential in evaporator-driven ("heat-absorption-side") optimization. Targeted upgrades can achieve better performance improvements.

In summary, optimization strategies should be refrigerant-specific: **R32 systems benefit most from compressor efficiency improvements** to mitigate high pressure-ratio power losses, whereas **R290 systems should prioritize evaporator efficiency** to exploit their superior phase-change heat transfer properties. Aligning tailored component strategies with refrigerant characteristics can deliver meaningful system-level efficiency gains with better economic benefits.

Economic Assessment of RAC Efficiency Improvement

Economic feasibility is a critical element in evaluating RAC performance, particularly with respect to energy efficiency. Efficient RACs should deliver measurable energy savings while keeping costs manageable, to ensure affordability and foster consumer adoption.

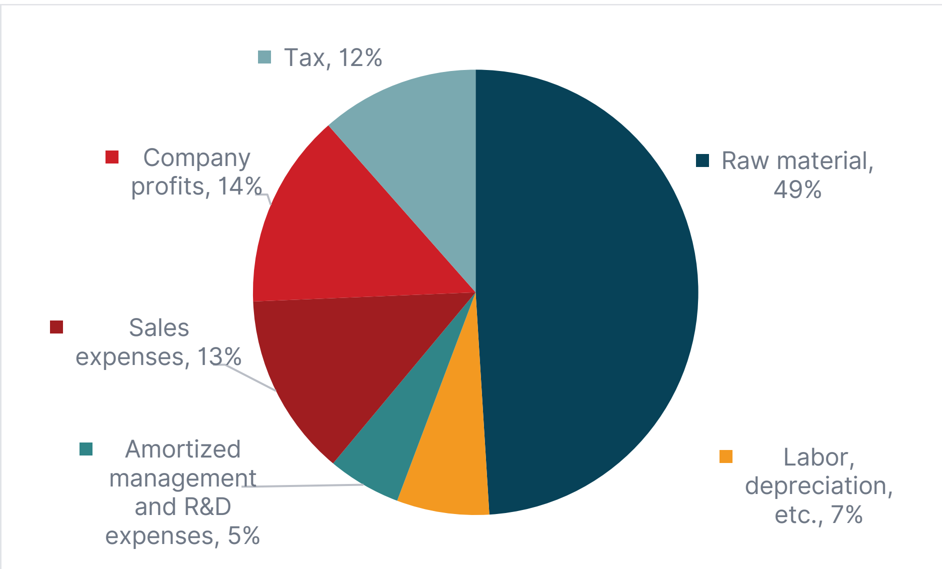
1. Cost Structure of RACs

The cost structure of RACs can be divided into two categories: direct and indirect costs.

- **Direct costs** include materials, labor, and manufacturing expenses such as equipment depreciation, energy use, and facility maintenance. Together, these form the basic production costs. Direct costs account for around 45% to 55% of total RAC costs and are a major factor in product pricing.
- **Indirect costs** also make up a large share of the overall costs. R&D is a significant indirect cost, with each new RAC model requiring a 1.5 to 2-year development cycle and extensive testing. Other indirect costs include logistics, compliance certification (such as energy efficiency standards and label registration), marketing and distribution, taxation, and company profit margins. These costs represent about 40% to50% of the retail price and are critical for market promotion and long-term business operations.

Within the overall cost structure, raw materials, especially core components, make up the largest share. Figure 6 illustrates the price breakdown of a representative RAC model sold online, where raw materials account for roughly half of the retail price. The compressor, as the unit's key component, represents around 30% of the total cost. Compressor costs vary depending on whether produced is in-house or purchased externally, and they also differ across brands.

FIGURE 6 COST BREAKDOWN OF A RAC SOLD ONLINE IN CHINA (2024)



Source: Industry research report by Xiaoniu Hangyan, [*https://www.hangyan.co/reports/3473489435205567901?page_num=9*](https://www.hangyan.co/reports/3473489435205567901?page_num=9)

2. RAC Energy Efficiency: Costs and Benefits

For any product, cost considerations span the entire value chain, from R&D to production and end use. In the R&D phase, companies must manage the marginal costs of technology investment. In production, they need to balance materials with process efficiency. At the consumer level, products must deliver strong value for money. The same applies to RACs. Only by effectively balancing costs and benefits can high-efficiency RACs achieve broad adoption, turning energy efficiency gains into a sustainable market reality rather than just a technical breakthrough.

To examine this relationship, the report's research team analyzed the link between costs and the rise in APF from 4.0 to 6.25 with a 56% improvement. The analysis draws on 2018–2024 survey data from China's RAC industry chain, engineering reverse analysis, and a lifecycle cost (LCC) model. The study highlights the marginal contributions of three technical pathways: traditional technology optimization, new technology adoption, and combined innovation[xvi], as shown in Table 4.

TABLE 4 RAC ENERGY EFFICIENCY LEVELS: TECHNOLOGY OPTIONS AND COST IMPLICATIONS

APF LEVEL	4.0-4.5	4.5-5.3	5.3-6.0	6.0-6.25
Efficiency Gain	12.5%	17.8%	13.2%	4%
Pathway	Traditional optimization		New technology adoption	Combined innovation
Key Measures	Larger heat exchanger (+15%); Inner-grooved copper tubes; Hydrophilic aluminum foil	Advanced compressor: inverter, rare-earth permanent magnet motor, with twin-rotary	Refrigerant shift R32→R290; Copper tube upgrade φ7mm→φ5mm; Deep-cavity triple-fold heat exchanger	Microchannel evaporator; Continuous enthalpy-spray converter; AI-based predictive control
Cost Impact	≈18.7%	Compressor cost + 25%		
Marginal Cost Elasticity (MCE)	≈1.3	≈2.0	≈2.7	≈3.5

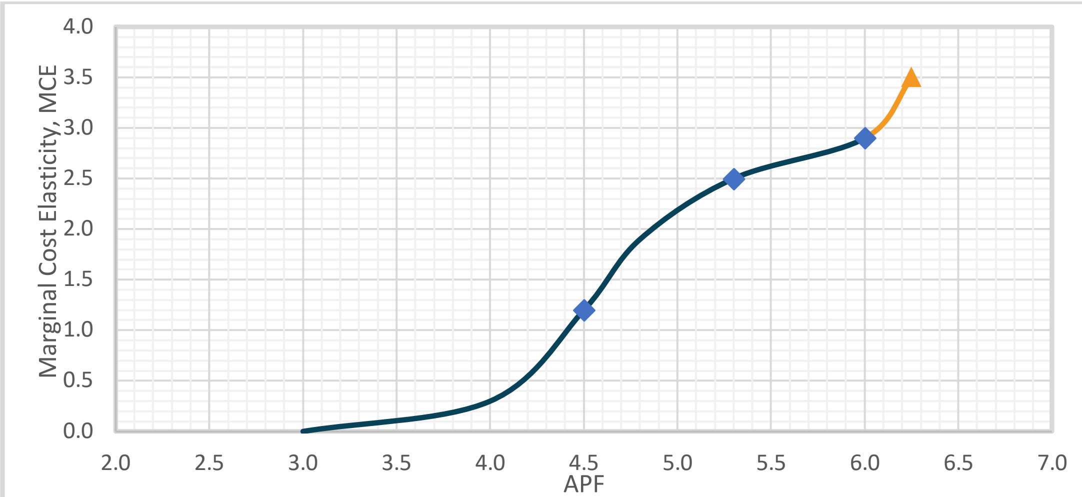
Note: MCE indicates how marginal cost changes relative to variations in production.

China's RAC manufacturing sector is still in the 'traditional optimization' stage but is shifting toward new technology adoption, or even combined innovation. With the transition toward low-GWP refrigerants, costs for production line upgrades, safety and explosion-proof measures, as well as investments in R&D, certification, and management will significantly increase over a certain period. As illustrated in Figure 7, these changes also drive significant increases in marginal costs.

At the ultra-high efficiency level (APF 6.0–6.25), manufacturing requires more sophisticated processes. Added expenses for AI-driven algorithms, cloud computing integration, and enhanced fire and explosion protection further increase incremental costs. In this efficiency range, the cost curve becomes steeper, highlighting a distinct non-linear trade-off: higher efficiency comes at a much higher cost.

[xvi] By 2024, RAC products based on "combined innovation" had not entered the market.

FIGURE 7 MARGINAL COST ELASTICITY ACROSS RAC ENERGY EFFICIENCY LEVELS



Note: The chart is for illustrative purposes and does not represent a specific case. The curve has been smoothed to show the general trend.

Marginal benefit (MB) in energy efficiency refers to the incremental value generated across the entire RAC industry chain for every 0.1 increase in APF. It is driven by four key factors, which together define the overall benefits from efficiency improvements, making marginal benefit a critical indicator of incremental industry gains.

- **User savings**: lower electricity bills as consumers benefit from improved efficiency.
- **Manufacturer pricing power**: higher efficiency often enables premium prices for more efficient products.
- **External benefits**: reduced carbon emissions and their positive impact on society and the environment.
- **Policy incentives**: subsidies, green financing, and tax relief that provide fiscal support for efficient products.

Using the 1.5-HP inverter split RAC (cooling capacity 3500 W) sold in 2022 as a benchmark, the evolution of marginal benefit from APF 4.0 to 6.25 follows a three-stage pattern. As shown in Table 5, marginal benefit declines as efficiency rises and marginal costs increase, while when marginal benefit falls below marginal cost, the industry faces the “efficiency trap”. This means further investments in efficiency become harder to justify unless backed by strong policy support.

TABLE 5 COSTS AND BENEFITS OF 1.5-HP INVERTER SPLIT RACS ACROSS ENERGY EFFICIENCY LEVELS (2022 BASELINE)

APF LEVEL	4.0-4.5	4.5-5.3	5.3-6.25
Efficiency Gain	12.5%	17.8%	17.9%
Key Measures	Heat exchanger area +15%; Inner-grooved copper tubes; Hydrophilic aluminum foil	Rare-earth permanent magnet DC inverter + twin-rotary compressor; R32 refrigerant	Refrigerant R32 → R290; Microchannel flat aluminum tubes; Continuous enthalpy spray; AI predictive control
Marginal Cost, MC	¥53 /0.1 APF	¥85 /0.1 APF	¥105 /0.1 APF
Marginal Benefit, MB	MB rises steeply, net benefit ¥35 per 0.1 APF; “Low-hanging fruit”	MB slows; net benefit shrinks to ¥19 per 0.1 APF; Industry concentration (CR5) rises from 68% to 78%	MB drops sharply, MB < MC, net benefit –¥12 per 0.1 APF; High efficiency – high cost, as “efficiency trap”

Note: Cost and benefit are derived from China’s local manufacturing and application. 1 Chinese Yuan (¥1) ≈ 0.14 US Dollar.

Energy efficiency, cost, and benefit are dynamically linked. Advances in technology and innovation can reset the balance between marginal benefits and marginal costs, allowing higher APF levels to still deliver attractive returns. Continuous refinement of existing technologies, combined with new materials, processes, or control algorithms, helps spread fixed costs and R&D expenses. This lowers unit costs and postpones or mitigates the onset of the “efficiency trap”.

Externally, efficiency policies such as MEPS, energy labeling schemes, and fiscal incentives directly enhance the marginal benefits of high-efficiency products. These elements should be central considerations in policy design.

Ultra Efficient RACs: Achievability and Emission Reduction Potential

HIGHER RAC ENERGY EFFICIENCY IS CHALLENGING

While existing and emerging technologies offer multiple pathways to improve RAC efficiency, their adoption and large-scale commercialization remain challenging. Technology maturity, market acceptance, and alignment with standards ultimately determine whether innovations can deliver meaningful energy-saving outcomes. Beyond technical potential, industry must address the multiple barriers that challenge efficiency improvements. These include

- **Technical and economic constraints**. Thermodynamic limits set the boundaries of efficiency gains. Natural hydrocarbon refrigerants pose a trade-off between environmental benefits and system safety requirements. Techno-economic barriers restrict market diffusion: as efficiency rises, marginal benefits diminish, and balancing costs with returns becomes difficult.
- **Limitations in efficiency evaluation methods**. Current test methods, conditions, and indicators often diverge from real-world usage, failing to capture performance across diverse environments. Studies[27,28] have noted that testing protocols themselves shape R&D priorities and the adoption of RAC efficiency technologies, with their scientific rigor directly influencing innovation trajectories. At the market level, the advantages of high-efficiency products are not fully recognized, weakening both policy effectiveness and market promotion.

In this context, overcoming these bottlenecks to unlock the full potential of efficiency gains and emission reductions stands as a critical challenge for the global air-conditioning industry.

Towards Ultra Efficient RACs: Exploring APF 6.25

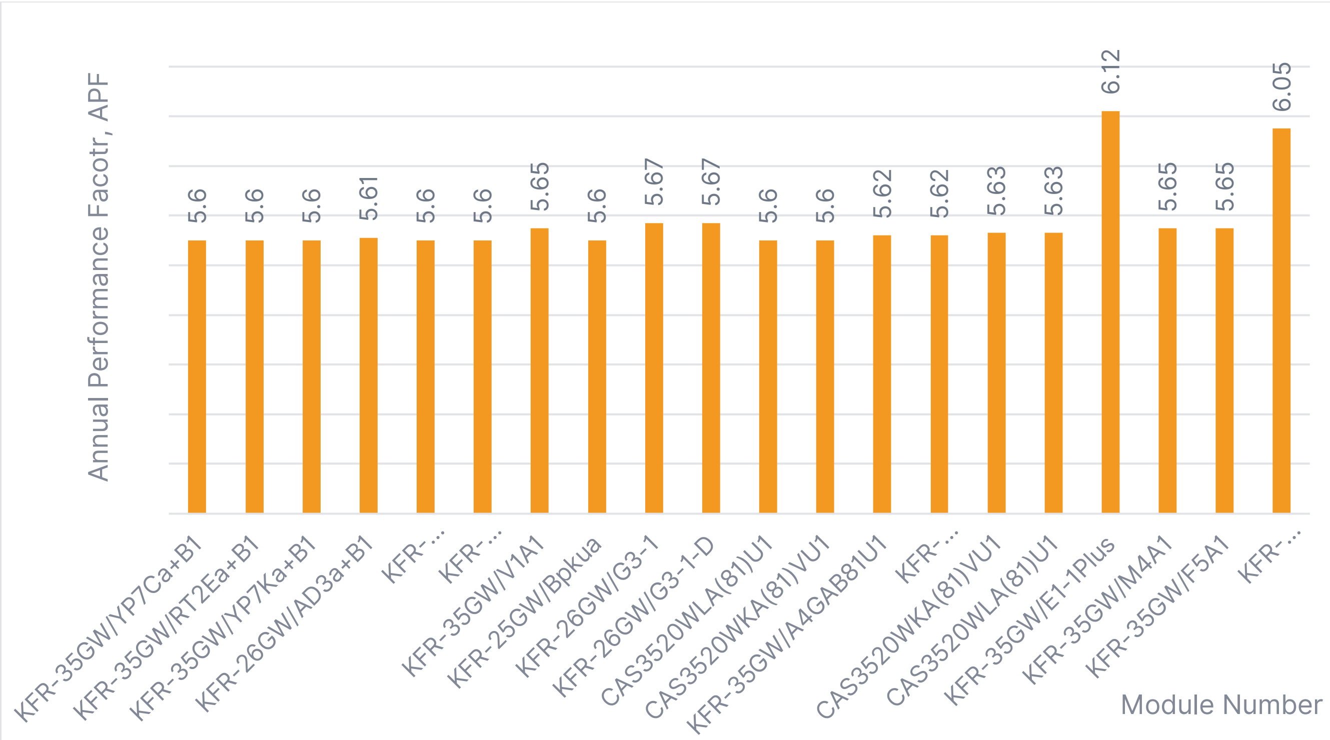
Despite the challenges outlined above, efforts to advance high-efficiency RACs remain ongoing. Achieving further efficiency improvements hinges on three critical dimensions: optimizing core components, integrating systems through inverter technologies, and applying intelligent control with multi-energy coupling.

Building on these pillars, the research team conducted a systematic assessment of the technological potential and cost implications of ultra-high efficiency RACs. Under the framework of China's GB21455-2019 testing method and evaluation metrics, the team set a forward-looking target: **achieving an APF of 6.25 within the next decade, while limiting overall costs to a 10% increase**. This target reflects cutting-edge perspectives on technological progress and offers practical guidance for defining development process pathways in the future.

TECHNOLOGIES FOR ACHIEVING ULTRA-HIGH EFFICIENCY RACS

Achieving ultra-high efficiency RACs requires a system-engineering effort. Emerging technologies span multiple dimensions, with overall system integration including core components, refrigerant cycles, intelligent control, new materials, and advanced process collaboration. By 2024, certain RAC products had already reached APF values above 6.0. A market survey of high-efficiency RACs from six leading brands is presented in Figure 8.

FIGURE 8 AFP LEVELS OF HIGH-EFFICIENCY RACS AVAILABLE IN THE CHINESE MARKET (2024)



Note: The data was collected by the project team.

To explore the feasibility of ultra-high efficiency RACs, the research team selected and retrofitted a representative high-efficiency model, the GA3300, which had a baseline APF of 5.20. Manufactured by a leading Chinese RAC brand and sold in 2024, this model served as the benchmark for analysis. The team examined the potential to raise the APF from 5.20 to 6.25. Table 6 summarizes the technological options and process improvements identified as a feasible pathway to achieve this target.

TABLE 6 SUMMARY OF TECHNOLOGIES ADOPTED IN SAMPLE ULTRA-HIGH EFFICIENCY RAC

		ADOPTED TECHNICAL MEASURES TO BOOST ENERGY-EFFICIENCY
Core Components	Compressor and affiliated motor	▪ Replace induction motor with PMSM/BLDC: low-loss iron loss with high-performance silicon steel, less copper loss with optimized winding design (slot fill factor, wire diameter), reshaped magnetic path to reduce flux leakage. ▪ Refine inverter logic/algorithms and hardware; dual-rotary, soft valves, EVI, variable compression ratio compressor; micro-nano surface treatment lowers friction.
	Heat exchanger	▪ Structural optimization ▪ Fin tweak: split-type, wettable skin; smaller tubes with inner wettability; upgraded expansion & brazing ▪ Oil-free/lean-oil processing in tube cutting, bending, and fin stamping
	Expansion device	▪ Intelligent EEVs
Cycle improvement		▪ Superheat & subcool control
New materials & processes		▪ Carbon-based enhanced heat transfer with interfacial wettability control ▪ 2D micro/nano interfacial material ▪ Directional heat conduction
Air-side optimization		▪ Fan blade ▪ Fan motor ▪ Airflow control
Control system		▪ Art-load operation control ▪ Dehumidification/defrost control ▪ Multi-factor multi-objective control logic & algorithm
Others		▪ Standby power control ▪ Thermal-bridge control

ECONOMIC ANALYSIS OF ULTRA-HIGH EFFICIENCY RACS

Upgrading the sample RAC to achieve an ultra-high efficiency level with an APF of 6.25 requires both hardware improvements and broader system support. This shift is estimated to increase overall costs by approximately 10%.

Of this increase, roughly 7.5% comes from direct costs for materials, driven mainly by upgrades to critical components. These include adding more advanced materials to heat exchangers to boost heat transfer, adopting high-efficiency compressors and fans, refining expansion devices, and updating control algorithms. These measures significantly improve energy efficiency but also raise material and component expenses, making them the largest contributor to cost growth.

The remaining 2.5% reflects other costs, such as R&D allocation, product certification, adjustments to manufacturing processes, and additional testing to guarantee performance and reliability. While these investments are not visible in the hardware itself, they are essential for advancing technology, ensuring product quality, and meeting regulatory and market entry requirements.

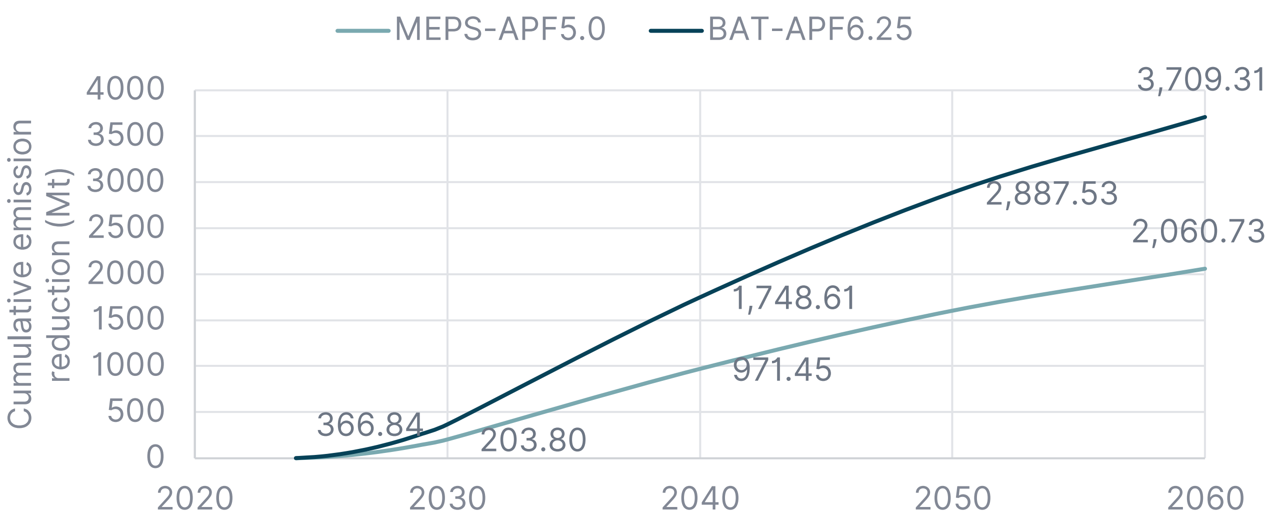
Potential for CO_2 Emission Reductions

As technology progresses, RACs are evolving toward ultra-high efficiency levels. These next-generation appliances improve indoor environments and cut energy use and operating costs. When widely adopted, ultra-high efficiency RACs can directly lower electricity demand and greenhouse gas emissions, underscoring their global significance.

Building on this research, the Mepsy[xvii] tool was applied to assess scenarios in which RACs achieve an APF of 6.25. Under China's RAC deployment patterns, the BAT-APF 6.25 scenario indicates that ultra-efficient RACs deliver substantial emission reductions over time. By 2040, cumulative CO_2 reductions reach **1.75 Gt**, rising to **2.89 Gt** in 2050, and ultimately **3.71 Gt** by 2060.

This trajectory demonstrates that scaling up APF 6.25 RACs can play an important role in long-term carbon reduction. Widespread deployment would support China's "dual carbon" goals and meaningfully contribute to global commitments like double energy efficiency improvements as well as net zero targets.

FIGURE 9 CUMULATIVE EMISSION REDUCTION POTENTIAL OF RACS ACROSS EFFICIENCY SCENARIOS



Note: Mepsy, developed by CLASP, is an analytical methodology designed to evaluate the economic and environmental impacts of energy efficiency policies for appliances and equipment, such as MEPS. The Mepsy model employs a bottom-up stock accounting approach, which aggregates historical unit sales and retirements to estimate the national stock of appliances in use.

[xvii] Mepsy is CLASP's digital tool to model the impacts of energy and carbon reduction policies. Pre-loaded with data from 162 countries, it supports analysis and prioritization for the most energy-intensive appliances and equipment. Mespy is used to analyze efficiency policy options for space heating equipment, ACs, residential water heaters, refrigerators, motors, lighting, fans, televisions, beverage coolers, distribution transformers. Mor information is available by https://www.clasp.ngo/tools/mepsy/.

Recommendations for Advancing Ultra-High Efficiency RACs

According to the latest report from the United Nations Environment Programme (UNEP)[29], global cooling demand could more than triple by 2050, with cooling-related greenhouse gas emissions nearly doubling compared to 2022. To address extreme heat and other climate challenges while cutting emissions, affordable high-efficiency RACs remain a crucial solution.

Advancing RAC efficiency relies on three key pillars: **policy support, standards, and international cooperation**. Policy incentives provide a strong foundation for industry growth, energy efficiency standards drive technological progress, and global collaboration and knowledge sharing provide wider opportunities for green innovation and a low-carbon transition. Together, these elements form a systemic pathway to accelerate efficiency improvements in the RAC sector.

PROACTIVE POLICY SUPPORT FOR ADVANCING HIGH-EFFICIENCY RACS

Policy incentives are a cornerstone for improving RAC efficiency. Financial subsidies and preferential tax measures can ease the cost burden on manufacturers developing and producing high-efficiency products. Policymakers could prioritize key technologies, such as inverter compressors, intelligent control systems, and low-GWP refrigerants solutions to drive broader adoption. Consumer incentives, such as subsidies for purchasing efficient RACs can guide sustainable consumption, stimulate demand, and accelerate market uptake.

Policies, specifying manufacturing guidelines and industrial standards, should also encourage green and smart manufacturing, ensuring that RAC production processes achieve energy savings and emission reductions. By guiding enterprises to adopt advanced production technologies and management practices, policies can help lower energy use and pollutant emissions during manufacturing. This proactive approach reinforces the transition to high-efficiency RACs and positions the industry as a driver of sustainable growth.

Comprehensive policy support further promotes collaboration across the industry supply chain, fostering positive interaction among government, manufacturers, and end-users. Establishing a stable and predictable policy environment ensures that efficiency improvements can be sustained over time. Well-designed incentive frameworks provide long-term confidence for both manufacturers and consumers, ensuring that efficiency gains deliver economic and environmental benefits.

MEPS AS A DRIVER OF RAC TECHNOLOGICAL UPGRADING

Energy efficiency standards play a pivotal role in enhancing RAC performance. Strengthening and advancing MEPS is essential for driving technological progress. Standards serve as a market threshold but also as a powerful engine for industrial upgrading, providing a stable, long-term direction for technological development at the policy level. According to the IEA[30], by 2024, MEPS already cover approximately 89% of global air conditioners. Setting mandatory standards effectively encourages manufacturers to continuously improve product performance and raise overall market efficiency.

Looking ahead, RAC efficiency standards should be further refined to support the adoption of innovative refrigeration technologies and intelligent applications. Corresponding testing and evaluation methods must also evolve in line with product advancements. For example, the ongoing dynamic testing approaches, compared with traditional fixed-temperature methods, will better reflect the actual operating conditions of RACs and more accurately demonstrate the advantages of high-efficiency and ultra-high efficiency units. Such dynamic testing will be beneficial to the applications of variable speed drivers and intelligent controls, leading to less energy consumption.

When setting efficiency benchmarks, most countries should align with the world's best MEPS[xviii], while leading nations should aim for the Best Available Technology (BAT). Efficiency

[xviii] Find the world's most ambitious energy performance standards for lighting, industrial electric motor systems, air conditioners, refrigerators, water heaters, and space heating equipment at [World's Best MEPS: Tracking Leaders in Appliance Energy Efficiency Standards - CLASP]

improvements should be dynamically balanced against cost and benefit considerations to push performance levels higher. Ambitious standards drive domestic technological progress but also provide valuable references for other countries, supporting the global transition toward more sustainable cooling solutions.

GLOBAL COLLABORATION AND KNOWLEDGE SHARING

Global collaboration and knowledge exchange are essential to advancing the low-carbon transition in the RAC sector. International cooperation can accelerate the adoption of environmentally friendly technologies, including low-GWP refrigerants, high-efficiency compressors, intelligent control systems, advanced heat exchangers, and green manufacturing processes. Strengthening technical exchange channels ensures that innovations are shared more widely and adapted quickly across different markets. For instance, in October 2025, China's Ministry of Commerce released the *Implementation Opinions on Expanding Green Trade*[31], which encourages Chinese enterprises to expand imports and exports of green and low-carbon products and technologies.

Stronger partnerships between multinational companies and research institutions help establish unified technical standards and market frameworks and enable faster diffusion of green innovations. Joint research programs, demonstration projects, and knowledge-sharing platforms can provide practical pathways for scaling up advanced RAC technologies, and reduce duplication of efforts, lower costs, and speeds up the transition to high-efficiency cooling solutions.

By leveraging global collaboration, the RAC industry can unlock greater opportunities for improving RAC efficiency and emission reduction potential, while fostering a more resilient and sustainable international refrigeration industry.

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