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**Working Paper**

## Cooling efficiency improvement

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## **ADB Working Paper Series**

### **COOLING EFFICIENCY IMPROVEMENT**

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No. 1411  
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**Asian Development Bank Institute**

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**Abstract**

With the improvement of people's living standards all over the world, the demand for cooling (both space cooling and refrigeration) continues to grow. The increase in cooling-related energy consumption has a growing impact on global climate change. The importance of improving the energy efficiency of cooling systems is increasing. This paper introduces a series of concepts and methods related to cooling systems and their energy efficiency, including the working principle of cooling systems and methods for evaluating their energy efficiency, as well as technologies and approaches to improve energy efficiency; these include efficient heat transfer, airflow management, noise reduction, advanced compressor technology, variable capacity control technology, compressor-free cooling, improved operation and maintenance, early replacement of inefficient equipment, etc. This paper also presents a case study from the Asian Development Bank's Ningbo Climate-Friendly Cooling Technical Assistance Project (TA-9670). The paper concludes with policy recommendations on how to take action to improve cooling energy efficiency.

**Keywords:** cooling, refrigeration, heat pump, energy efficiency, efficiency improvement, retrofit

**JEL Classification:** O33

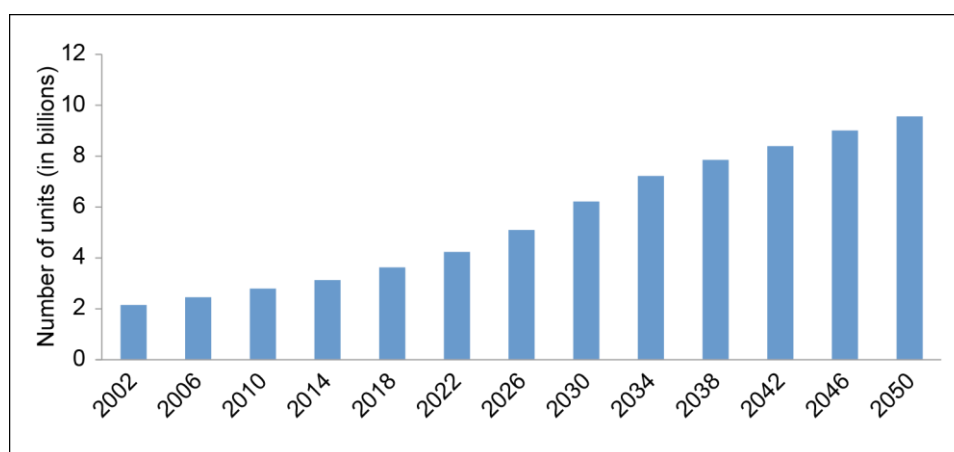
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## 1. INTRODUCTION

According to a University of Birmingham report (Peters 2018), approximately 3.6 billion cooling appliances were in use globally in 2018, which together consumed nearly 3,900 TWh of energy—or 3.4% of the world’s total energy demand. With the advancement of economic development and the improvement of people’s living standards, the global demand for cooling is expected to grow rapidly for a long time in the future. According to the Green Cooling Initiative (GCI), by 2050 there may be more than 9.5 billion cooling units worldwide (Figure 1), with the total electricity consumption increasing to 9,500 TWh by then. In a more extreme scenario (e.g., accelerated cooling appliances uptake to meet all cooling demand targets), there could be 14 billion cooling units by 2050, consuming 19,600 TWh of electricity per year if the appliance efficiency is business as usual (Peters 2018). It is clear that improvements in cooling energy efficiency will reduce the cooling-related energy consumption, thereby meeting the cooling demand in the middle of this century while controlling the increase in cooling energy consumption and reducing the resulting carbon dioxide emissions, helping to achieve the goals of the Paris Agreement.

**Figure 1: Number of Cooling Appliances in Use Globally by 2050**



Source: Peters, T. 2018. *A Cool World Defining the Energy Conundrum of Cooling for All*. University of Birmingham.

## 2. THE BASICS OF COOLING AND HEAT PUMP

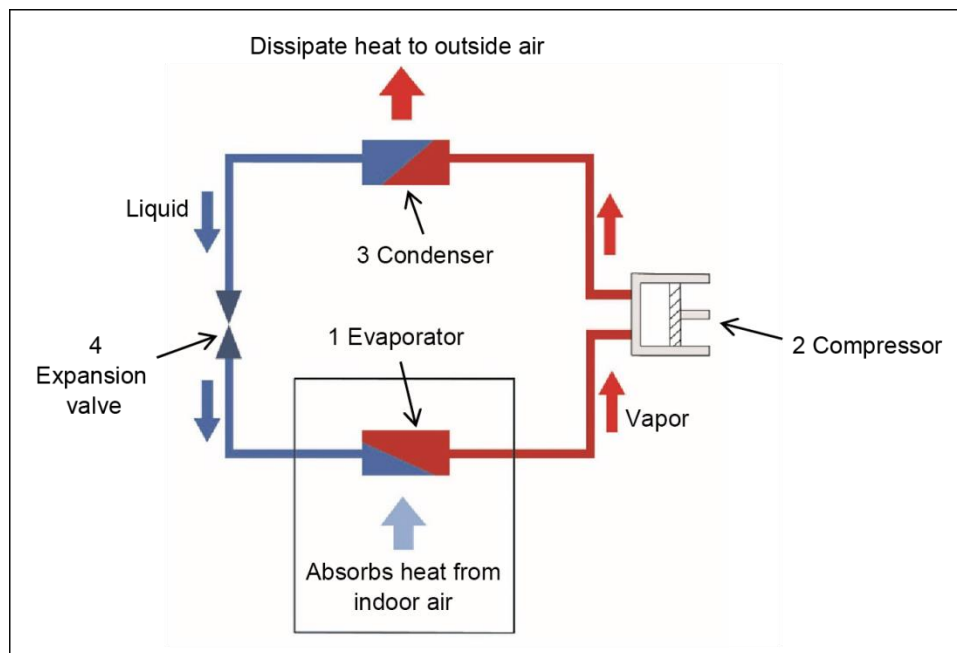
The operation of cooling systems consumes a lot of energy. Cooling here refers to both space cooling and refrigeration. Under the current energy system dominated by fossil energy, the increase in cooling energy consumption brings great challenges to reducing climate change impacts. Improving the energy efficiency of cooling systems can reduce the intensity of cooling energy use. To understand how to improve the cooling energy efficiency, however, one needs to first understand what components are in the cooling system, what the working principles of each component are, and how the entire cooling process works.

## 2.1 Refrigeration

Heat is naturally transferred from hot to colder objects, while the reverse process can only be realized by artificial means, which is called “refrigeration.” Refrigeration is the process of extracting heat from a body or system to bring its temperature below ambient temperature (IIR 2008).

Take the refrigeration cycle of an air conditioner using HFC-32 refrigerant in summer as an example (see Figure 2). The refrigeration cycle is a closed-loop system consisting of a compressor, a condenser, an expansion valve, and an evaporator, which are connected by copper pipes, steel pipes, etc. Metaphorically, the refrigerant circulation is similar to the blood circulation in the human body. The refrigerant is similar to the blood; the compressor is similar to the heart, providing impetus for refrigerant flow; pipes, in which the refrigerant circulates, are similar to blood vessels; the evaporator and condenser are like the lung and other organs, in which the refrigerant absorbs and dissipates heat. The working principle is as follows.

**Figure 2: Refrigeration Cycle of Air Conditioner in Summer**



Source: Authors' Own.

The purpose of air conditioning is to transfer the heat of indoor air to outdoor air. To achieve this goal:

1. **The refrigerant needs to absorb the heat of indoor air (the temperature of the refrigerant needs to be lower than that of indoor air), which requires an evaporator.** When the HFC-32 refrigerant vapor-liquid mixture (about 1.0 MPa and 5°C) enters the evaporator, it absorbs heat from the indoor air, thereby cooling the room, and the liquid refrigerant evaporates into a low-pressure and low-temperature vapor (about 0.8 MPa and 10°C).<sup>1</sup>

<sup>1</sup> The evaporator consists of pipes, fins, and a fan. The HFC-32 refrigerant is inside the pipe and indoor air outside the pipe. The fan enhances the heat exchange effect.

2. **After the refrigerant absorbs the heat of indoor air, it needs to discharge the heat to the outdoor air, which requires the temperature of the refrigerant to be higher than that of the outdoor air. To ensure that the temperature of the refrigerant is higher than that of the outdoor air, it is necessary to compress the indoor refrigerant vapor into high-temperature vapor, and this compression process needs a compressor to complete.** The compressor absorbs the HFC-32 refrigerant vapor (created from step 1 above) and compresses it into a high-pressure, high-temperature HFC-32 vapor (about 3.0 MPa and 90°C).<sup>2</sup>
3. **The compressed refrigerant vapor discharges heat to the outdoor air, and the process of heat discharge needs a condenser.** The HFC-32 refrigerant vapor, which is of a higher temperature than that of the air out of the pipe, then enters the condenser where it is cooled into a high-pressure liquid (about 2.7 MPa and 44°C), with heat being dissipated to the outdoor air (about 34°C).<sup>3</sup>
4. **The condensed refrigerant liquid needs to be changed to be lower than the indoor air temperature, which requires an expansion valve.** The high-pressure HFC-32 refrigerant liquid (about 2.7 MPa and 44°C) flows to the expansion valve where it is expanded and becomes a low-pressure, low-temperature vapor-liquid mixture (about 1.0 MPa and 5°C).<sup>4</sup> This completes one full loop. This cycle repeats itself.

To improve the energy efficiency of cooling systems, some measures need to be taken on the equipment side. These measures include: 1) improving the heat exchanger efficiency of the condenser and evaporator; 2) increasing the compressor's energy efficiency; 3) regulating the refrigerant flow according to the change of user's cooling load. In terms of the system, the following measures can help improve efficiency: 1) noise reduction; 2) appropriate ventilation and full use of natural ventilation; 3) good operation and maintenance, with reduced refrigerant leakage; 4) optimal matching of system components for higher energy efficiency; 5) replacement of the equipment when the energy efficiency of the used cooling equipment has been greatly reduced (see Section 6.4 for more details on some of the measures).

## 2.2 Heat Pump

When the heat dissipated to outside by the condenser is utilized for heating indoor air or heating water, the device becomes a heat pump. Compared with an electric heater, a heat pump can produce three times or even more heat for every kilowatt-hour of energy consumed, which greatly improves the energy utilization efficiency. The working principle of a heat pump is shown in Figure 3. Likewise, a heat pump transferring heat from a low-temperature object to a high-temperature one needs to be realized by artificial means. When both the cold temperature resulting from the evaporation and the heat dissipated from the condenser can be utilized, the system has both cooling and

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<sup>2</sup> The compressor works like a bicycle pump. After HFC-32 refrigerant vapor is compressed, its volume decreases, while its temperature and pressure rise.

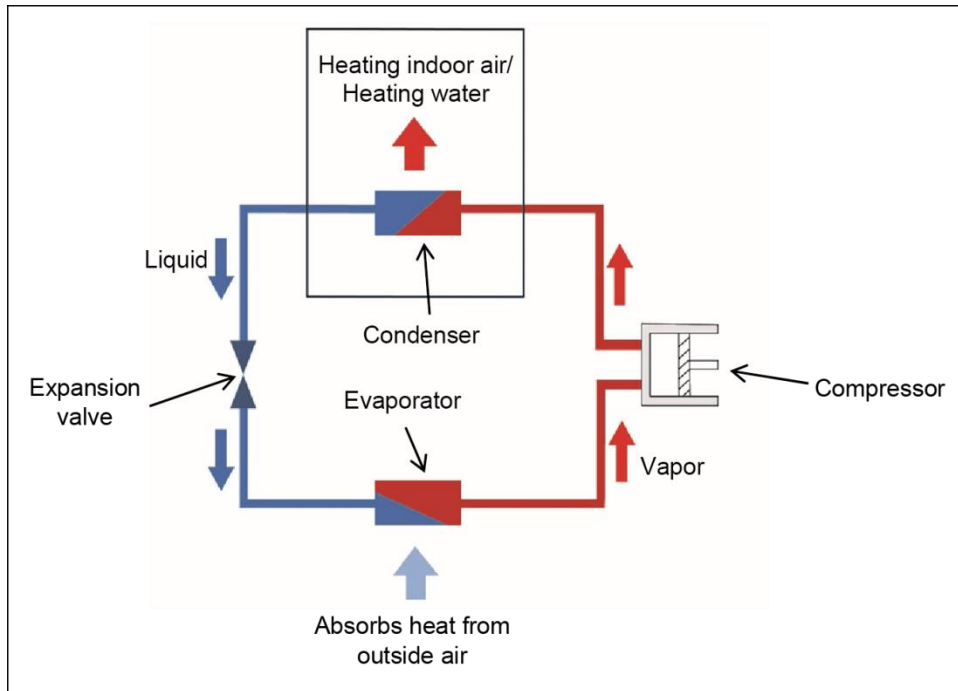
<sup>3</sup> Like the evaporator, the condenser consists of pipes, fins, and fan. The HFC-32 refrigerant is inside the pipe and outdoor air outside the pipe. The fan enhances the heat exchange effect. Both the evaporator and the condenser are heat exchangers.

<sup>4</sup> The function of the expansion valve is the exact opposite to that of the compressor. When the liquid HFC-32 flows through the expansion valve, its volume increases, while its temperature and pressure decrease. The expansion valve opening can be adjusted to realize the adjustment of the refrigerant flow.



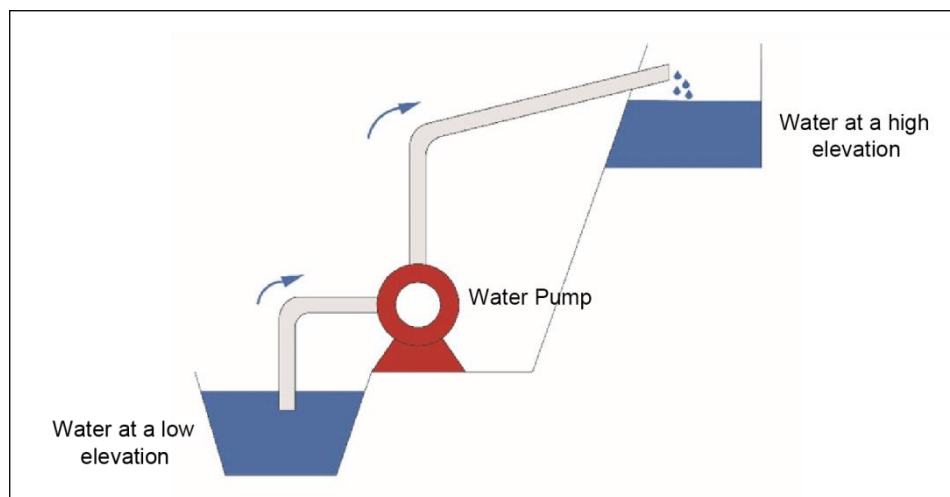
heating functions. A four-way reversing valve is needed in the system to achieve forward and backward refrigerant flow.

**Figure 3: Heat Pump**



Source: Authors' own.

Similarly to the water pump (shown in Figure 4), which raises water from low to high elevation, the heat pump transfers heat from a low-temperature object to another at a high temperature. The greater the difference between the low and high elevation, the more energy the water pump needs. A heat pump works on the same principle: The greater the temperature difference between the heat sources (such as the temperature difference between indoors and outdoors when heating), the more energy the heat pump needs and the lower the efficiency and reliability. Taking the People's Republic of China (PRC) as an example, heat pump heating is suitable for regions with an average temperature above  $-10^{\circ}\text{C}$  in the coldest month (January), including in the Yangtze River Basin, the Yellow River Basin, and in the north of the PRC. In the northeast of the country, the average temperature in the coldest month (January) is below  $-10^{\circ}\text{C}$ , and the heat pump cannot really be used for heating. But with the advancement of technology, the application of heat pumps is gradually expanding to regions with lower temperatures.

**Figure 4: Water Pump Working Principle**

Source: Authors' own.

### 3. METHODS OF EVALUATING COOLING ENERGY EFFICIENCY

Before discussing how to save energy and improve energy efficiency, it is necessary to understand the method of evaluating cooling energy efficiency.

Energy efficiency is the ratio of cooling/heating output to energy input.

$$\text{Energy efficiency indicator} = \frac{\text{cooling/heating output}}{\text{energy input}}$$

Evaluating cooling efficiency is complicated because the operating condition of cooling equipment is constantly changing, such as temperature and humidity. So normal conditions are set to evaluate the equipment energy efficiency. In the early days, the coefficient of performance (COP) or energy efficiency ratio (EER) was adopted to describe the effectiveness of the equipment, and those indicators were tested under full-load conditions.

With the rapid increase in the amount of cooling equipment and related energy consumption in the world, attention has been increasingly paid to the energy-saving element of cooling equipment, which has promoted the development of energy-saving technology and energy-saving evaluation methods. But the equipment is not at full load most of the time during its operation. Therefore, a COP/EER that considers full-load conditions cannot accurately evaluate the cooling equipment energy efficiency in practical use. A more accurate evaluation method is to test the equipment's integrated performance when it is functionally running under different load conditions<sup>5</sup>; that is, to evaluate its performance in both COP/EER and integrated performance, rather than merely to evaluate its performance in COP/EER under full load. In addition, driven by the push to replace coal to reduce greenhouse gas (GHG) emissions and air pollution, the use of heat pumps is growing and the proportion of integrated cooling and heating equipment is increasing. Therefore, it is becoming more and more

<sup>5</sup> The equipment's integrated performance is the weighted value of equipment performance under different load conditions, such as 25% load, 50% load, 75% load, and 100% load, or under different outdoor temperature conditions, such as 25°C, 30°C, 35°C, etc.

important to also evaluate the heating performance of combined heating/cooling equipment (Zhang 2019).

For this reason, countries like the PRC are using the seasonal energy efficiency ratio (SEER)<sup>6</sup> to evaluate the cooling efficiency of cooling-only room air conditioners. The PRC also uses the heating seasonal performance factor (HSPF)<sup>7</sup> for measuring the heating efficiency of heat pump room air conditioners (State Administration for Market Regulation and Standardization Administration of the People's Republic of China 2019). Additionally, the coefficient of performance (COP) and integrated part load value (IPLV)<sup>8</sup> are used to evaluate the performance of chillers (State Administration for Market Regulation and Standardization Administration of the People's Republic of China 2015). The indicators in the Chinese evaluation standards are similar to those in the US standards (AHRI Standard 210/240-2023; AHRI Standard 550/590-2020) and the EU standards (European Committee for Standardization 2022), but the calculation parameters and methods are different due to different climatic conditions.

## 4. COOLING TECHNOLOGY AND ITS APPLICATION IN IMPROVING COOLING ENERGY EFFICIENCY

### 4.1 Efficient Heat Transfer

Cooling equipment transfers heat through different types of heat exchangers to meet different applications and requirements. The common heat exchangers for cooling equipment include condensers, evaporators, heat recovery heat exchangers, superheaters, etc. The trend of international heat exchangers technology development for cooling systems is to develop a new type of heat exchanger featuring high efficiency, small size, light weight, good safety, and low cost. The mainstream products include minichannel/microchannel heat exchangers, falling film heat exchangers, elliptical tube heat exchangers, non-uniform structure enhanced heat exchangers (special-shaped fin, asymmetric tube, deformed spirals, and so on) (Zhang 2019). These heat exchanger products make it easier to extract heat from the space to be cooled, thus improving the energy efficiency of the cooling systems.

Most room air conditioners use copper tube aluminum fin heat exchangers. When HCFC-22 is used as the refrigerant, the outer diameter of the copper tube is mostly 9.52 mm, which gradually decreases to 7 mm when R410A is adopted and 5 mm when HFC-32 is used. As the technology improves, the tube diameter will be further reduced, with 4 mm and 3 mm tubes currently being developed. These efforts will improve the heat exchange efficiency, lower the cost of materials, and reduce the size of the heat exchangers.

In addition, the reduction in tube diameter will require less refrigerant charge and enhance the pressure resistance. In order to protect the ozone layer and combat global warming, refrigerant substitution is being carried out around the world. Most of the new environmental friendly refrigerants are flammable, toxic, of high working

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<sup>6</sup> SEER: the total heat removed from the conditioned space during the annual cooling season, W·h, divided by the total electrical energy, W·h, consumed by the cooling/heating equipment during the same season, (W·h)/(W·h).

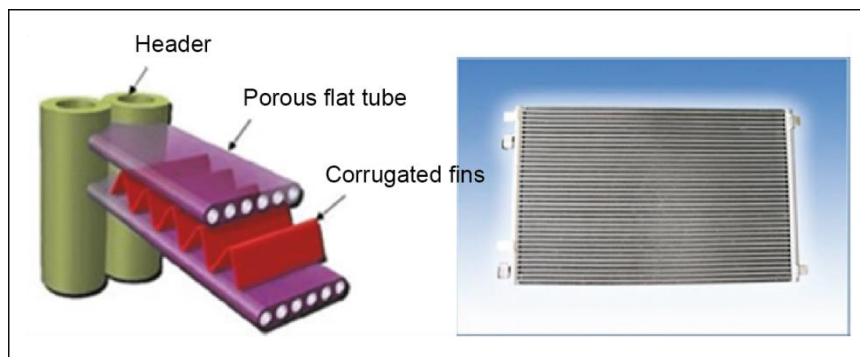
<sup>7</sup> HSPF: the total space heating required during the space heating season, W·h, divided by the total electrical energy, W·h, consumed by the heating equipment during the same season, (W·h)/(W·h).

<sup>8</sup> IPLV: the weighted value of equipment performance under the load conditions (25% load, 50% load, 75% load, and 100% load).

pressure, or expensive. There are strict restrictions on the charging amount of flammable or toxic refrigerants. For expensive refrigerants, the less the charging amount, the lower the manufacturing cost. The use of small-diameter heat exchangers reduces the refrigerant charging amount and enhances pressure resistance, which is of great significance for the promotion of more environmentally friendly flammable refrigerants and high-pressure refrigerants in the future. The smaller the tube diameter, the greater the resistance to the refrigerant flow in the heat exchanger tube, so the more tubes are needed. As a result, even the distribution of refrigerant, defrosting, and dewatering, as well as the cleaning of contaminants on the tube surface, become more difficult. Thus, appropriate measures need to be taken to address these difficulties.

Heat exchangers with a tube diameter of less than 1 mm are called “microchannel heat exchangers.” All-aluminum microchannel heat exchangers (shown in Figure 5) have been widely used in automotive air conditioners around the world. They are gradually expanding into other devices such as room air conditioners, commercial air conditioners, heat pump air heaters, and so on. Compared with the copper tube aluminum fin heat exchanger, the all-aluminum microchannel heat exchanger does not use expensive copper, so the material cost is greatly reduced; however, the processing becomes more difficult, so the manufacturing cost increases.

**Figure 5: Structure and Shape of All-Aluminum Microchannel Heat Exchanger**



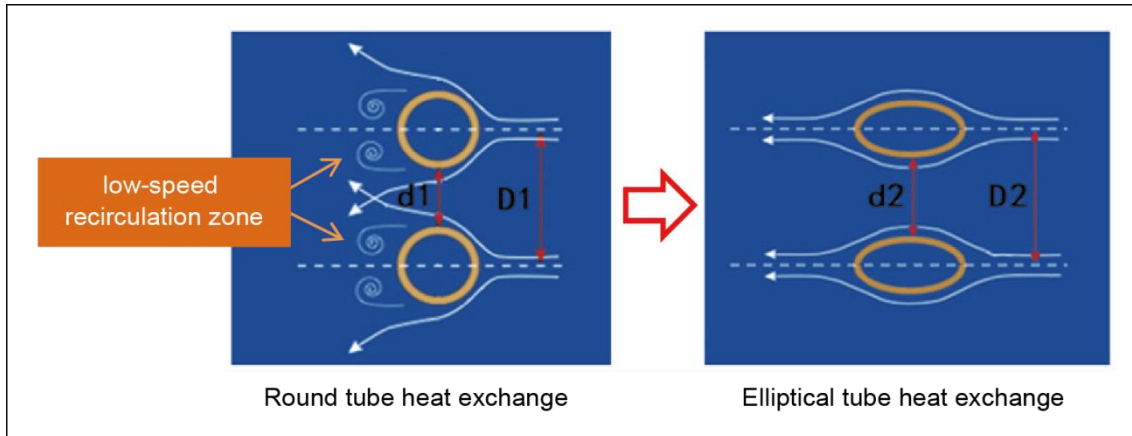
Source: Zhang, Z. 2019. Refrigeration and Air-conditioning Technology Innovation and Practice. Beijing: China Textile and Apparel Press. p. 43.

The falling film heat exchanger is commonly used in the evaporator of the chiller. The refrigerant spraying from the nozzle on the top of the evaporator falls to the heat exchange tube and spreads around the tube surface to form a downward flowing film. The evaporation of the refrigerant cools the hot fluid in the tube. Unlike a flooded evaporator, phase changes may occur at the liquid-solid and gas-liquid interfaces and cause film boiling. Thus, the falling film evaporation shows a high heat transfer performance. The falling film type demonstrates greater efficiency with less refrigerant charge. Good installation—that is, being installed horizontally with even refrigerant distribution—is the key to good falling film heat exchanger performance.

The round tube heat exchanger has a low-speed recirculation zone, which decreases the heat transfer coefficient. Efforts have been made to address this challenge. For example, elliptical tube heat exchangers (shown in Figure 6) have been promoted in countries such as the PRC, which can significantly reduce the low-speed recirculation zone. Elliptical tube heat exchangers have multiple advantages over round tube heat exchangers, including increased channel cross-sectional area (the distance between the surfaces of the two pipes is increased,  $d_2 > d_1$ , when the distance between the axes of the two pipes is equal,  $D_2 = D_1$ ), decreased flow resistance, faster flow

velocity, less turbulence, larger effective heat exchange surface, and markedly improved heat transfer performance. The elliptical tube heat exchanger is more difficult to process, thereby increasing its manufacturing cost. Elliptical tube heat exchangers are mainly used for water-air heat exchange because of the lower pressure-bearing capacity.

**Figure 6: Comparison of Heat Exchange Between Round and Elliptical Tubes**



Source: Zhejiang DUNAN Artificial Environment Co., Ltd. (2019).

## 4.2 Advanced Compressor Technology

The compressor is the “heart” of the cooling system, and is the main energy-consumption component and the power source to complete the refrigerant cycle. Common compressor types include the reciprocating piston compressor, rolling piston compressor, scroll compressor, screw compressor, centrifugal compressor, etc. Different types are used in different application scenarios. The compressor technology development needs to be consistent with the goals of environmental protection, energy saving, and expansion of the application scope.

Requirements to protect the ozone layer and slow global warming are driving the adoption of new environmentally friendly refrigerants. Chapter on Climate-safe Refrigerants discusses in detail the physical and environmental impact properties of different types of refrigerants. Refrigerants such as CO<sub>2</sub>, NH<sub>3</sub> (ammonia), HC-290, HFC-32, HFO-1234yf, HFO-1234ze(E), HFO-1234ze(Z), HCFO-1233zd(E), etc. are increasingly being used which has helped advance the development of compressor technology.

CO<sub>2</sub> is used in heat pump water heaters, automotive air conditioners, and freezers and cold storage equipment. The CO<sub>2</sub> heat pump water heater can provide hot water above 80°C and can maintain normal operation in a low-temperature environment below -20°C. In a transcritical CO<sub>2</sub> system, the working pressure of the compressor can exceed 10 MPa, which is three to five times the working pressure of the conventional compressor. Consequently, there are strict requirements for the material, design, manufacturing process, and maintenance of the compressor. In order to solve the problem of large throttling loss in the CO<sub>2</sub> transcritical cycle, it is necessary to develop a CO<sub>2</sub> compressor with an expander to improve its energy efficiency (Zhang 2019).

In the field of low-temperature refrigeration, the application of the NH<sub>3</sub>/CO<sub>2</sub> cascade system is increasing. In this system, the CO<sub>2</sub> compressor is in a subcritical state, and the working pressure of the CO<sub>2</sub> part generally does not exceed 5 MPa. At the same time, the charge amount of NH<sub>3</sub> is small. Thus, the safety and reliability of the NH<sub>3</sub>/CO<sub>2</sub> cascade system are greatly improved.

HC-290 has been widely used in small freezers, mobile air conditioners, dehumidifiers, etc., and gradually extended to room air conditioners. Due to the higher flammability, the HC-290 compressor needs to take strong safety measures such as an explosion-proof design, while minimizing the refrigerant charge and leakage.

HFC-32 has become the leading refrigerant for room air conditioners worldwide and is expanding into the industrial and commercial sectors. Compared to R410A, compressors using HFC-32 as an alternative refrigerant have greater energy efficiency, a higher cooling capacity, and less refrigerant charge. Although HFC-32 has low flammability, an HFC-32 compressor still needs to take certain explosion-proof measures, but its explosion-proof requirement is lower than for HC-290 compressors.

In addition, the expansion of refrigeration applications has also driven the development of compressor technology. Both the low ambient temperature air source heat pump and the high-temperature heat pump are used in an increasing number of applications. The low ambient temperature air source heat pump can heat at ambient temperatures below -20°C. The high-temperature heat pump, meanwhile, can provide heat higher than 100°C. The expansion of refrigeration applications means there are higher requirements for compressor materials, pressure resistance, and reliability, etc. The heat pump can obtain three times or more heat per unit of energy consumption than the electric heater, thereby greatly improving the energy utilization efficiency of the equipment.

### **4.3 Variable Capacity Control Technology**

Since the load of the cooling system varies with time and environmental conditions, a variable capacity control system is required to meet the needs of the user. Traditional capacity control methods include on/off capacity control, adjustment of the working volume of the compressor, Alternating Current (AC)/Direct Current (DC) adjustable speed control, etc. The development and improvement of variable capacity control technology provides a more reliable guarantee for system operation under different working conditions, and improves the seasonal energy efficiency ratio and actual operating efficiency of the system.

In recent years, AC/DC speed regulation technology has developed rapidly. As the core component of cooling equipment, compressors are moving in the direction of AC/DC adjustable speed technology. Rotary compressors and scroll compressors used in small and medium-sized equipment generally use this technology, while the technology is increasingly employed in screw compressors and centrifugal compressors used in large and medium-sized equipment. Another trend in AC/DC speed regulation technology is from a single compressor speed control to the coordinated management of related components in a cooling system, including compressors, valves, fans, water pumps, cooling towers, and more (Zhang 2019). When the user's load becomes higher, AC/DC speed regulation technology can quickly increase the rotation speed of compressors, fans, and other components, thereby increasing the cooling capacity in time to meet the user's needs.

AC/DC adjustable speed technology makes the temperature fluctuation of the temperature control object smaller, the continuous cooling capacity modulation more stable and reliable, and the operating noise lower, which increases the comfort and reduces the overall energy consumption of the cooling system. For example, at night in summer, the outdoor ambient temperature is lower than during the day, thus reducing the indoor heat load. At this time, the compressor and fan speed of the AC/DC adjustable speed air conditioner can be reduced, thereby reducing noise and energy consumption.

Of course, the AC/DC adjustable speed cooling system needs to have a speed control module, which increases the cost of the equipment. However, as the scope of application of this technology expands, the cost of modules is getting lower and lower.

In recent years, cutting-edge technologies such as automatic control, big data, and artificial intelligence have begun to be applied to cooling systems; variable-capacity control technology has provided the basis for the expansion of these emerging technologies, and the expansion of these cutting-edge technologies in the cooling sector will bring more opportunities for energy saving and efficiency improvement.

#### 4.4 Noise Reduction

Noise level is one of the important evaluation indicators of environmental quality. Countries have established noise limits for various occasions. Taking the PRC as an example, its national standard *Environmental Quality Standard for Noise* (GB 3096-2008) stipulates that the environmental noise limit of administrative office buildings, residential buildings, schools, hospitals, etc. is 55 decibels (dB) during the day, and 45 dB at night. With the improvement in people's living standards and the pursuit of a higher-quality work and living environment, people hope that the noise in work and living places is lower than the national noise limit, which leads to higher requirements for cooling equipment.

Cooling equipment noise is produced by vibrations when the equipment is in operation. Compressors, pumps, fans, and other moving parts in cooling systems will generate noise during operation, and the flow of refrigerant, water, and air in the system will also generate noise. The noise level reflects the intensity of the vibration: The higher the vibration intensity, the louder the noise and the higher the energy consumption. Many countries have noise limits for refrigeration equipment under normal operating conditions. For example, for air conditioners in the PRC, the noise limits for indoor and outdoor units with different cooling capacities are different. The indoor noise limit for split air conditioners of less than 2.5 kW is 40 dB, and the indoor noise limit for self-contained air conditioners of less than 2.5 kW is 52 dB. For room air conditioners greater than or equal to 2.5 kW and less than 14 kW, no matter whether it is a split type or self-contained type, the indoor noise cannot exceed 60 dB.

When the noise generated by the moving parts or fluid flow of the cooling equipment exceeds the limit, it means that there is some abnormality or malfunction inside the equipment, which will lead to increased energy consumption. It is necessary to give attention to solving the noise in the design, manufacturing, and operation of cooling equipment to reduce its energy consumption:

- 1) Design process: Cooling equipment and systems adopt a noise reduction design, such as optimizing the piping layout, avoiding noise resonance from various components, using suitable shock absorption devices, using mufflers, etc.

- 2) **Manufacture process:** Improve the machining accuracy and assembly accuracy of the parts, keep the lubrication surface in a good state of lubrication to reduce mutual friction of the parts.
- 3) **Installation process:** Improve the installation quality of the cooling system and reduce leakage. Install the main noise equipment in a special machine room or outdoors, which can effectively reduce the noise in the user space.
- 4) **Use process:** Good operation and maintenance includes keeping the air and water and other subsystems clean and avoiding the loosening of the fixture. When the cooling system starts and stops, it will make a lot of noise. The use of speed regulation technology to adjust the cooling system load can greatly reduce the number of equipment starts and stops. Speed control technology is also used to reduce the speed of compressors, fans, and water pumps at low loads, which can significantly reduce noise.

## 4.5 Airflow Management

Air conditioning is used for multiple purposes to adjust indoor air temperature (cooling or heating), humidity, and airflow velocity and direction as well as helping with disinfection, increasing the oxygen content, and reducing indoor pollutants. These are achieved through airflow management.

In recent years, the importance of opening windows has been increasingly recognized. In certain regions and seasons, some buildings can use natural ventilation alone, while others use a combination of natural and mechanical ventilation. In situations where natural ventilation is not possible and only mechanical ventilation is used, it still needs to exchange fresh outdoor air with indoor air. Proper airflow distribution will reduce a building's energy consumption and provide a more comfortable and healthier indoor environment.

Mechanical ventilation mainly includes hybrid ventilation, personalized ventilation, and stratum ventilation. Hybrid ventilation means mixing clean outdoor air with indoor air to meet indoor air quality requirements, thereby reducing energy consumption while providing acceptable indoor air and thermal comfort. Personalized ventilation delivers purified clean air to the breathing zone, directly intervening in the human microenvironment and reducing unnecessary ventilation areas. Compared with traditional general ventilation, personalized ventilation has obvious advantages in terms of individual control and energy saving. Stratum ventilation delivers pollution-free horizontal airflow to the breathing zone through the sidewall air supply outlet and expels it through the sidewall return outlet. The applications of these ventilation methods are different under different indoor conditions; therefore, the airflow distribution should meet specific conditions and requirements.

The wide spread of airborne viruses such as COVID-19 in public spaces creates new challenges for airflow distribution management. Pandemics have made airflow management increasingly important. The countermeasures include ultraviolet sterilization, high-efficiency filtration, expanding the proportion of fresh air, and fresh air in local areas. Ventilation systems in public places should meet the requirements of normalized epidemic prevention and control (Xu et al. 2021). In addition, a ventilation system should increase the use of automatic directional ventilation, online monitoring, big data, and other means to improve the efficiency of air distribution.



## 4.6 Compressor-less Refrigeration

Typically, a vapor compression refrigeration system shows greater energy efficiency than other refrigeration systems at refrigeration temperatures of  $-40^{\circ}\text{C}$  and above. However, in some special situations, such as in dry regions and places with more waste heat, nonvapor compression refrigeration has also seen rapid development. Common nonvapor compression refrigeration technologies mainly include absorption refrigeration, evaporative cooling, adsorption refrigeration, jet refrigeration, emerging solid-state refrigeration, and semiconductor refrigeration, with absorption refrigeration and evaporative refrigeration currently being applied on a large scale.

### 4.6.1 Absorption Refrigeration

Absorption refrigeration is a traditional refrigeration method. A lithium bromide absorption cooling system uses water as the refrigerant and lithium bromide solution as the absorbent. It works as follows:

- 1) When the concentration of absorbent is high (about 64%), the lithium bromide solution absorbs the water vapor in the evaporator and produces a cooling effect by taking away the heat.
- 2) When the concentration is reduced to a certain extent (about 59%), the lithium bromide solution is heated by an external energy source. As the water in the solution evaporates, the concentration of lithium bromide rises.
- 3) The evaporated water is cooled in the condenser and flows to the evaporator where it is further absorbed by lithium bromide. This cycle repeats over and over again.

External energy sources for heating lithium bromide include fuel oil, natural gas, and waste heat. The development of lithium bromide absorption cooling is related to changes in energy supply. For example, in the PRC, lithium bromide cooling developed rapidly in the 1990s because of the severe shortage of electricity in the country at that time, and lithium bromide absorption cooling can use fuel oil and natural gas to provide a heat source. However, when the power supply is sufficient, the application of direct-fired lithium bromide absorption cooling units has been greatly reduced in the PRC due to the large footprint and high cost compared with vapor compression cooling units. Lithium bromide cooling can be a technology option for areas with an unstable electricity supply but other heat sources. In addition, the PRC's practice has proved that the use of lithium bromide absorption refrigeration to recover industrial waste heat has obvious energy-saving value. However, waste heat resources have the characteristics of being of low quality and scattered. How to use waste heat resources efficiently and economically still needs in-depth research.

### 4.6.2 Evaporative Cooling

The evaporation of water in the air absorbs heat, which lowers the temperature of the air, creating a cooling effect, which is the principle of evaporative cooling. The key equipment in evaporative cooling is the heat exchanger, which realizes water evaporation. Evaporative cooling equipment does not require a compressor; its structure is relatively simple, energy consumption is less, and the upfront investment is low. However, evaporative cooling requires water. Using evaporative cooling in water-scarce regions will be a problem.

In dry areas, moisture evaporates more easily and more rapidly, so the cooling effect is better. For this reason, evaporative cooling should be promoted and applied in arid regions. The evaporation of water increases the humidity in the air, so evaporative cooling also has the function of humidification. It can play a greater role in situations where cooling and humidification are required at the same time (such as in textile mills).

When the moisture content in the air is high, the human body feels uncomfortable. Therefore, more comfortable air conditioning uses evaporative cooling. It could use indirect evaporative cooling, a combination of indirect and direct evaporative cooling, or a combination of evaporative cooling and dehumidification. In addition, when the evaporative cooling alone cannot meet the cooling requirements, a combination of evaporative cooling and vapor compression cooling can be adopted. The use of evaporative cooling in a vapor-compression-cooled cooling tower can expand the use of evaporative cooling while achieving greater energy efficiency.

## 4.7 Operation and Maintenance

Cooling systems are complex and their operation is a dynamic process. Effective maintenance is required to keep system components aligned and functioning properly. Components can wear out or even get damaged or become dirty and even clogged during operation, resulting in reduced energy efficiency and even failure. Therefore, good maintenance is the key to keeping the system running efficiently. The fresh air and return air of the air-conditioning and ventilation system also contain various pollutants such as dust, bacteria, and viruses. Together with the condensed water, these contaminants can accumulate in the air ducts, filters, and heat exchangers. If not cleaned in time, they will become a source of pollution, polluting indoor air and harming human health.

Refrigerant leaks can both damage the ozone layer and contribute to global warming. Therefore, responsible use of refrigerants is critical, including enhanced leak monitoring and the promotion of recovery, recycling, reclamation, and proper disposal of refrigerants during system maintenance and end-of-life processes. Chapter on Climate-safe Refrigerants provides more detailed information on preventing and reducing refrigerant leaks. In addition, the operation of cooling systems also involves safety issues. For example, in the case of ammonia refrigeration systems, many major accidents have occurred due to illegal or improper operation. With the accelerated pace of refrigerant substitution, flammable or high-pressure or even toxic refrigerants will become more widely used, which will require good maintenance to ensure safety.

The following operation and maintenance management methods are recommended: 1) Use Internet technology to strengthen automatic control of the system and monitor the operating status of each component; 2) Maintain regular maintenance such as cleaning the evaporator, condenser, air duct, filter, etc., removing foreign objects, replacing wearing parts and lubricating oil, checking safety devices, and monitoring refrigerant leakage and water leakage; 3) Repair and correct problems to ensure safe and reliable operation of the system and various components. In short, good operation and maintenance management can prolong the service life of the equipment and achieve energy saving at the same time.

## 4.8 Whole-System Approach

In addition to the energy efficiency improvement of the cooling equipment itself, overall system performance improvement can achieve greater energy savings. The energy efficiency improvement of the whole system is mainly realized by the optimal matching of each component in the system as well as the integration services.

### 1) The optimal matching of system components

Taking the central air-conditioning system as an example, the system includes subsystems of refrigerant, water, air, and control. Taking into consideration the meteorological conditions and loads during the actual system operation, dynamic modulation of the optimally matched components can significantly improve the energy efficiency of the entire air-conditioning system (see the case in Section 6.5.2).

### 2) The integration services

A system-wide approach is also embodied in integration services. This means that cooling equipment manufacturers or energy service companies provide cooling customers with comprehensive services, including design, consultation, installation and commissioning, operation management, maintenance, personnel training, and so on. Through the service of optimal matching and integration of system components, cooling customers not only get a more efficient cooling system, but also a better service experience. This full-chain business from manufacturing to service also brings more profit-making channels and new development opportunities for cooling equipment manufacturers.

## 4.9 Early Replacement of Cooling Equipment

As a task of the Asian Development Bank's Technical Assistance Project in Ningbo, PRC (TA-9670), Ningbo city has collected information on cooling equipment from institutional customers in the city. The surveyed customers include various electricity users in numerous industries in Ningbo, including manufacturing, food processing, refrigeration, ice-making facilities, dairy factories, auto parts stores, supermarkets, shopping malls, restaurants, stadiums, hotels, conference centers, libraries, hospitals, amusement parks, vocational colleges, universities, government facilities, transportation hubs, and banks.

Survey responses from 314 institutional users indicate that a large number of older cooling units are still in operation, some of which are more than 30 years old. The following table lists the respective number of devices that are eight years old or more.

Technology advancements have resulted in continuous improvement in the energy efficiency of cooling equipment. Energy efficiency standards are also constantly being raised. Stricter energy efficiency standards make the energy efficiency level of old cooling units lower than that of new units. As a result, continuing to use old units will consume more energy than newer units with higher energy efficiency to provide the same level of service.

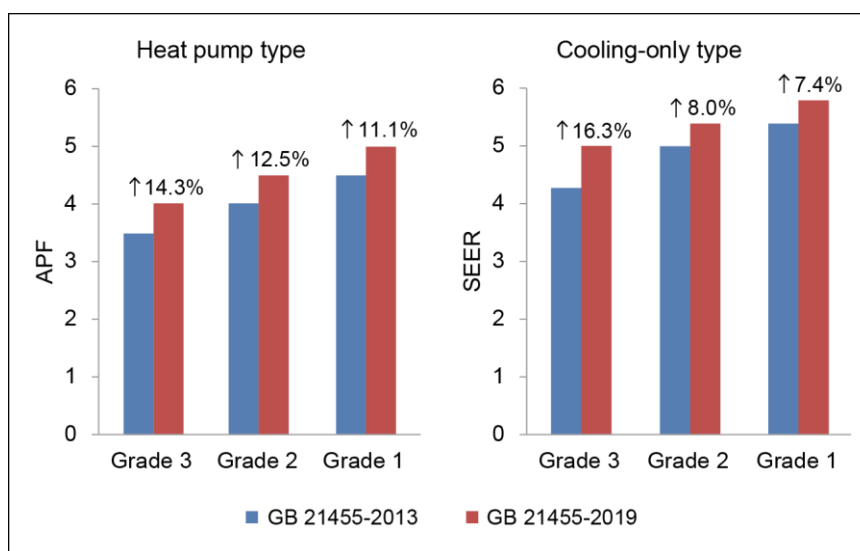
**Table 1: Distribution of Surveyed Equipment with a Service Age of Eight Years or More in Ningbo, PRC**

Years in Operation	Number of Cooling Devices
8–9 years	1,948
10–11 years	1,189
12–13 years	2,103
14–15 years	573
16–17 years	359
18–19 years	19
20 years and above	50
Total	6,241

Source: Shen, B. et al. (2021). *TA-9670: Developing a Climate-friendly Cooling Sector through Market and Financing Innovation*. Report submitted to the Asian Development Bank. August.

Taking speed-adjustable room air conditioners (cooling capacity ≤ 4.5 kW) in the Chinese market as an example, the relevant Chinese energy efficiency standards revised in 2019 make the minimum allowable values of room air conditioner energy efficiency higher than the standards promulgated in 2013 by 7.4% ~ 16.3% (as shown in Figure 7) (State Administration for Market Regulation and Standardization Administration of the People’s Republic of China 2019; State Administration for Market Regulation and Standardization Administration of the People’s Republic of China 2013).

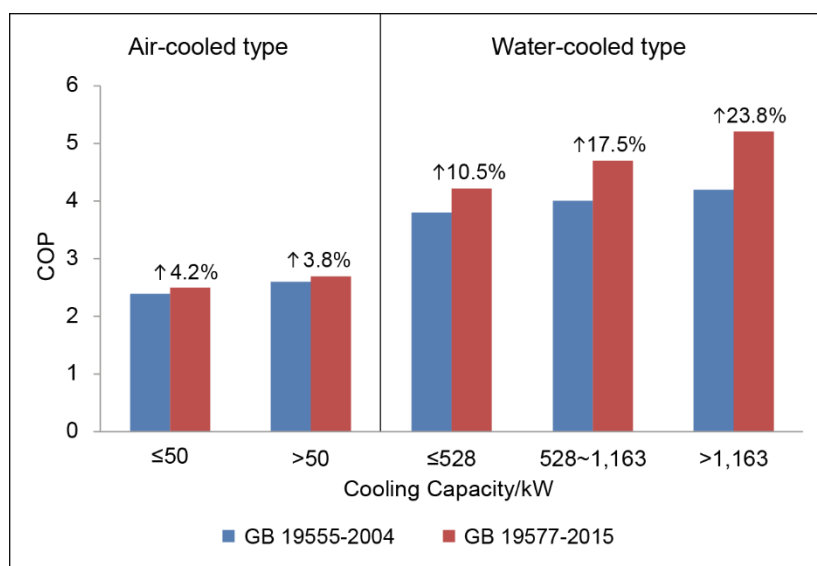
**Figure 7: Comparison of Energy Efficiency Indicators Between New and Old Standards for Speed-Adjustable Room Air Conditioners (Cooling Capacity ≤ 4.5 kw)**



Source: Authors' own.

Another example is the increase in minimum energy efficiency standards for chillers in the PRC. For different types of chiller units, the PRC’s 2015 version of the standard has an increase in the range of 3.8% to 23.8% compared to the 2004 version of the minimum energy efficiency requirements (see Figure 8). For large-size chillers (cooling capacity (CC) > 1,163 kW) used in large public buildings, the minimum energy efficiency requirements are increased the most (State Administration for Market Regulation and Standardization Administration of the People’s Republic of China 2015; State Administration for Market Regulation and Standardization Administration of the People’s Republic of China 2004).

**Figure 8: Comparison of Minimum Allowable Values of Energy Efficiency of Chillers in 2004 and 2015**

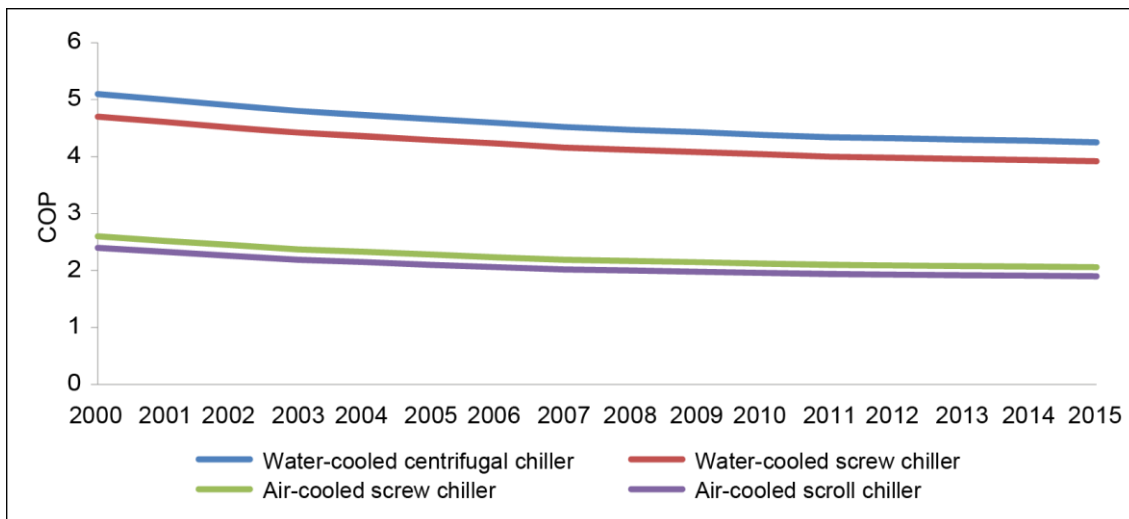


Source: Authors' own.

In addition to the fact that the energy efficiency level of old equipment is lower than that of new equipment, the energy efficiency of old equipment is also greatly deteriorated due to the long use time. As the cooling equipment ages, its heat exchange efficiency will decrease, and the flow resistance will increase year by year, resulting in a decrease in the energy efficiency of the entire system. Poor maintenance can also cause system energy efficiency to decline over time. Figure 9 shows the energy efficiency decline of different types of cooling equipment installed in 2000. The graph is based on information on actual equipment operation collected in TA-7960.

Clearly, continuing to use old equipment will not only waste energy, but also increase the cost of electricity for users. Promptly replacing old equipment with newer equipment that meets higher energy efficiency performance standards and strengthening the maintenance of cooling equipment are effective ways to reduce this waste.

**Figure 9: Energy Efficiency Decline Curve of Different Types of Cooling Equipment Installed in 2000**



Source: Shen, B. et al. 2021. *TA-9670: Developing a Climate-friendly Cooling Sector through Market and Financing Innovation*. Report submitted to the Asian Development Bank. August.

## 5. COOLING ENERGY EFFICIENCY RETROFIT ASSESSMENT: A CASE STUDY

Energy efficiency retrofit is a means of improving the energy efficiency of energy-using equipment and systems such as cooling. However, a successful retrofit requires an effective assessment of the required energy efficiency improvements. This section uses an evaluation study of energy-saving measures in Ningbo shopping plazas as a case to illustrate how to conduct such an energy retrofit assessment. The Ningbo study is part of the Asian Development Bank’s Technical Assistance Project in Ningbo, PRC (TA-9670).

### 5.1 Cooling System Information for Ningbo Shopping Plaza

The Ningbo Shopping Plaza with its total construction area of 30,000 square meters was officially opened in 1998. The current air-conditioning system in the building contains 30 air-cooled water chilling (heat pump) units of the same type that were installed in 2011 as a replacement, and the other two air-cooled screw chilling (heat pump) units that were initially installed in 2004 (see Table 2 and Figure 9). These units are used for cooling in summer (usually from June to October) and heating in winter (heating in winter runs for a shorter period of time, typically from December to February). The annual electricity consumption of the air-conditioning and heating system is approximately 2,380,000 kWh.

**Table 2: Parameters of Air-Conditioning Units Operating in Ningbo Shopping Plaza**

Unit Type	Scroll Air-cooled Water Chilling (Heat Pump) Unit	Screw Air-cooled Water Chilling (Heat Pump) Unit
Quantity	30	2
Year of installation	2011	2004
Refrigerant	R22	R22
Cooling capacity per unit	130 kW	444 kW
Cooling input power per unit	44 kW	147 kW
Cooling COP	2.95	3.0
Heating capacity per unit	140 kW	–
Heating input power per unit	43 kW	–

Source: Shen, B. et al. 2021. *TA-9670: Developing a Climate-friendly Cooling Sector through Market and Financing Innovation*. Report submitted to the Asian Development Bank. August.

**Figure 10: Photo of Air-Conditioning Unit in Ningbo Shopping Plaza**

Photo by Yaolin.

Source: Shen, B. et al. 2021. *TA-9670: Developing a Climate-friendly Cooling Sector through Market and Financing Innovation*. Report submitted to the Asian Development Bank. August.

From these parameters, we can draw the following conclusions: (1) The refrigerant is R22, which is harmful to the ozone layer and global climate (for R22, ODP = 0.055, GWP = 1,830; see Chapter on Climate-safe Refrigerants for relevant information); (2) The cooling equipment has a low level of energy efficiency. The air-cooled screw (heat pump) units installed in 2004 were manufactured before the PRC promulgated the minimum energy efficiency standard for chillers (GB 19577-2004), so their energy efficiency is low; (3) The equipment is not operating optimally due to a lack of professional maintenance of the equipment and the energy efficiency of the system has dropped significantly over many years of operation.

## 5.2 Recommended Technical Improvement Measures

The following measures can be taken to improve the energy efficiency of the cooling units in Ningbo Shopping Plaza:

#### 1) Retrofit of refrigerant subsystem

A feasible solution is to install an 800RT adjustable-speed high-efficiency centrifugal chiller to operate in combination with the existing air-conditioning units to provide joint cooling for the building. At the same time, the air-cooled water (heat pump) unit with a short service life can be used for heating in winter or for backup cooling when it is extremely hot in summer. At the same time, the screw chiller (heat pump) unit installed in 2004 should be replaced with units that meet higher efficiency standards. In addition, the following measures can be adopted: replacing the large number of small units with a small number of large chillers to improve the overall cooling energy efficiency; adopting speed regulation technology to enable the equipment to adapt to load changes and maintain high energy efficiency when operating at low loads; and replacing air cooling with water-cooled units to further improve energy efficiency.

#### 2) Retrofit of chilled water subsystem

Chilled water pumps can use speed regulation technology, which helps the subsystem adapt to changes in cooling load and maintain high energy efficiency during low-load operation.

#### 3) Retrofit of air handling subsystem

The alternating current fan (AC fan) driven by the pulley can be replaced by an electronically commutated fan (EC fan). In addition, installing an electrostatic precipitator and a titanium dioxide sterilization device can improve the air quality in the Plaza. Placing an air quality display screen at the central entrance of the building to show that the indoor air quality is good can help attract customers to shop.

#### 4) Installation of building automation subsystem

Installing a building automation subsystem makes a lot of sense for cooling energy efficiency. Such a subsystem can implement the optimal cooling operation strategy—that is, set operating parameters according to the change of cooling load, coordinate operations of various subsystems including a refrigerant subsystem (compressor motor speed, expansion valve opening), chilled water subsystem (water temperature, valve on and off, running number and speed of water pumps), cooling water subsystem (water temperature, valve on and off, running number and speed of water pumps, number of cooling towers and fan speed), air handling subsystem (fan speed), etc. The building automation subsystem can also help realize the unattended operation and one-key start-stop of the machine room, reduce labor costs, and improve the standardized operation of the cooling system. In addition, the automation subsystem will greatly improve the reliability of the machine room through the automatic fault-tolerant processing of system failures.

### 5.3 Cost–Benefit Analysis

Analyzing the cost-effectiveness of technical improvement measures is an important part of a comprehensive assessment of these measures. The cost–benefit calculations of retrofitting the air-conditioning system in Ningbo Shopping Plaza are listed in Table 3.



**Table 3: Estimation of Cost and Benefit of Energy Efficiency Retrofit**

Type of Retrofit	Capital Cost (RMB yuan)	Energy-saving Rate (%)	Annual Cost Saving (RMB yuan)	Investment Payback Period (year)
Refrigerant subsystem	2,352,225	44	474,183	4.96
Chilled water subsystem	45,600	14	15,370	2.97
Air handling subsystem	125,000	58	33,893	3.69
Building automation subsystem	351,760	5	117,667	2.99
In total	2,874,585	41.4	641,113	4.48

Source: Shen, B. et al. 2021. *TA-9670: Developing a Climate-friendly Cooling Sector through Market and Financing Innovation*. Report submitted to the Asian Development Bank. August.

The results show that the investment payback periods of these measures vary, but when they are packaged, the overall investment cost can be recovered in less than four and a half years. It should be noted that only the simple payback period is calculated here, and the annual energy-saving benefit of the retrofitted system after the investment is recovered is not considered. A better way to measure the cost-effectiveness of an energy-saving measure is to comprehensively evaluate the energy-saving benefits and investment costs plus the operation and maintenance costs throughout the operating life cycle of the cooling system.

## 6. POLICY RECOMMENDATIONS

To accelerate the deployment of energy-efficient and climate-friendly cooling technologies, it is necessary for Asian governments to take effective policy measures. This section provides specific recommendations in six areas.

- 1) **Formulate and improve energy-saving policies.** Recommended actions include: establishing top-runner programs similar to those implemented in Japan and the PRC to encourage manufacturers to develop and market ultra-efficient products; publishing catalogs of cooling-related energy-saving key technologies and application cases to guide the actions of energy-saving product users; providing necessary research funding to support the research and development of advanced cooling technologies; strengthening the publicity of energy savings to raise public awareness of the use of energy-efficient products.
- 2) **Establish and improve energy efficiency standards, labels, and certification systems.** The work of improving energy efficiency standards for cooling equipment includes establishing minimum efficiency standards, creating energy-saving evaluation metrics, and developing equipment efficiency ratings. The work also includes extending the formulation of energy efficiency standards to more cooling equipment categories as well as strengthening the supervision of the implementation of the standards, imposing necessary penalties for noncompliance with the standards, and prohibiting products that do not meet the minimum energy efficiency requirements from entering the market. At the same time, it is necessary for the government to establish and improve the energy efficiency labeling system, so that consumers can clearly understand and compare the energy efficiency level of equipment, as well as establishing energy-saving product certification systems to guide consumers to choose high-efficiency products.

- 3) **Incentivize the adoption of energy-efficient products and technologies.** It is recommended for governments to formulate incentive policies to encourage energy-saving retrofits and provide fiscal and taxation support for the adoption of high-efficiency products and technologies. Governments can also consider creating recognition programs to recognize energy-saving products and technologies that have made outstanding contributions to energy efficiency and clean cooling.
- 4) **Improve the accessibility and affordability of financing.** In addition to government incentives, there is also a need for governments to promote the accessibility and affordability of financing for climate-friendly cooling. This is very important for the commercialization of green cooling solutions, as high-efficiency technologies tend to have higher initial investments.
- 5) **Government leads by example.** The government should lead by example through giving priority to high-efficiency cooling equipment in government procurement and installing high-efficiency cooling systems in government buildings and other facilities associated with the government.
- 6) **Strengthen professional capacity for climate-friendly cooling.** This includes improving the technical capabilities of cooling specialists to meet the needs of developing high-efficiency and climate-friendly cooling technologies. At the same time, good operation and maintenance have a great impact on the energy use of the cooling system. Asian governments need to establish effective training systems to strengthen training in cooling equipment operation and repair and maintenance, improve the skills of relevant technical and management personnel, and establish a certification system for personnel engaged in cooling system operation and maintenance to make sure they are technically qualified.

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