Regional: Regional Support to Build Disease Resilient and Energy Efficient Centralized Air-conditioning Systems – Assessment Report on Smart, Disease-Resilient and Energy-Efficient Centralized Air-conditioning Systems

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For Asian Development Bank

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Assessment Report on Smart, Disease-Resilient, and Energy-efficient Centralized Air-conditioning Systems

(Final)
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<td>AHRI</td>
<td>Air Conditioning Heating and Refrigeration Institute</td>
</tr>
<tr>
<td>AHU</td>
<td>Air-handling unit</td>
</tr>
<tr>
<td>AIM</td>
<td>The American Innovation and Manufacturing Act</td>
</tr>
<tr>
<td>ANN</td>
<td>artificial neural network</td>
</tr>
<tr>
<td>ASHRAE</td>
<td>American Society of Heating Refrigerating and Air Conditioning Engineers</td>
</tr>
<tr>
<td>BMS</td>
<td>building management system</td>
</tr>
<tr>
<td>CAC</td>
<td>central air-conditioning</td>
</tr>
<tr>
<td>CFC</td>
<td>chlorofluorocarbon</td>
</tr>
<tr>
<td>COP</td>
<td>coefficient of performance</td>
</tr>
<tr>
<td>CPU</td>
<td>central processing unit</td>
</tr>
<tr>
<td>DAC</td>
<td>desiccant air-conditioning</td>
</tr>
<tr>
<td>DCV</td>
<td>demand control ventilation</td>
</tr>
<tr>
<td>DDC</td>
<td>direct digital control</td>
</tr>
<tr>
<td>DOAS</td>
<td>dedicated outdoor air system</td>
</tr>
<tr>
<td>EER</td>
<td>energy-efficiency ratio</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>ESP</td>
<td>electrostatic precipitator</td>
</tr>
<tr>
<td>FCU</td>
<td>fan-coil unit</td>
</tr>
<tr>
<td>GHG</td>
<td>greenhouse gas</td>
</tr>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrocarbons</td>
</tr>
<tr>
<td>HCFC</td>
<td>hydrochlorofluorocarbon</td>
</tr>
<tr>
<td>HEPA</td>
<td>High-efficiency Particulate Filter</td>
</tr>
<tr>
<td>HFC</td>
<td>Hydrofluorocarbon</td>
</tr>
<tr>
<td>HFO</td>
<td>hydroflouro olefin</td>
</tr>
<tr>
<td>HVAC</td>
<td>heating, ventilation, and air-conditioning</td>
</tr>
<tr>
<td>HVAC&amp;R</td>
<td>heating, ventilation, air conditioning and refrigeration</td>
</tr>
<tr>
<td>IAQ</td>
<td>indoor air quality</td>
</tr>
<tr>
<td>IAQP</td>
<td>indoor air quality procedure</td>
</tr>
<tr>
<td>IEQ</td>
<td>indoor environmental quality</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>IPLV</td>
<td>integrated part-load value</td>
</tr>
<tr>
<td>ISHRAE</td>
<td>Indian Society for Heating, Refrigeration, and Air-Conditioning Engineers</td>
</tr>
<tr>
<td>LCCP</td>
<td>Life-cycle Climate Performance</td>
</tr>
<tr>
<td>LEED</td>
<td>Leadership in Energy and Environmental Design</td>
</tr>
<tr>
<td>MAC</td>
<td>Media Access Control Address</td>
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<tr>
<td>MIMO</td>
<td>multiple-input multiple-output</td>
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<tr>
<td>MLF</td>
<td>Multilateral Fund</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>ODP</td>
<td>ozone depleting potential</td>
</tr>
<tr>
<td>ODS</td>
<td>ozone-depleting substances</td>
</tr>
<tr>
<td>OEM</td>
<td>originating equipment manufacturer</td>
</tr>
<tr>
<td>PCO</td>
<td>photocatalytic oxidation</td>
</tr>
<tr>
<td>PHI</td>
<td>photo-hydro-ionization</td>
</tr>
<tr>
<td>PID</td>
<td>proportional, integral, and derivative</td>
</tr>
<tr>
<td>PLC</td>
<td>programmable logic controller</td>
</tr>
<tr>
<td>RTD</td>
<td>resistance thermometer detectors</td>
</tr>
<tr>
<td>SCOP</td>
<td>seasonal coefficient of performance</td>
</tr>
<tr>
<td>SNAP</td>
<td>significant New Alternative Policy</td>
</tr>
<tr>
<td>TEWI</td>
<td>total Equivalent Warming Impact</td>
</tr>
<tr>
<td>TRNSYS</td>
<td>Transient System Simulation Tool</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>UN Framework Convention on Climate Change</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>UV</td>
<td>ultraviolet</td>
</tr>
<tr>
<td>UGVI</td>
<td>ultraviolet germicidal irradiation</td>
</tr>
<tr>
<td>VAV</td>
<td>variable-air-volume</td>
</tr>
<tr>
<td>VFD</td>
<td>variable frequency drive</td>
</tr>
<tr>
<td>VOC</td>
<td>volatile organic compounds</td>
</tr>
<tr>
<td>VRF</td>
<td>variable refrigerant flow</td>
</tr>
<tr>
<td>VRP</td>
<td>ventilation rate procedure</td>
</tr>
</tbody>
</table>
1. Introduction

1.1 Climate Classification

Climate classification is an essential aspect of heating, ventilation, and air-conditioning (HVAC) system design. There have been a variety of classification schemes in history. The climate classification used here is the Köppen classification, which divides the world’s climate zones into five types: tropical, dry, temperate, continental, and polar. In our project, the polar climate is not relevant. A crucial factor to be considered is the local climate. Given the different climate zones, central air-conditioning (CAC) systems should be planned accordingly in these buildings.

A tropical climate is characterized by high temperature and a relatively high humidity level. The heating and humidification scenarios in HVAC systems are thus not so important, but the dehumidification needs are often intensive.

A dry climate has a low level of humidity, thus the dehumidification control in this system is not important. Evaporative cooling and passive design have much room to explore. Temperate zones are the suitable places where a zero-energy building is most likely to be constructed, as the climate in this zone is relatively cozy for human habitancy. Continental climate zones have a cold winter, which may offer an opportunity for a good use of water-source heat pumps.

A German botanist-climatologist, Wladimir Köppen, invented Köppen’s classification scheme. It systematically categorizes the climate on the earth based on local vegetation, which is intrinsically determined by the local terrestrial climate. Five types are represented by the capital letters A (tropical), B (dry), C (temperate), D (continental), and E (polar). Except for B, all the other types are categorized by different temperature standards. The Table 1 displays details of the categorizing principle for each major group.

<table>
<thead>
<tr>
<th>Major group</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A: Tropical</strong></td>
<td>An average monthly temperature higher than 18°C (64.4°F.) Annual precipitation exceeds 1,500 millimeters in this zone. High humidity levels and warm temperatures result in frequent, almost daily cumulus or more giant cumulonimbus cloud formations.</td>
</tr>
</tbody>
</table>
B: Dry

The complete absence or deficient levels of annual precipitation. The arid atmospheric conditions result from the combined evaporation and transpiration levels, which in total exceed the total amount of precipitation. Vegetation is sparse or completely absent as a result of the dry climate with insufficient precipitation.

C: Temperate

Warm summers with high levels of humidity and mild winter seasons. The warmest month is at least 10°C (60°F) or higher, while the coldest month is lower than 18°C (64.4°F) but higher than -3°C (26.6°F).

D: Continental

The average temperature of the warmest month is above 10°C (50°F), while the coldest month is below -3°C (26.6°F).

E: Polar

The warmest month of the year is below 10°C (50°F). Extremely dry, with annual precipitation of less than 25 cm (10 inches).

cm = centimeters.

Source: [1]

With these categorizing principles, as shown in Figure 1, the climates around the globe can be classified for different countries.

Figure 1: World Map of Köppen’s Classification

Source: [1]
The Table 2 shows the classification of developing member countries of Asian Development Bank according to the Köppen climate classification method.

<table>
<thead>
<tr>
<th>Major Group</th>
<th>Developing Member Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Tropical</td>
<td>Afghanistan; Armenia; Azerbaijan; Bangladesh; Cambodia; Cook Islands; Federated States of Micronesia; India (South); Indonesia; Kiribati; Lao People’s Democratic Republic; Malaysia; Maldives; Marshall Islands; Myanmar; Nauru; Niue; Palau; Papua New Guinea; Philippines; Samoa; Singapore; Solomon Islands; Sri Lanka; Thailand; Timor-Leste; Tonga; Tuvalu; Vanuatu; Viet Nam.</td>
</tr>
<tr>
<td>B: Dry</td>
<td>India (middle); Kazakhstan; Mongolia; Pakistan; Turkmenistan; Uzbekistan.</td>
</tr>
<tr>
<td>C: Temperate</td>
<td>Bhutan; Brunei Darussalam; Georgia; Fiji; Hong Kong, China; Nepal; People’s Republic of China (South); Republic of Korea; Taipei, China; Tajikistan.</td>
</tr>
<tr>
<td>D: Continental</td>
<td>Kyrgyz Republic; People’s Republic of China (North).</td>
</tr>
</tbody>
</table>

Source: Author.

1.2 Public Building Classification

The definition of a public building varies in different countries and geographical areas. Below are a few definitions in different countries:

- The Czech Republic: all buildings that are not apartments or are nonresidential.
- Finland: buildings that provide public services.
- France: a building that is occupied by a government body.
- The building regulations of the UK define public buildings as:
  - Building consisting of or containing a theater, public library, hall, or other place of public resort.
  - A school or other educational establishment not exempted from the operation of building regulations by section 4(1)(a) of the Act (7); or
  - A place of public worship; but a building is not to be treated as a place of public resort because it is, or it contains, a shop, storehouse, or warehouse, or is a dwelling to which members of the public are occasionally admitted.
• But a building is not to be treated as a place of public resort because it is, or it contains, a shop, storehouse, or warehouse, or is a dwelling to which members of the public are occasionally admitted.

• People’s Republic of China: according to different perspectives, public buildings can be classified in different ways. The commonly used classification is according to function. The classifications are as follows:
  - Office building:
  - Commercial buildings, such as malls, supermarkets, and financial buildings.
  - Service industry buildings, such as hotels, entertainment buildings, etc.
  - Educational buildings, such as schools, institution buildings, etc.
  - Medical and health buildings, such as clinics, hospitals, etc.
  - Other public buildings, such as centralized bus stations, railway stations, airports, etc.

• In the United States, according to 10 CFR 420.2 [2], the term public building means “any building which is open to the public during normal business hours, including:
  - Any building that provides facilities or shelter for public assembly, or which is used for educational office or institutional purposes;
  - Any inn, hotel, motel, sports arena, supermarket, transportation terminal, retail store, restaurant, or other commercial establishment that provides services or retail merchandise;
  - Any general office space and any portion of an industrial facility used primarily as office space;
  - Any building owned by a state or political subdivision thereof, including libraries, museums, schools, hospitals, auditoriums, sports arenas, and university buildings; and
  - Any public or private nonprofit school or hospital.”

For this report, the simpler definition “any building which is open to the public during normal business hours” has been used throughout the document. Further, different building types have a different attribute based on their needs such as climate zoning, hygienic requirements, cooling/heating load profiles. Based on discussion within the project team, the assessments have been focused on the four specific building types have been covered in this report. These building types are offices, malls, nursing care, and educational buildings. The following provides a brief description of the building energy use attributes:

• Offices have a higher occupant density, with a lot of internal heat gains. It also has an intensive artificial lighting load, which leads to a high level of electricity usage and a high demand on
the cooling system side. Daylight design is a key to providing a good environment for office working efficiency.

- Malls are a place for shopping and a place for entertainment like eating and watching films. Thus, the air-conditioning demands in each part of the mall are also very different. Its large size usually involves many zonings, which typically need cooling and heating meantime. Heat recovery potential is therefore possible.

- Nursing care buildings differ from other building kinds, as the air inside should be separated and circulated in a demanding way to minimize the risk of spreading pathogens and protect the inside vulnerable occupants. It is recommended that the HVAC system should be an all-air system with 100% fresh air flow, or a fan-coil system plus dedicated outdoor air system (DOAS) under dry working conditions.

- Education buildings are similar to offices. The difference lies in the occupant density. The density in offices is usually evenly distributed during worktime, but the user density in education facilities and buildings typically varies with time. It also has far more space functions than the office, requiring a flexible system and dedicated local ones for partly used spaces like a sports hall.

2. Energy-Efficiency in Centralized Air-conditioning System

2.1 Introduction

With the rapid development of the global economy, a significant amount of energy consumption has been observed along with the increasing severity of environmental deterioration. According to the global status report for building and construction by International Energy Agency [3], “the buildings and construction sector accounted for 35% of final energy use and 38% of energy and process-related carbon dioxide (CO₂) emissions in 2018.” Thus, to lessen the energy consumption in buildings has become a worldwide focus and pursuit.

The building codes or standards in general can be specified by either the national government provincial government, or states. In countries with large internal climatic variations, the national building codes might be too general to incorporate considerations of local climatic uniqueness. In this case, a highly generalized building standard or code is normally formed, adopted, and applied nationwide. Each province or state will then adapt and amend based on the national standard to meet local conditions and these adjustments will become mandates to be followed in later industrial practices.
As shown in Figure 3, energy-efficiency design of buildings can be mainly classified into three categories. These categories are the building characteristic, the building service system, and the design under specific weather conditions. Building characteristic incorporates a variety of factors such as building shape,
orientation, insulation, and window. Together, these parameters define the exterior attributes of a particular building. Building service systems, typically, consumes maximum energy inside the buildings. Common components are HVAC systems, hot water supply, lighting systems, electrical appliances, and control management. Designs under specific weather conditions require the consideration of outdoor air temperature, relative humidity, solar radiation, and wind speed. For example, with global warming, a significant increase in cooling demand is a trend. When an attempt is made to improve building energy efficiency, all three aspects should be integrally considered. For example, upgrading the building insulation will directly affect the internal thermal requirement, which impacts the design of HVAC.

### 2.2 Energy-Efficiency Strategies

Multiple approaches can be taken when improving the building’s energy efficiency. This section will briefly introduce several aspects critical to energy-efficient building design.

#### 2.2.1 Methodology

Building energy efficiency needs to be addressed throughout all phases of a building’s life cycle. The Figure 4 illustrates a road map for building energy-efficiency strategies and approaches.

![Figure 4: Road Map of Building Energy Efficiency](image)

Source: Author.

The realization of low energy consumption in buildings is closely related to the climate. Starting from the design of the building envelope and architecture form, also known as passive design, to the design of the building’s HVAC system, the climatic conditions are inseparable from passive architecture design. The American standard ASHRAE 90.1 [5] defines building envelope parameters and equipment efficiency in
several climatic environments. Figure 5 shows the complete procedures in different phases to achieve a long-term energy-efficiency target.

Figure 5: Actions in Different Phases to Achieve an Energy-Efficiency Target

Source: Author.
2.2.2 Envelope
The building envelope is defined as a physical boundary between the interior and the exterior of the building. The most common envelope components are walls, windows, and roof. Since the occupants within the building require comfort from aspects like temperature, lighting, and humidity, such physical boundary is essential to create, control, and maintain the interior environment. However, it should be noted that due to the inevitable thermal gradient between indoors and outdoors, a certain amount of heat loss or heat transfer is unavoidable. Insulation of the building envelope is therefore one vital aspect of achieving such a goal and improving the building’s energy efficiency. Parameters like the coefficient of heat transfer, which depends on the material of the envelope, have a direct impact on the actual thermal performance. The airtightness is important where a significant amount of heat loss is generated due to a large thermal gradient between the interior and the exterior of the building.

2.2.3 Cooling and Heating Systems
The cooling and heating system is an integral part of the overall thermal control and performance of a building. It is important to select high-efficiency cooling and heating systems to reduce the energy consumption of the building while maintaining a constant and stable level of comfort for occupants. The efficiency can be defined as coefficient of performance (COP) or energy-efficiency ratio (EER), integrated part-load value (IPLV), and seasonal coefficient of performance (SCOP) to define the efficiency of plant equipment proving heating and cooling. Variable-air-volume (VAV) system is also an energy-saving method, as it can adjust the air volume according to the load of each room.

2.2.4 Renewable Energy
The most used renewable energy sources are solar and wind energy. Selecting appropriate renewable energy applications requires the consideration of multiple aspects such as the available renewable energy, associated implementation and maintenance costs, incentives, local regulations, and the characteristics of the energy profile. Geothermal energy can also be an effective renewable energy for building cooling and heating. Solar energy utilization is instrumental in reducing building energy consumption and even achieve net-zero-energy buildings.

2.2.5 Energy-Saving Measures
Figure 6 gives options for energy-saving measures in different situations.
### Energy demand control via passive design

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation and shape factor</td>
<td>Microclimate environment</td>
<td>Roofs, facades, glazing/Window-wall-ratio</td>
<td>Shading</td>
</tr>
<tr>
<td>Airtightness</td>
<td>Thermal storage envelope</td>
<td>Natural day-lighting</td>
<td>Natural ventilation</td>
</tr>
</tbody>
</table>

**Comments**
- First steps to optimize the buildings
- Use tress, terrain, surrounding structures to improve EE
- Case-by-case study required
- Exterior shading design is the priority
- Critical for fresh air conditioning load
- Dry and large diurnal range area
- Recommended whenever possible
- Not recommended for hot and humid areas

### Use energy-efficient mechanical system

#### Internal gains

<table>
<thead>
<tr>
<th><strong>Energy saving appliances</strong></th>
<th><strong>LED lighting</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recommended whenever possible</strong></td>
<td><strong>Recommended whenever possible</strong></td>
</tr>
</tbody>
</table>

#### Energy, heating & cooling source system

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Natural gas, combined heat+cool+power demand</strong></td>
<td><strong>Small facility possible</strong></td>
<td><strong>When electricity rate favorable overnight</strong></td>
<td><strong>Helpful when there is waste heat available nearby</strong></td>
<td><strong>Heat should be balanced for the earth</strong></td>
<td><strong>Simultaneous heat and cool, large span, like malls</strong></td>
<td><strong>Recovered heat for domestic hot water</strong></td>
<td><strong>Dry and large diurnal range area</strong></td>
</tr>
</tbody>
</table>

#### Distribution sub-system

<table>
<thead>
<tr>
<th>Fresh air heat recovery</th>
<th>Desiccant dehumidification system</th>
<th>VFD of fans and pumps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particularly effective in humid areas</strong></td>
<td><strong>Effective when low-grade heat available</strong></td>
<td><strong>Recommended whenever possible</strong></td>
</tr>
</tbody>
</table>

#### HVAC system terminals

<table>
<thead>
<tr>
<th>CO₂ controlled ventilation</th>
<th>Radiant systems, e.g. capillary ceiling, radiant floor</th>
<th>DOAS stand-alone fresh air systems</th>
<th>Displacement ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Offices /other spaces where occupancy varies widely</strong></td>
<td><strong>Condensation control is vital</strong></td>
<td><strong>Particularly effective in humid areas</strong></td>
<td><strong>Large and tall spaces</strong></td>
</tr>
</tbody>
</table>

---

**Figure 6: Energy-Efficiency Strategy Recommendations**


**Source:** Author.
2.3 ASHRAE Energy Standard for Buildings

The standard ANSI/ASHRAE/IESNA Standard 90.1 [5], Energy Standard for Buildings Except for Low-Rise Residential Buildings, provides the minimum requirements for energy-efficient design of most buildings, except low-rise residential buildings. Standard 90.1 has been a benchmark for commercial building energy codes in the United States (US) and a key basis for codes and standards around the world for more than 35 years. It offers, in detail, the minimum energy-efficiency requirements for the design and construction of new buildings and their systems, new portions of buildings and their systems, and new systems and equipment in existing buildings, as well as criteria for determining compliance with these requirements. It is an indispensable reference for engineers and other professionals involved in the design of buildings and building systems [5]. Additionally, the International Energy Conservation Code registers compliance with 90.1 as an alternative way of meeting that code, while the US Green Building Council’s LEED also references 90.1, making it one of the most successful and widely adapted energy codes to date in the world. This standard presents exhaustive details covering nearly all the elements that influence the energy performance of a building. For example, the HVAC systems section includes alterations to the minimum equipment efficiency ratings, fan power limitations, energy recovery, reheat limitation, economizers, and duct sealing and leakage [5].

- Fan power. Calling for more efficient fans, ASHRAE 90.1-2010 will reduce the amount of fan power allowed to be used in a building. This can be achieved through lower static pressure duct systems, which translates to fewer bends, wider ducts, and shorter runs—all of which impact architectural space planning. Additionally, individual VAV fans with motors greater than or equal to 10 hp need a variable speed drive, or another means of reducing fan power consumption.

- Energy recovery. In some climate zones (see ASHRAE Table 6.5.6.1), energy recovery may be required for air-handling systems with as little as 30% outside air.

- Reheat limitations. Reheat is not allowed unless the air being reheated is less than or equal to 30% of the peak flow or the minimum required ventilation rates. This effectively encourages HVAC designers to look toward DOAS in commercial spaces, as well as likely eliminating constant volume systems for hospitals and labs. Employing separate perimeter heating, or finned tube radiation, is another simple way to meet this requirement.

- Economizers. Economizers are now required for all climate zones, except 1A and 1B (see ASHRAE climate table), for systems with more than 54,000 British thermal units (Btu)/hour (previously 134,000 Btu/hour). This applies to air-conditioning units 4.5 tons and larger, which includes just about every commercial setting. A waterside economizer may be able to be substituted to achieve the same result.
• Duct sealing and leakage. Ductwork higher than 3-inch water gauge and all outdoor air ducts need to be Seal Class A and Leakage Class 4. By surface area, 25% needs to be tested to demonstrate conformance.

• Minimum equipment efficiencies. Minimum performance requirements of heating and air-conditioning equipment, including chillers, boilers, and packaged equipment, continue to increase from the previous standard. Designers must pay special attention to which path of compliance will be used when testing chillers with or without variable frequency drive.

• Heat rejection. This now effectively limits the use of centrifugal fans in cooling towers.

• HVAC commissioning. Possibly the most significant ASHRAE 90.1-2010 update, HVAC commissioning is now required for control systems on most projects greater than 50,000 square feet (sq. ft.).

Table 3 shows an example of the minimum efficiency requirements for a device in this standard.

Table 3: A Sample Table of Efficiency Requirements for A Chiller

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Size Category</th>
<th>Units</th>
<th>Path A</th>
<th>Path B</th>
<th>Test Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-Cooled Chillers</td>
<td>&lt;528 kW</td>
<td>COP</td>
<td>22.802</td>
<td>25.663</td>
<td>NA²</td>
</tr>
<tr>
<td>Air-Cooled without Condenser, Electrically Operated</td>
<td>All Capacities</td>
<td>COP</td>
<td>22.802</td>
<td>25.777</td>
<td>NA²</td>
</tr>
<tr>
<td>Water-Cooled, Electrically Operated, Reciprocating</td>
<td>All Capacities</td>
<td>COP</td>
<td>2.582</td>
<td>2.582</td>
<td>2.582</td>
</tr>
<tr>
<td>Water-Cooled, Electrically Operated, Positive Displacement</td>
<td>&lt;64 kW</td>
<td>COP</td>
<td>2.558</td>
<td>2.545</td>
<td>2.545</td>
</tr>
<tr>
<td>Water-Cooled, Electrically Operated, Centrifugal</td>
<td>≤208 kW and ≤685 kW</td>
<td>COP</td>
<td>2.582</td>
<td>2.582</td>
<td>2.582</td>
</tr>
<tr>
<td>Water-Cooled, Electrically Operated, Centrifugal</td>
<td>208 kW and ≤1055 kW</td>
<td>COP</td>
<td>2.582</td>
<td>2.582</td>
<td>2.582</td>
</tr>
<tr>
<td>Water-Cooled, Electrically Operated, Centrifugal</td>
<td>≤110 kW and ≤685 kW</td>
<td>COP</td>
<td>2.582</td>
<td>2.582</td>
<td>2.582</td>
</tr>
<tr>
<td>Water-Cooled, Absorption, Single Effect</td>
<td>All Capacities</td>
<td>COP</td>
<td>21.000</td>
<td>21.000</td>
<td>NA²</td>
</tr>
<tr>
<td>Water-Cooled, Absorption, Single Effect</td>
<td>All Capacities</td>
<td>COP</td>
<td>21.000</td>
<td>21.050</td>
<td>NA²</td>
</tr>
<tr>
<td>Absorption Double-Effect, Indirect-Fired</td>
<td>All Capacities</td>
<td>COP</td>
<td>21.000</td>
<td>21.000</td>
<td>NA²</td>
</tr>
<tr>
<td>Absorption Double-Effect, Direct-Fired</td>
<td>All Capacities</td>
<td>COP</td>
<td>21.000</td>
<td>21.000</td>
<td>NA²</td>
</tr>
</tbody>
</table>

¹The chillers for equipment requirements after performance part 1.2 to be tested to demonstrate the design having a temperature difference of 2°C. The requirement is not to apply to a performance chiller with design having a temperature difference of 4°C.
²Compliance with this standard is by meeting the minimum requirements of Path A or Path B. However, both the AHRI 550/560 and ASHRAE must be met to fulfill the requirements of Path A or Path B.
³Section 15 contains a complete specification of the referenced test procedure, including the referenced version of the test procedure.
⁴A1 means that the requirement is not applicable and cannot be used for compliance.
3. Disease Resilience of Central Air-conditioning System

Considering the impact of the coronavirus disease (COVID-19), pneumonia, and other epidemic diseases during a pandemic, the design of air-conditioning systems must respond to this scenario. The capacity of air-conditioning systems should be reconsidered to meet the fresh air exchange needs of users during a pandemic as well as the filtration system should be able to disinfect the re-circulated air. The adaptability of CAC systems for epidemics comes at the cost of energy efficiency. If conditions allow, natural ventilation could be used to reduce the load on the air-conditioning system as much as possible to reduce the excessive design capacity. Alternatively, a reliable and durable filtration system with a complete disinfection program for the circulating air should be used.

3.1 Definition of Centralized Air-Conditioning Systems

Figure 7: Centralized Air-Conditioning Systems

Source: [6]
In the building sector, the HVAC system accounts for 35% of energy consumption in residential and commercial buildings. A CAC system is a critical component of HVAC, through which air, water, or both are used as working fluids to achieve the heating or cooling effects. CAC, as shown in Figure 7, circulates cool air through a system of supply and return ducts. Supply ducts and registers (i.e., openings in the walls, floors, or ceilings covered by grills) carry cooled air from the air conditioner to the rooms. This cooled air becomes warmer as it circulates through the room, then it flows back to the central air-conditioner through return ducts and registers.

Air-conditioners help to dehumidify the incoming air, but in extremely humid climates or in cases where the air conditioner is poorly sized, it may not achieve a low humidity as required. Operating an additional dehumidifier in an air-conditioned space will increase the energy use, both for the dehumidifier itself and CAC because the air-conditioner will require more energy to cool the room.

Desiccant air-conditioning (DAC) systems have been another promising alternative to conventional vapor-compression cooling systems, as the DAC system can achieve independent temperature and humidity control, and thermal energy can be used to power the DAC system. The DAC system utilizes desiccants that are hygroscopic materials to remove moisture from the air. It is different from the conventional dehumidification method that condenses moisture by cooling the air down below its dew-point temperature and then reheating it to a comfortable temperature. Desiccant materials generally include liquid desiccants (e.g., lithium chloride solution, calcium chloride solution, ionic liquid) and solid desiccants (e.g., silica gel, zeolite, metal-organic framework).

### 3.2 Guideline for Centralized Air-conditioning Systems for Public Buildings

Due to COVID-19, the hazard of air circulation carrying infectious pathogens through CAC has been recognized. To ensure safety and minimize the risk of infection, several modifications should be made in the design and operation of CAC systems. For example, in an air-conditioning ventilation system is an all-air system, the return air valve should be closed, and the system adapts to whole outdoor air during pandemic.

When designing for public buildings, occupant density is an important parameter to be considered as humans are not only an essential heat source but also a humidity source. In an area with a high occupant density, an all-air system or a fan coil with an outdoor air system is recommended. In areas with a lower density like the elevator, a fan coil with an outdoor air system is recommended. In areas where a large amount of indoor air needs to be exhausted, such as restaurants, a constant air volume system or a fan coil with outdoor air is recommended.
When the air-conditioning system is a fan-coil unit with an outdoor air system, the following conditions shall be met during pandemic:

1. Ensure that the fresh air is taken directly from the outdoors. Taking air from the corridor, ceiling, and machine room is not recommended.
2. Ensure the operation of the exhaust system.
3. Ensure the ventilation of the internal area for spaces with large entrances.
4. Keep the fresh air system running all day.

Installing a fan-coil system without fresh air is not recommended. The doors or windows must be opened to enhance sufficient air circulation during a pandemic.

3.2.1 Recommendations for Offices

In general, the office building should be equipped with an all-air system or a fan coil with an outdoor air system. All-air systems, shown in Figure 8, transfer cooled or heated air from a central plant via ducting, distributing air through a series of grilles or diffusers to the room being served. It normally features a lower equipment cost, but on the other hand, the installation cost or difficulty could be higher due to the size of an office building. Furthermore, it can be a challenge to regulate temperature properly, while keeping the system compact and energy efficient. The all-air system is generally ranked in second place compared to other systems (variable refrigerant flow [VRF] for example) about the amount of energy used to achieve the desired result, particularly for small- and mid-sized office buildings.

![Figure 8: All-Air System for Multiple Zones](source: [7].)
Some spaces require different airflow of supply air due to the changes in thermal loads. Therefore, a VAV all-air system is a potentially suitable solution for achieving thermal comfort. The VAV system consists of a central air-handling unit that provides supply air to the VAV terminal control box located in each zone to adjust the supply air volume, as shown in Figure 9. The temperature of the supply air of each zone is controlled by manipulating the supply airflow rate. The main disadvantage is that the controlled airflow rate can negatively impact other adjacent zones with different or similar airflow rates and temperatures. Also, part-load conditions in buildings may require a low airflow rate, which reduces the fan power, resulting in energy savings. It may also reduce the ventilation flow rate, however, which can be problematic to the HVAC system and affect the indoor air quality of the building.

![Figure 9: All-Air HVAC Systems with VAV Terminal Units.](source)

Source: [7].

In tropical zones, the temperature is usually high, as well as the need for dehumidification. As most countries are near the coast, a seawater-source air-conditioning system is therefore possible. Due to different levels of economic development among the Asian Development Bank’s developing member countries, the choices of HVAC systems also vary. In developed countries like Singapore, the most used system is VAV, with cooling air uniformly filtered in the central part, and the air volume is adjusted according to the temperature setting in each room. However, this method should be treated carefully. To maintain the air exchange rate, there is a minimum limit on the amount of cool air, which leads to a limit of maximum temperature usually around 24 to 26 °C. Or in some cases, lower than 24 °C. Generally, the solution to address this limit is through a reheat process. However, Singapore stipulated strict building energy conservation rules, and reheating is not allowed in buildings.
In developing countries in Southeast Asia, due to the limitation of power infrastructure, the air-conditioning installation rate is relatively low. The proportion of commercial air-conditioners is limited, and household air-conditioners are dominated by split units.

In dry zones, where water is a scarce resource, it is recommended that an all-air system should be used, indicating that the facades of buildings should be properly designed to extract and guide the wind flow. The evaporative cooling can contribute a lot to the air-conditioning system in public buildings in dry areas. For the temperate zone, where the climate is also relatively mild, the solutions vary. Customers can choose the system based on their economic requests and specific demands.

In a continental zone with a cold winter, it is recommended that a large office building is equipped with a water-source heat pump system. Water-source heat pumps are used to provide considerable energy savings for public buildings under cold weather. A large building of various zones can be conditioned by several individual heat pumps since each heat pump can be controlled according to the zone control. A centralized water circulation loop can be used as a heat source and heat sink for heat pumps. Therefore, heat pumps can act as the primary source of heating and cooling. It is also known as a water-loop heat pump. For a heating process, the boiler or solar collectors will be used to supply heat to the water circulation, while a cooling tower is alternatively used to reject heat collected from the heat pumps to the atmosphere. This system may save chillers as a result. If a building requires a heating process for zones and a cooling process for other zones at the same time, the heat pumps could redistribute heat from one part to another ideally with no need for a boiler or cooling tower operation.

### 3.2.2 Recommendations for Malls

The function of CAC in malls is to provide a comfortable indoor environment for occupants. Nowadays as malls tend to become a large entertainment and commerce complex, one could find various sub-climate zones inside a mall. Zones within malls can be divided into several main types, such as the shopping area, dining area, cinema, and so on. Here a VAV all-air system and/or a four-pipes system is recommended to be used. The four water pipes include a heating loop and a cooling loop, to distribute to the perimeter areas and core areas, where those two areas usually share different cooling or heating demands at the same time. Heat recovery in this case could take place at the side of the condensing heat of chillers.

There are two main types: fan-coil units and induction units.

Fan-coil units for air-water systems are like that of all-water systems except that the supply air and the conditioned water are provided to the desired zone from a central air-handling unit and central water systems (e.g., boilers or chillers). The ventilation air can be separately delivered into space or connected to the fan-coil units. The major types of fan-coil systems, are 4-pipe systems, as shown in Figure 10.
Induction units are externally similar to fan-coil units but internally different. An induction unit induces the airflow in a room through a cabinet by using high-velocity airflow from a central air-handling unit, which replaces the forced convection of the fan in the fan coil by the induction or buoyancy effect of the induction unit. This can be performed by mixing the primary air from the central unit and the secondary air from the room to produce suitable and conditioned air into the room or zone.

### 3.2.3 Recommendations for Nursing Care Buildings

A nursing care building is a comprehensive medical building with many rooms such as surgery, treatment, and clinical appointments. The pollutants in each room should be separated from one another. Especially in the time of the COVID-19 pandemic, the importance of air-conditioning in health care centers has not been clearer than ever.

To meet this need, the system can be an air-water system for critical medical spaces. Outdoor air is the primary air system along with a radiant panel system. The coil in each room should run in dry cooling conditions.

As for auxiliary spaces, a fan-coil unit can be used, as shown in Figure 11. The unit can be vertically or horizontally installed. The fan-coil unit can be placed in the room or exposed to occupants, so it is essential to have appropriate finishes and styling. The fan-coil units are eventually connected to boilers to fetch...
heating and to water chillers to get cooling to the conditioned space. The desired temperature of a zone is detected by a thermostat that controls the water flow to the fan-coil units. In addition, occupants can adjust fan-coil units to achieve the desired temperatures. The fan-coil unit should be separated from the dedicated ventilation air to ensure a constant outdoor air supply.

![Diagram of Fan-Coil Units](image)

**Figure 11: Fan-Coil Units.**

Source: [7]

Air-water systems are introduced as a hybrid system to combine both advantages of all-air and all-water systems. The volume of the medium airflow is reduced, and the outdoor ventilation is brought to satisfy the desired zone ventilation as needed. The water medium is responsible for carrying the thermal load in a building by a majority, while outside air is only used to take care of ventilation.

### 3.2.4 Recommendations for Education Buildings

As for education buildings like schools, the characteristics include different cooling and/or heating load scenarios among rooms, and the occupant is normally dense. The systems suitable are all-air systems and air-water coil systems.

Similar to the office building, the VAV system can be used in education buildings such as classrooms. Each room has an independent temperature thermostat, and the air-conditioner can be cut off when the people in the rooms have left.

For the shared large space, like a sports or musical hall, a dedicated air-conditioning system is to be provided. As long as the climate allows, the swimming pool should be designed outdoors, as its conditioning is extremely energy-consuming.
3.2.5 Summary

To conclude, the design of HVAC systems in different climate zones is different and climate features of the region must be taken into consideration on a case-by-case basis, although the function of the AC system is the same—to provide a comfortable environment for the occupant with less energy consumption.

When choosing an HVAC solution, several factors should be considered, including the budget, energy standards in the country, and the comfort requirements of the occupants.

For the public buildings, four types are covered in this report: office, mall, nursing care building, and education building. Different buildings have various attributes regarding zoning, hygienic requirements, cooling and/or heating load profiles, etc.

Offices have a higher occupant density, with a lot of internal heat gains. It has also an intensive artificial lighting load, which not only leads to a high level of electricity usage but also a high demand for the cooling system. Daylight design is a key to providing a good environment for office working efficiency.

Malls are nowadays not only a place for shopping but also a place for entertainment like eating and watching films. Thus, the air-conditioning demands in each part of the mall are also different. Its large size usually involves many zonings, which typically need cooling and heating meantime.

Nursing care buildings differ from other building kinds, as the air inside should be separated and circulated in a demanding way to minimize the risk of spreading pathogens and to protect the inside vulnerable occupants. It is recommended that the HVAC system should be an all-air system with 100% fresh air flow, or a fan-coil system plus DOAS under dry working conditions.

Education buildings are similar to offices. The difference lies in the occupant density. The density in offices is usually even distributed during the worktime, but the density in education facilities and buildings typically varies with time.

With the differences mentioned, CAC systems in these buildings accordingly need different planning. Another crucial factor to be taken into consideration is the local climate. The climate classification used here is the Köppen classification, which divides the world’s climate zones into five types, tropical, dry, temperate, continental, and polar. In our project, the polar climate is not relevant.

The tropical climate has a high temperature and a relatively high humidity level. The heating and humidification scenarios in the HVAC system are thus not so important. Dry climates have a low level of humidity. The dehumidification control in this system is thus not important. Temperate zones are the
suitable places where a zero-energy building is most likely to be constructed, as the climate in this zone is relatively suitable for human habitancy.

4. Indoor Air Quality in Centralized Air-conditioning System

4.1 Introduction to Indoor Air Quality and Disease Resilience

Indoor air quality (IAQ) plays an important role as most of the time people spend about 80% – 90% inside enclosed areas. Sometimes, indoor air is more polluted than outdoor air. The typical sources of indoor air pollutants are listed below:

- Outdoor untreated air
- Combustion of biomass fuels
- Burning of coal
- Furnishings - volatile organic compounds (VOCs)
- Paints/solvents - chemical fumes
- Cleaning Agents – chemical fumes
- Biological pollutants like dust mites and pollen
- Infectious agents produced in mattresses, carpets, and humidifiers
- Improper ventilation and filtration

IAQ is considered to be “healthy” when the air does not contain contaminants in harmful concentrations and is acceptable when the majority of people feel satisfied. It is important to have a correct benchmark when evaluating IAQ. ISHRAE (Indian Society for Heating, Refrigeration, and Air-Conditioning Engineers) has launched an indoor environment quality standard ISHRAE 10001:2016, and updated version in 2019 that gives target levels for the most typical indoor air parameters in the indoor environment. It gives the target levels for three different classes:

- A-class: Aspirational (comparable with internationally prevalent standards),
- B-class: Acceptable,
- C-class: Marginally Acceptable.
### Table 4: Classification Defined in ISHRAE Standard

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Class A</td>
</tr>
<tr>
<td><strong>CO₂</strong></td>
<td>ppm</td>
<td>Ambient + 350</td>
</tr>
<tr>
<td><strong>PM 2.5</strong></td>
<td>µg/m³</td>
<td>&lt;15</td>
</tr>
<tr>
<td><strong>PM 10</strong></td>
<td>µg/m³</td>
<td>&lt;50</td>
</tr>
<tr>
<td><strong>CO</strong></td>
<td>ppm</td>
<td>&lt;2</td>
</tr>
<tr>
<td><strong>TVOC</strong> <em>(equivalent to isobutylene)</em></td>
<td>µg/m³</td>
<td>&lt;200</td>
</tr>
<tr>
<td><strong>CH₂O</strong></td>
<td>µg/m³</td>
<td>&lt;30</td>
</tr>
<tr>
<td><strong>SO₂</strong></td>
<td>µg/m³</td>
<td>&lt;40</td>
</tr>
<tr>
<td><strong>NO₂</strong></td>
<td>µg/m³</td>
<td>&lt;40</td>
</tr>
<tr>
<td><strong>O₃</strong></td>
<td>µg/m³</td>
<td>&lt;50</td>
</tr>
<tr>
<td><strong>Total Microbial Count</strong></td>
<td>CFU/m³</td>
<td>Indoor ≤ ambient</td>
</tr>
<tr>
<td><strong>Occupant Satisfaction</strong></td>
<td>%</td>
<td>90</td>
</tr>
</tbody>
</table>

Source: [8].

Standard covers the following parameters for IAQ apart from thermal comfort, lighting, and acoustic:

- Carbon dioxide (CO₂)
- Particulate matter (PM) 2.5
- PM 10
- Total volatile organic compounds (TVOC)
- Sulfur oxide (SOx)
- Nitrogen oxide (NOx)
- Carbon Monoxide
- Ozone
- Aldehyde
- Microbial count
- Occupant satisfaction

Indoor environmental quality (IEQ) refers to the quality of a building’s environment related to the health of occupants within it. IEQ is determined by many factors, including lighting, air quality, thermal comfort, acoustics, and damp conditions as shown in Figure 12. IEQ goals often focus on providing stimulating and comfortable environments for occupants and minimizing the risk of building-related health problems.
There are ASHRAE Standards 62.1 and 62.2 which define how to calculate the quantity of indoor air for safe working environments. There are two major concepts to manage indoor air quality: ventilation rate procedure (VRP) and indoor air quality procedure (IAQP). IAQP method assumes that contaminants of concern will be reduced by an air purification system that allows for less outdoor air to be used than under the VRP. In this strategy, CO$_2$ creates the biggest challenge, and therefore some amount of outdoor air is always required, or as an alternative very high number of indoor plants can be used to remove CO$_2$. In the VRP, the idea is that well-filtered outdoor air is used to dilute all indoor pollutants including CO$_2$, VOCs, and odors.

Temperature and relative humidity also play an important part in conditions to mitigate the COVID-19 virus and hence mentioned below are some suggestions based on studies.

**Temperature**

It is recommended that the room temperature be maintained between 24°C and 30°C. However, in humid climates, the temperature should be closer to 24°C for dehumidification, and for dry climates closer, to or at 30°C.

**Relative Humidity**

Relative humidity is important for the comfort and health of humans. At lower relative humidity, the skin dries and at higher relative humidity, the growth of fungus, mold, etc. is possible and is uncomfortable. Based on the studies, at lower relative humidity, the growth of pathogen is higher and so is at higher relative humidity. However, between 40% to 60%, the impact of pathogens is minimal as may be seen in Figure 13. This range is also recommended for comfortable inside conditions for humans.
### 4.2 Basics of Virus Transmission Through Centralized Air-conditioning

The COVID-19 virus is transferred via infected microscopic airborne particles and contaminated aerosol droplets. These may be ingested by human beings or get deposited by contact with surfaces, where they remain active for hours. The virus enters a human through direct airborne ingestion or body contact, and subsequent ingestion through nasal and aural passages into their lungs.

The ventilation is the most important parameter in any enclosed area as the person carrying the virus can easily transmit the same while in the room. The viral load once in the room is to be either diluted or filtered before it is transmitted to other people in the area. There are now many studies on mathematical numbers and formulas of viral load, defining how much time and how many people can be in an enclosed area safely before being infected with the virus.
4.2.1 Filtration
Filtration is broadly defined in two categories: passive and active. Filters are supposed to remove particles of various sizes when air is passed through them. The major difference between passive and active is that in active filtration, electricity charges are used while none are used in passive filtration.

Types of Filtration Technologies

Passive Technology
The passive type of filtration is with the standard particulate filters, where the air is drawn into the equipment and passed through a filter to remove contaminants before clean air is released on the other side. These filters are static and do not need any power for filtrations.

They are capable of filtering various sizes of particles as per requirements. These are constructed with different elements as per filtration requirements as shown in Figure 14.

![Figure 14: Basic Principle of Particulate Matter Filters](image)

Source: [11].

The various combinations of these filters are also used for more critical requirements as shown in the Figure 15:
The following is a brief on filters.

**Pre-filter stage.** Control of coarse and fine particulate matter; protection of subsequent filters Media: non-woven glass micro-fiber, mini-pleated for high-capacity

- **PM10** - Inhalable coarse particles, such as those found near roadways and dusty industries. These particles are smaller than 10 micrometers in diameter.
- **PM2.5** - Fine particles, such as those found in smoke and haze, are 2.5 micrometers in diameter and smaller. These particles can be directly emitted from sources such as forest fires or are formed when the gases emitted from power plants, industries, and automobiles react in the air.

**Activated carbon filter.** Activated carbon is also called activated charcoal which goes through a process with oxygen to open the pores between atoms. The main function of activated charcoal is to adsorb the odors or colored substances from liquids or gases.

**HEPA filters.** HEPA filters remove 99.97% of contaminants in the air that are 0.3 microns in size, making these filters highly effective at sanitizing the air. HEPA filters can capture small particles such as bacteria, mold, dust mites, and pollen. Unlike carbon filters, HEPA filters are not designed to remove odors, smoke, fumes, or chemicals. HEPA filters also trap microorganisms, which is why it is recommended to use both HEPA filters and carbon filters.
Active technologies. Active technologies are the type where the air chemistry is changed. Some of the active technologies used are ionization, bi-polar ionization, photocatalytic oxidation (PCO), electrostatic precipitator (ESP), ozone generators, etc. The efficacy of some of these is not yet clearly proven and some of these technologies may have contra-indications. Ultraviolet germicidal irradiation (UVGI), if deployed correctly has proven to be useful in inactivating bioaerosols. Few of the active technologies are called emerging technologies by the World Health Organization and the efficacy of these systems in real applications is yet to be established.

There are a few active technologies such as ionization that are evolving technologies and require further research, especially on the impact on occupant health.

UVGI – UVGI has been shown to kill microorganisms at a certain wavelength and after a certain exposure time and light intensity. The exposure time can vary from one minute to as much as 15 minutes depending on the light intensity of the UVGI. The optimal wavelength is 254 nanometers. Installing UVGI on the coil of an AHU will not guarantee sterilization of the air as the contact time off the air with the UVGI is in milliseconds. However, if it can be installed in the lining of a duct, the exposure time can be increased, and it may be beneficial. Human beings should not be exposed to UVGI. The lamps lose their intensity over a period and must be changed as per the manufacturer's recommendation if installed. If the wavelength changes to a much higher level or lower level than the optimal it may also produce ozone as a byproduct.

Ionization. This is a device that disperses negatively (and/or positively) charged ions into the air. These ions attach to particles in the air giving them a negative (or positive) charge so that the particles may attach to nearby surfaces such as walls or furniture or attach and settle out of the air.

The particles are not removed but adhere to surfaces causing black walls and curtains. Since the largest surface in an inhabited room is the human lung, this is also a likely surface where the charged particles can become lodged. This can cause severe short- and long-term health problems. Ionizers do not filter gases or odors and most ionizers also produce harmful ozone as a byproduct.

Electrostatic precipitators. Electronic air cleaners remove small particles, but because they use high voltage to generate ionized fields, they can produce ozone either as a byproduct or by design. One must be aware that they need to be serviced regularly and typically the maximum efficiency is about 95% which decreases upon use and sometimes is even below 20%.

The electrostatic precipitators (ESP) comprise the electrical system incorporating a rectification unit to transform AC volts to DC volts. This transformation from AC to DC voltage is required to achieve the necessary electric field that will ionize the particulates as they pass through the ESP. DC voltage is fed to
the discharge electrodes, which results in a **negative electric field** being generated around them. The negative electric field around the discharge electrodes causes a **negative charge** to be imparted onto the particulates, which causes them to be attracted to the **positively charged collector plates**.

**Photocatalytic Oxidation** – PCO cleaners use UV lamps along with a substance called a catalyst titanium dioxide (TiO2) that reacts with the light and changes the VOC containments into other compounds. They are designed to destroy gaseous pollutants by changing them into harmless products, but they are not designed to remove particulates. Depending on the chemical reaction, sometimes harmful byproducts may also be created in very small quantities.

**Photo-hydro-ionization** - This technology is a combination of UV-light enhanced by a hydrated quad-metallic compound target to develop advanced oxidation plasma. By engineering the proper UV-C light wavelength, the PHI cell provides hydro-peroxides, superoxide ions, and hydroxide ions that revert to oxygen and hydrogen after oxidizing the pollutant. PHI technology removes bioaerosols (bacteria, viruses, fungi, etc.), VOCs, and formaldehyde from the air. It also reduces odors in the air. It also has a positive impact on particulate removal as ions released into the air make ultra-fine particulates stick together (coagulation) in a similar way as with plasma technology. There is no standardized test to evaluate the effectiveness of plasma technology.

### 4.3 Centralized Air-conditioning Systems of Public Buildings and the Impact of COVID-19

COVID-19 is airborne. It stays in the air for a longer time is being recirculated in the following CAC system. The following shows how the air circulation happens and what needs to be done.

**Centralized Air-Conditioning System to Air-Handling Units Feeding Multiple Areas**

The system with CAC having air-handling units (AHU) is fed with hot or cold water via pumps being generated by chiller, hot water generator, or other technologies. In this system, the conditioning is done using air as media. The AHU, as shown in Figure 16, has a fan or fans used for the supply and return path of air where the conditioned air is supplied through the insulated ducts via grilles or diffusers and returned air by either ducted or through the false ceiling via grilles or diffusers. The supply air duct supplies the conditioned air into the multiple rooms and the return air is picked up and mixed while it returns to the AHU directly or in the AHU room via duct or false ceilings. So, while the return air is mixed in all the areas where the supply air is given, it is important that the recirculated air may be either diluted with more fresh air and/or also have good filtration levels so that any viral load generated by an infected person may be reduced.
The outside fresh air is mixed with the return air to supply in the room and the additional outside is either exhausted out by an independent system or used to maintain positive pressure in the conditioned room.

It is important also to have good air distribution systems as a strategy for air to carry viral load directly to return air and then to AHU for dilution and filtration.

The balance between the supply of fresh air and exhaust air must be carefully done if the exhaust is not proper, the fresh air quantity will be reduced.

![Schematic Diagram of an Air Handling Unit](source)

Figure 16: Schematic Diagram of an Air Handling Unit

Centralized Air-Conditioning System to Fan-Coil Units Feeding Individual Areas

The CAC system with fan-coil unit (FCU), shown in Figure 17, is designed to condition the individual areas or zones only. The FCUs are fed with hot or cold water through the major equipment via water pumps, which either reject or absorb the energy. The air is recirculated in the respective enclosed area for conditioning the air. The filtration level in the FCU is of very low grade as the fans used have lower static pressure.

It is important to dilute the air to reduce the viral load in the area fed by FCU and hence, the fresh air is inducted in the conditioned areas with good filtration. While adding fresh filter-conditioned air in the areas, the power consumption will go up to cater to the additional load of fresh air and needs to be accounted for.

Another strategy to control the viral load in such areas with FCU is to have a room air purifier with HEPA filters of adequate capacity to filter any pathogens generated by an infected person. The location of FCU...
also plays an important factor in good air distribution. The other option where windows are openable type, is to partly open windows.

![Figure 17: Conventional Air Distribution System](image)

Source: [13].

Centralized Air-conditioning System with Radiant Cooling and/or Heating System

The CAC system with radiant conditioning is where polymer pipes are installed either in the floor wall or ceilings and the area is conditioned using conduction, convection, and radiation of energy. The pipes carry the hot and cold water and transfer the energy in the conditioned area and is one of the most efficient systems as compared to standard where the conditioning is done using air as conditioning media. The conditioning has two types of thermal loads—one is sensible, and the other is latent load. By radiant system, the majorly sensible thermal load is catered, and the other latent load is catered using a DOAS which brings in the fresh filtered air in the conditioned area. The recirculation in these systems is minimal and we need to ensure enough fresh air to reduce the viral load in the area.

Centralized Air-conditioning System VRF Type with Cooling and/or Heating Units Feeding Individual Areas.

- The CAC system with VRF-type systems is a system where the refrigerant is the medium that absorbs/rejects the heat in the individual units. It is also classified as a large ductless system with a larger capacity for cooling or heating. This system can provide multiple indoor individual cooling and/or heating units for rooms or zones with single outdoor units. The heat transfer from indoor and outdoor units is done by circulating the refrigerant in the insulated pipes. Since these indoor units are either feeding the individual areas or zones, they recirculate within the room or zones. To ensure the air quality is maintained, the filter needs to be checked, cleaned, and replaced if needed. All the surfaces of the unit need to be disinfected. For the indoor unit coils, UVGI may be added. The drain pan needs to be regularly disinfected.
Individual Split Air-conditioning System
These individual split Acs are units that have one indoor unit and one outdoor unit. The heat is rejected and absorbed directly by the refrigerant circulated in the insulated pipes. These units feed an individual area and do not have any option of providing fresh air, it is 100% recirculation units.

To reduce the viral loads in these areas, it is important either to bring in the fresh air or add a room air purifier with a HEPA filter of adequate capacity. The fresh air could be through the opening of any windows along with a small exhaust fan or by installing a treated fresh air unit. This will account for additional power and cost.

4.4 Recommendations for Maintaining Safe Indoor Environment from COVID-19

4.4.1 Offices, Commercial Buildings, Educational Institutes, Malls
These types of buildings normally have conditioning done either using AHUs or fan-coil units, radiant, or VRF technologies for different areas. The following are recommended for safe environments:

- Increase ventilation rates by about six air changes per hour.
- Induction of additional fresh air in occupied areas using good filtrations say minimum efficiency reporting value (MERV) 8
- Addition of good filters in recirculating AHUs. Minimum MERV 13
- Redesign the air distribution systems to make sure the airflow takes the route to enter the filter before being supplied in the conditioned zone.
- In areas where fresh air is not possible, add air purifiers with HEPA filters of adequate capacity. These air purifiers must be added to make the total of a minimum of six air changes per hour in the area.

4.4.2 Nursing Care Facilities
These areas have conditioning done normally using VRF or split air-conditioning system. Different areas in the care facilities have different requirements of conditions to be maintained and quantity of fresh air with positive and negative pressures. In the operation theater and critical areas including those allotted for COVID-19 patients, it is important to have these areas under negative pressure concerning surroundings. Special care must be taken for exhaust from COVID-19 patient rooms as it may contain viruses. The following are recommended for safe environments:

- Increase ventilation rates in all areas.
- Induct additional fresh air in areas using good filtrations.
• Place operating theaters, critical, and COVID-19 patient rooms, under negative pressure, and install HEPA filters only for exhaust.
• Redesign the air distribution systems.
• Add air purifiers with HEPA filters of adequate capacity in areas where fresh air is not possible.

4.5 Operation and Maintenance of Centralized Air-conditioning Systems

Since all the enclosed areas have different usages and may have multiple occupancy and transient visitors, it is important to ensure proper operation and maintenance of various types of CAC systems, as follows:

For Air-Handling Units with Ducts

• Clean and replace filter
• Upgrade filtration level
• Add UVGI for coils
• Disinfect all surfaces of the units
• Disinfect and clean the coil as per the manufacturer's standard
• Disinfect the drain pan
• Clean and disinfect the ducts and grills (supply and return)
• Follow protocols for disposing of the filters while replacing

Fan-Coil Units

• Check and replace filter
• Disinfect all surfaces of the units
• Add UVGI for coils
• Disinfect and clean the coil as per manufacturer's standard
• Disinfect the drain pan

Variable Refrigerant Flow System

• Check and replace filter
• Disinfect all surfaces of the units
• Add UVGI for coils in indoor units
• Disinfect and clean the coil as per manufacturer's standard
• Disinfect the drain pan

Split Aircon
• Check and replace filter
• Disinfect all surfaces of the units
• Disinfect and clean the coil as per the manufacturer's standard
• Disinfect the drain pan

Centralized System

• The high side of the CAC system such as chiller, pumps, cooling towers, pipings, insulations, fans, etc. shall be maintained and serviced as per manufacturer standards.

4.6 Summary

The COVID-19 virus is airborne, with an approximate particle size of 0.1 micrometer. Recirculated air in air-conditioned enclosed spaces plays a vital role in spreading the virus. It remains airborne for a longer time in the air, and it is advised to maintain 2 2-meter distance to avoid its effect. It does not move in air on its own but is trapped in respiratory droplets and droplet nuclei (dried respiratory droplets) that are predominately of size 1 micrometer or larger. It can survive on the surface for a longer time and can get carried away with air.

The importance of good ventilation by dilution of air by outdoor air seems to be the best solution for the enclosed conditioned areas. In the areas, where air-conditioning is not done or used, there may be situations of thermal stress on humans which may do other harm to the body.

There are IAQ standards available at ASHRAE and ISHRAE that mention the calculations of air quantities for outdoor requirements (minimum ventilation rate) and inside air quality best suited for humans. While they do not cover COVID-19, they can be used as reference to as having good air quality in enclosed areas.

A few strategies for maintaining a safe indoor environment from COVID-19 in enclosed areas are as follows:

• Increase ventilation rate – Mechanical or natural. By adding 2 to 4 outdoor air changes per hour.
• Increase filtration level – The filter rating of MERV 13 or above is recommended.
• Temperature – For good and acceptable thermal comfort.
• Humidity - For good and acceptable thermal comfort and to reduce the survival rate of COVID-19.
• Air distribution – Check the flow to reach out to all areas.
• Balancing of air for supply and exhaust for ventilation.
• Monitoring of IAQ to check the outdoor air.

5. Smart Centralized Air-conditioning System
The control system is the brain of the CAC system; and, to have a smart CAC system, a smart CAC control system is needed. In this section, the composition of the control system and control approaches will be introduced, as well as measurements to achieve energy efficiency and disease resilience.

5.1 Introduction

The control system of the CAC system, shown in Figure 18, mainly includes field instruments, local control panels and junction boxes, and a remote-control system. The accuracy of the field instrument can affect the control of the CAC system. To achieve energy efficiency and thermal comfort, suitable field instruments should be selected. The control method of the control system is also important to achieve energy efficiency and thermal comfort. In the following paragraphs, widely used instruments and control system hardware and software will be introduced.

![Diagram of CAC system components](image)

**Figure 18: Typical composition of the CAC system**

Source: Author.

5.1.1 Instrument of Centralized Air-conditioning System

According to system requirements, temperature measurement instruments, pressure measurement instruments, flow measurement instruments, and level measurement instruments are usually used in the CAC system.

5.1.1.1 Temperature Measurement

In the CAC system, temperature gauges and resistance thermometer detectors (RTD) are widely used. RTDs are generally of type Pt 100 and are applied for measuring values below 300 °C. In a typical CAC
system, RTDs are often used to measure the temperature of chilled water in the inlet and outlet of chillers, air temperature in different rooms, AHU outlet air temperature, and AHU inlet air temperature.

Temperature gauges of bimetal thermometers are widely used in CAC systems. It converts the media’s temperature into mechanical displacement using a bimetallic strip. The bimetallic strip consists of two different metals having different coefficients of thermal expansion. In a typical CAC system, a temperature gauge is often used to measure the inlet and outlet temperature of chilled water, AHU outlet air temperature, etc.

5.1.1.2 Pressure Measurement
In the CAC system, pressure gauges and pressure transmitters are widely used. Pressure and differential transmitters are used to measure the pressure and differential pressure or level of industrial liquids and gases. Accurate and stable process measurements ensure the safe, reliable, and profitable operation of the CAC system. In a typical CAC system, pressure and differential transmitters are often used in pressure measurement of the outlet header of the chilled water pump, outlet header of the cooling water pump, differential pressure between the inlet and outlet of filters.

Pressure gauges are among the most common pressure measurement devices worldwide. Mechanical pressure gauges are local indicators without an external power supply. The indication is generated by the elastic deformation of a mechanical sensing element when pressurized. In a typical CAC system, Pressure gauges are often used in the outlet of the chilled water pump and the outlet of the cooling water pump.

5.1.1.3 Relative Humidity Measurement
Relative humidity is a measure of the moisture in the air, compared to the potential saturation level. Warmer air can hold more moisture. With 100% humidity, the air moisture condenses—this is called the dew-point.

Relative humidity is an important parameter in the CAC system and an indicator of thermal comfort. Various sensing methods are used to determine the percentage of relative humidity, including the measurement of changes in resistance, capacitance, impedance, and frequency.

The advantage of humidity sensors is high sensitivity, but the main disadvantage is poor linearity and interchangeability. The measurement accuracy is the most important index of the sensor, the higher the accuracy, the more expensive the price. Usually, the relative humidity sensor is integrated with the temperature sensor.

In a typical CAC system, relative humidity sensors are often used in the following places:

- AHU outlet air humidity
• AHU inlet air humidity

5.1.1.4 Flow Measurement
Water flow and air flow are the two types of flow parameters that are often been measured in the CAC system. The common types of flowmeters in the CAC system are:

• Differential pressure type
• Electromagnetic type
• Ultrasonic.

In a typical CAC system, flow measurement may be used in the flow of returned chilled water and the flow of returned air (usually use differential pressure type flow measurement).

5.1.1.5 Level Measurement
Level measurement is not very often used in the CAC system, mainly the level of the expansion water tank of the cooling water system is measured. Differential pressure type level measurement is often used. Since differential pressure measurement has been described in the previous section, it will not be described here.

5.1.1.6 Carbon Dioxide Measurement
Increasingly efficient building insulation can help mitigate the effects of climate change, but heavily insulated buildings are not always good for human health. Poor ventilation can result in lower oxygen levels and a build-up of carbon dioxide (CO$_2$). Even moderate levels of CO$_2$ can hurt health and productivity. At 1,000 ppm, people begin to experience drowsiness and have difficulty concentrating. Consequently, there is a growing demand for smart IAQ sensors that can “smell” rising levels of CO$_2$ and either alert the user or trigger a system response.

With the COVID-19 pandemic, awareness of IAQ is rising, making accurate, affordable monitoring solutions like the CO$_2$ sensor more important than ever. It has been shown that a correlation exists between the concentration of CO$_2$ and aerosols, one of the transmission pathways of COVID-19. Therefore, if the CO$_2$ level in an indoor space can be reliably measured, the risk of virus transmission can be actively managed.

CO$_2$ sensors can also contribute to achieving energy efficiency, if more people are entering a room, the CO$_2$ level will rise, and the CAC system can open the fresh air dampers to bring more fresh air to the room. When people leave, the CO$_2$ level drops, then the CAC system can close the fresh air dampers.
Widespread adoption of CO₂ sensors has so far been hampered by size, performance, and cost constraints. With the development of technology, small size, accurate, reliable, and real-time CO₂ measurement technology has been invented.

5.1.2 Control System Hardware of Centralized Air-conditioning System

Different manufacturers have different control hardware and software. Usually, in a small and simple CAC system, each chiller or AHU has its controller, and then there is an overall control system for the whole CAC system. For the dedicated controller of each chiller or AHU, a direct digital control (DDC) controller or small-sized programmable logic controller (PLC) is usually used. There are also systems that each chiller, AHU, and pump is only equipped with a local electric control cabinet, the centralized control system finishes all the control. PLCs are usually used as the hardware of the control system.

5.1.2.1 Direct Digital Control Controller

DDC is the control system most deployed today. The sensors and output devices (e.g., actuators, relays) used for electronic control systems are usually the same ones used on microprocessor-based systems.

The DDC loop consists of three main components: a sensor, a controller, and a controlled device. The sensor measures the data, the controller (processor) processes the data, and the controlled device causes an action. Sensors and controlled devices are connected directly to the processor (computer). The controller's function compares its input (from the sensor) instructions, such as setpoint, throttling range, and action, and then produces an output signal. The control logic usually consists of a control response and other logical decisions unique to the specific control application.

The primary element for DDC, shown in Figure 19, is the digital computation unit memory protection unit (MPU) or central processing unit (CPU) in the controller. The basic components are:

1) Microprocessor
2) Memory
3) Input/Output (I/O) Multiplexers
4) Analog-to-Digital (AID) & Digital-to-Analog (D/A) Converters
5) Communications Port
5.1.2.2 Programmable Logic Controller

PLCs are widely used in industrial automation control, especially in sequence control. It is easy to use and has many advantages, such as wide adaptability, high reliability, strong anti-interference ability, simple programming, and so on.

Composition of Programmable Logic Controller

In terms of structure, a PLC is divided into fixed type and combined type (modular type). The fixed PLC includes CPU, I/O, display panel, memory block, power supply, etc. These elements are combined into a non-detachable whole. Modular PLC includes CPU module, I/O module, memory, power supply module, backplane, or rack. These modules can be combined and configured according to certain rules.

Composition of the Central Processing Unit

CPU is the core of PLC. CPU is mainly composed of an arithmetic unit, controller, register and the data bus, control bus, and status bus. CPU unit also includes a peripheral chip, bus interface, and related circuits. The CPU controller controls the CPU to read, interpret, and execute instructions. CPU speed and memory capacity are important parameters of PLC. They determine the working speed, IO number, and software capacity of PLC.

Input/Output

The interface between the PLC and the electric circuit is completed by the I/O module. I/O modules have different types, such as digital input, digital output, analog input, analog output, and other modules.

Power Supply Module

PLC power supply is used to provide power for the integrated circuits of PLC modules. At the same time, some also provide a 24 V power supply for the input circuit. Power supply modules can provide AC power supply (220 VAC or 110 VAC) or, DC power supply (commonly used for 24 VDC).
Base Plate or Frame Rack

Most modular PLC uses the base plate or frame rack, it connects all the modules installed in the base plate or frame racks so that the CPU can access all the modules on the base plate.

Human Machine Interface

The simplest human–machine interface is the indicator light and button. At present, the LCD (or touch screen) integrated operator terminal is more and more widely used, and the computer (operation configuration software) is very popular as the man–machine interface.

Programmable Logic Controller Communication Network

![Figure 20: Typical Programmable Logic Controller Composition](image)

Source: Author.

The operation and management data can be collected and transmitted quickly and effectively depending on the advanced industrial network technology. The communication networking function of PLC, as shown in Figure 20, enables the exchange of information between PLC and PLC, between PLC and computer and other intelligent devices. Most PLCs have RS-232 and RS-485 interfaces, and some have built-in interfaces supporting their communication protocols. At present, PLC communication mainly uses data communication through MODBUS, PROFIBUS, or industrial Ethernet for networking.

5.1.2.3 Difference between Direct Digital Controller and Programmable Logic Controller

1) Scalability
DDCs are usually used for small system control. When the model is chosen, the calculation capacity and storage capacity of DDC are fixed and cannot be expanded. Usually, the I/O module of DDC can be expanded to 128 I/O points.

PLCs are usually used for large system control. For PLCs, the storage capacity and I/O module can easily be expanded. I/O modules of large-size PLCs can be expanded to more than 2,000 points.

2) Flexibility

The software or control logic of DDC is usually dedicated and solidified. DDC usually has many control algorithms or functions integrated into the controller. The built-in algorithms or functions include strictly tested PID algorithm, peak load control, optimized start and stop control, optimized equipment scheduling, energy-saving cycle control, various air-conditioning operation modes, holiday schedule, basic calendar schedule, and event schedule, trend recording and reporting functions, etc. With built-in logic blocks (especially the PID blocks) it is much easier to develop the program.

The control logic of PLC for the CAC system needs to be configured by using configuration software, such as IFIX, WINCC, INTOUCH, etc.

PLC is more flexible because it can be configured as per system requirement and need a more professional engineer to do the configuration. While DDC is easier to configure the flexibility is also limited.

2) Reliability

In the DDC system, usually, the extension modules are directly connected to controllers, and there is no redundancy in the DDC controllers, so if the controller fails, the system controlled by this controller will be affected.

In PLCs, the controller and communication bus can offer redundancy configurable. If one of the controllers or the communication bus fails, the other controller or communication bus can work, and it will not affect the operation of the system.

The redundancy configuration of PLCs will increase the reliability of the system but will also increase the cost of the system. When we make choices, we need to keep a balance between them.

4) Application area

Due to the easy configuration, small size, and cheaper price, DDCs are usually applied in residential and commercial building CAC systems while PLC is often used in industrial building CAC systems. It can provide a more reliable and flexible system. PLCs also have a shorter scan time that ensures accurate control, which is important for some industrial factories and laboratories.
5.1.3 Control Approaches to CAC System
CAC systems are nonlinear, and complex and, are multiple-input multiple-output (MIMO) devices with coupled parameters.

Different control approaches are implemented in the CAC system. They could be categorized as traditional, advanced, and intelligent controllers.

5.1.3.1 Traditional or Classical Control Category
Traditional control methods are divided into two subgroups: On/Off control methods and proportional, integral, and derivative (PID) control modes. The conventional control methods are used due to their low initial cost and their simple structure.

1. On/Off Control
The on/off control mode could be only maximum or zero. Due to the simplicity of this method, it is not too accurate.

A) Simple On-Off Control
The response of a simple on-off controller, shown in Figure 21, can be summarized in the following image. When the error is positive, the controller is switched ON. When the error is zero or negative, the controller output is set to OFF.

![Figure 21: On-Off Control Output](image)

Source: Author.

B) On-Off Control with Hysteresis
In the on-off control mode, the controller frequently switches the output from ON to OFF around the setpoint value. With high frequency around the setpoint, constant switching can lead to stress on the
actuators and potential failure. For this reason, most of the on-off controllers have an integrated hysteresis.

The on-off controller with hysteresis will not switch around the setpoint but between an upper and a lower limit. This way, the frequency of the switching will decrease but the variation (overshoot) around the setpoint will increase.

![Figure 22: Output of On-Off Controller with Hysteresis](source: Author)

The error is not anymore compared against zero but against a hysteresis value. The higher the hysteresis value, the lower the switching frequency and the higher the overshoot.

### C) On-Off Control with Deadband

The controller switching frequency has decreased, but the temperature variation (overshoot) around the setpoint has increased. In practice, the hysteresis is set for a particular application to get the best compromise between switching frequency and overshoot.

Instead of a hysteresis, an on-off controller can also have a dead band. The dead band (DB) represents the lower and upper limits of the error between which the controller does not react. In this case, the controller will have three states.
Figure 23: Output of On-Off Controller with Deadband

DB = Deadbead, BWD = Backward, FWD = Forward

Source: Author.

In the CAC control system, an on-off controller can be used in some simple control loops.

2. Proportional, Integral, and Derivative Control

PID control is the most widely used control method in industrial control. PID controller has been in use for nearly 70 years. It is widely used because of its simple structure, good stability, reliable operation, and convenient adjustment. When the structure and parameters of the controlled object cannot be fully mastered, or the accurate mathematical model cannot be obtained, and it is difficult to adopt other technologies of control theory, the structure and parameters of the system controller must be determined by experience and on-site debugging. Currently, the application of PID control technology is the most convenient. PID technology is most suitable when a system and the controlled object cannot be fully understood, or the system parameters cannot be obtained through effective measurement means.

PID control has been a dominant field in CAC control systems, but due to the linearity of PID controllers, using them in nonlinear CAC systems will make the performance variable.

5.1.3.2 Advanced Control Category

Due to nonlinear and complex character, some advanced control approaches have been used in the control of CAC systems, such as fuzzy logic control and artificial neural network control.

1. Fuzzy Logic Control
A fuzzy control system is a control system based on fuzzy logic—a mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0.

Although alternative approaches such as genetic algorithms and neural networks can perform just as well as fuzzy logic in many cases, fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller.

The fuzzy control system has the following characteristics:

a) A fuzzy control system does not depend on the accurate mathematical model of the system, especially suitable for complex systems (or processes) and fuzzy objects, because their accurate mathematical models are difficult to obtain or cannot be found at all.

b) The knowledge representation, fuzzy rules, and synthetic reasoning in fuzzy control are based on expert knowledge or the mature experience of skilled operators and can be continuously updated through learning. Therefore, it has the characteristics of intelligence and self-learning.

c) The man-machine interface of the fuzzy control system is easy to master and learn for the staff who have certain operation experience but are not familiar with the control theory, and it is easy to use "natural language" for human–machine dialogue, to provide better control information for the operator.

According to the CAC system character, thermal comfort is people's experience, it does not have accurate definitions.

2. Artificial Neural Network Control

An artificial neural network (ANN) is a computing system designed to simulate how the human brain analyzes and processes information. It is the foundation of artificial intelligence (AI) and solves problems that would prove impossible or difficult by human or statistical standards. ANNs have self-learning capabilities that enable them to produce better results as more data becomes available.

ANNs have emerged as a powerful learning technique for performing complex tasks in highly nonlinear dynamic environments. Some of the prime advantages of using ANN models are their ability to learn based on optimizing an appropriate error function and their excellent performance for approximation of nonlinear functions.

5.1.3.3 Typical Control Loop in Central Air-conditioning Systems

1. Single-Loop Closed-Loop Control Diagram
In a typical control system, the process will be disturbed by outside factors, and make the controlled variable deviate from the set point, the control system will according to the error between the actual value and set point of the controlled variable, adjust the output of the actuator to make the controlled value back to the set point.

Figure 24 shows a single-loop control system of an air-conditioning system.

![Figure 24: Single-loop Closed-Loop Control Diagram](image)

Source: Author.

2. Multi-Loop Closed-Loop Control Diagram

Complicated processes usually cannot be fulfilled by single-loop control systems. In this situation, a multi-loop control system will be applied. In the CAC system's control, cascade control is widely used, which is a kind of multi-loop control.

In a cascade control system, there are two closed loops, one is the inner loop, one is the outer loop, or the main loop. The main loop will finally ensure the variable fulfills the process requirement.

Figure 25 is a typical diagram of the cascade control system in a VAV CAC system.

![Figure 25: Cascade Control system Diagram](image)

Source: Author.
5.1.4 Control Strategies that are Frequently Used in Centralized Air-conditioning Control Systems

Control system is important in a CAC system, as it can help the system to achieve the required thermal comfort. Through some control strategies, the control system can assist the CAC system in achieving energy efficiency and operation automation.

5.1.4.1 Control Strategies to Achieve Energy Efficiency

To achieve thermal comfort and energy savings, many measures are used, ranging from the mechanical aspect to the control aspect, and the operation mode and maintenance. Usually, the control system will, according to the mechanical requirement, control the whole CAC system to work as required.

Following are some strategies that the control system also takes part in to achieve energy efficiency.

1. Variable Frequency Drive Technology

The main energy-consuming equipment in the CAC system are the pumps, fans, and compressors. Usually, the CAC system is designed to run at the maximum load but during the operation under different environmental conditions from the design condition, the actual load is different from the design load. Under this situation, if variable frequency drive (VFD) technology is not applied, the pumps and fans will run at the rated speed, CAC system will use valves or dampers to control the flow of the water and air, which will cause a waste of energy.

If VFD technology is used, the system can control the pumps, fans, and compressors at the required speed. The water and air supply flow is controlled by changing the speed of the motor. At low demand, pumps and fans run slowly and the power consumption decreases which will increase efficiency.

VFD technology can be applied to different equipment of the CAC system, such as the water pumps, cooling tower fans, blowers in AHU, and compressors in chillers. The control system will balance the operation of all the components in real-time to make sure that the power consumption is minimized at the total system level.

Variable air ventilation control is a sample of VFD technology. As people pay more attention to the requirements of air quality, variable air ventilation systems are applied in many CAC systems of office buildings and hotels.

The control system will according to the requirement of the room, through control of the airflow to control the air temperature of the room. The airflow will be controlled by adjusting the speed of the blower through VFD.

2. Temperature Setpoint Reset
Setpoint reset can be applied in air temperature control and chilled water temperature control.

Supply air temperature reset is a control scheme that allows an airside system to modulate the supply air temperature based on outside air temperature, worst-case room demand, or a combination of the two. When enabled, the temperature of supply air is increased, allowing for reduced compressor energy or reheat energy and increasing fan energy in a variable air ventilation system.

When the supply air temperature reset is based on the outside air temperature, the supply air temperature can be increased as the outside air temperature decreases, resulting in an energy-efficiency increase. Supply air temperature reset can also be based on the worst-case space load demands. If the worst-case space does not require conditioned air at the design supply air temperature, the temperature can be reset upward. According to different project data, by increasing the room temperature setpoint 1°C or decreasing the room temperature setpoint 1°C, energy consumption can be reduced by around 5%~8%.

A chilled water supply temperature reset can also be applied to achieve energy savings. Increasing the chilled water supply temperature has a significant impact on chiller compressor power consumption. This reduction is consistent for water-cooled chillers independent of chiller size and configuration. With the major chiller manufacturers implementing the latest chiller technology, including falling film evaporators, by decreasing the chilled water supply temperature by 1°C, the COP of the chiller can be increased by around 3.5%~4.5%.

3. Demand Controlled Ventilation

Fresh air energy consumption accounts for a large part of the total building energy consumption. If certain measures can be taken to eliminate excessive fresh air volume, the air-conditioning system will greatly save energy. Demand control ventilation (DCV) is a ventilation strategy to achieve energy efficiency. DCV is a real-time ventilation mode based on the occupant density of the space. It has great energy-saving potential compared with the traditional constant air volume ventilation system.

In DCV mode, according to the change in occupant density of the space, the volume of fresh air can be adjusted accordingly, so that the fresh air volume can always adapt to the occupant density, which not only ensures the IAQ but also prevents excessive ventilation and saves energy consumption.

In the actual operation, it is difficult to directly monitor the occupant density, and because of the uneven spatial distribution of occupants, even if the number of indoor personnel can be detected, it may not represent the IAQ level of a space. Research finds that CO₂ is directly related to the number of occupants, is easy to detect, and can reflect the concentration of space pollutants to a certain extent. Therefore, the
control of IAQ of underground buildings and other buildings like malls, is mostly realized by controlling the fresh air volume by CO₂ concentration, that is DCV based on CO₂.

![Comparison between conventional and DCV](image)

**Figure 26: Comparison between conventional and DCV**

Source: [14].

Figure 26 above illustrates the differences between regular time-controlled fixed-volume ventilation and DCV. The blue bars show the occupation level of a space such as an office over a day, while the orange line shows how regular time-controlled ventilation works. In this case, ventilation is time-controlled between 7 a.m. and 6 p.m. to save energy by not ventilating at night. The gray line illustrates how DCV works with CO₂ measurement. The CO₂ concentration in a room is measured with sensors and the amount of fresh air is controlled to maintain the concentration at the desired level. The amount of fresh air or ventilation varies according to the building’s occupancy level.

### 5.1.4.2 Control Strategies to Achieve Operation Automation

A well-designed control system can also help to achieve operation automation. The automatic control system can reduce the feasibility of operator misoperation, protect the system and equipment, and improve the reliability of the system.

Following are some frequently used control sequences in the CAC system.

**1. Control Sequence of Air-Handling Unit in the Variable Air Ventilation System**

Start sequence: open the fresh air valve → start the return air valve → start the supply air fan → open the exhaust air valve → start the return air fan → open the chilled water or hot water regulating valve → open the humidification valve (start the humidifier).
Shutdown sequence: close humidification valve (humidifier shutdown) → close chilled water or hot water regulating valve → stop return air fan → close exhaust air damper → stop supply air fan → close fresh air valve, close exhaust air damper, stop return air damper.

2. Control Sequence of Water-Cooled Chiller

Startup sequence: start cooling tower fan → start cooling water pump → start chilled water pump → start chiller.

Stop sequence: Stop chiller → (delay 5 minutes) → stop chilled water pump → stop cooling water pump → stop cooling tower fan.

5.1.5 Emerging Technology that Can Improve the Control and Operation of CAC System

5.1.5.1 Internet of Things in Centralized Air-conditioning Systems

With the development of Internet of Things (IoT) technology, all the equipment can be connected. IoT technology can be also applied in CAC systems. Many HVAC vendors are also keen on applying IoT technology in their systems.

Well-designed IoT system provides better controls and lead to reduce energy consumption of CAC systems. By integrating smart devices with motion sensors or CO₂ sensors into the CAC system, occupancy within a building can be continuously monitored. When no movement is detected or the CO₂ level is low for a prolonged period, the system can suggest, though an app notification, to turn heating (or cooling) down to lower the power consumption. The controls can also employ the latest networking and AI technologies and are thus capable of learning the occupants’ preferences and adjust to their comfort needs automatically over time.

Third-party data sources, such as weather feeds, can be incorporated as well. The system, expecting a rapid temperature surge, can start gradually cooling the building down to sustain the occupants’ comfort. It can prepare for the future in the most energy-efficient way.

A typical IoT-enabled CAC infrastructure includes actuators, various sensors, a gateway that connects the local network to the cloud where system managers can inspect the data from the sensors and draw insights from it; and embedded devices, such as mobile phones or tablets that allow users to access and manage their CAC appliances remotely.
5.1.5.2 Integration of Centralized Air-conditioning Control System and Building Management System

Nowadays, many buildings are equipped with a Building Management System (BMS) that can integrate all the systems in the building to achieve energy efficiency. For example, a BMS of a mall can control the operation of the CAC system according to the occupant’s data that it gets from the access control and monitoring system.

Some of the buildings may be equipped with solar panels to generate electricity. With the CAC control system integrated with the BMS, the operator can do the energy management accordingly. When the solar system can provide electricity, the system can change the power supply of the CAC system to the solar energy system.

5.2 Operation Model of a Smart Centralized Air-conditioning System

In building a disease-resilient and energy-efficient CAC system, the control system plays an important role. Balance between disease resilience and energy efficiency must be kept. After COVID-19, people realized that the CAC system needs to be adjusted for different situations. With a smart control system, the operation mode can be easily set and changed according to the situation.

The operation of the control system can be divided into three scenarios: epidemic, post-epidemic, and normal. In the epidemic scenario, disease resilience will be the most important to consider—the fresh air volume or percentage needs to be more than normal mode, if possible 100% fresh air operation will be implemented. During the pandemic, some companies may implement work-from-home arrangements. Under this situation, the fresh air volume can be optimized according to the occupation level of the space. Return air usage which can contribute to energy efficiency will be not used. The UVGI or other sanitized measures can be operated automatically to achieve disease resiliency.

In a normal scenario, energy efficiency will be the first consideration and fresh air volume will be adjusted according to the occupation level to satisfy the minimum air quality requirement. And other energy-efficiency measures will be adopted in normal mode operation.

In a post-epidemic scenario, some areas are safe, with no confirmed cases. The CAC system can be operated the same as in normal situations. If a confirmed case is found in the buildings or the building has been visited by confirmed or suspicious cases, the operation of the CAC system should be changed to the epidemic mode.
5.3 Summary

The basic requirement of a CAC system is to achieve thermal comfort and save energy. During the spread of COVID-19, another requirement has been raised, which is to constrain the spread of disease through the CAC system.

Sometimes thermal comfort and disease-resilient may conflict with the requirement of energy saving. In this case, choices need to be made in keeping a balance between different requirements.

The instrument and control system of the CAC system is to maintain the operation of the CAC system to achieve the requirements mentioned earlier.

A conclusion of the instrument and control system of the CAC system can be made as follows:

1) Instruments are the “eyes” of the CAC system. Accurate and reliable instruments are the basis of the control of the CAC system.
2) Different control approaches have been used in the CAC system. On-off control and PID control are widely used in the control of the CAC system. These are traditional control approaches. They have their advantages, but due to the character of the CAC system, these control approaches have their disadvantages also.
3) By considering all the mentioned features, a control scenario based on soft computing methods should be required which can cover the interlinear and MIMO characteristics of the system in a simple algorithm without involving the linearization of the system and difficult mathematics and analysis for finding the control law. As a result, the combination of neural network and fuzzy logic methods as a unique fuzzy-graph structure network based on the system’s tendencies and goals could be a suitable solution in this area.
4) Together with the information technology, the control system of the CAC system will be smart.

6. Refrigerant Management in Centralized Air-conditioning System

6.1 Introduction

Refrigerants can be defined as fluids used for heat transfer medium in air-conditioning and refrigeration systems. A refrigerant utilizes the latent heat to vaporize to carry heat from one zone and transfer it to outdoors or a different zone. Refrigerants absorb heat at low temperatures and low pressure and release
heat at a higher temperature and pressure. Refrigerants go through evaporation, condensation, compression, and expansion in the refrigeration cycle and, during these processes, they change their phase from liquid to gas and gas to liquid continuously.

Over the years, air-conditioners have helped improve people’s comfort, health, and quality of life worldwide. With an increase in population and growing economies, the demand for air-conditioning will increase globally. The global air conditioner stock is expected to increase from 660 million units in 2015 to more than 1.5 billion units by 2030, significantly increasing CO$_2$ emissions from this sector. In 2015 air-conditioners installed in 150 developing countries were responsible for 640 million tons of carbon dioxide equivalent (CO$_{2e}$) emissions [15].

Apart from the energy impacts, refrigerants used in air-conditioners require special attention as they can be hazardous to the environment. The risk of leakage of refrigerants during operation, maintenance, and installation processes can lead to significant damage to the ozone layer. One chlorine atom used in chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants can destroy 100,000 ozone molecules. Owing to their ozone-depleting potential, they are scheduled to be phased out by 2030 under the Montreal Protocol. Due to this, demand for non-ozone-depleting hydrofluorocarbons (HFCs) increases by 10%–15% per year, which has high global warming potential. Avoiding the use and production of HFCs and alternative low-GWP technology could avoid 0.5°C warming of the earth by the end of the century [16].

This study will cover the overview of refrigerants from their history, type, and properties. It will also cover the environmental impacts and international protocols and methods of life-cycle assessment of refrigerants for CAC systems.

6.1.1 History
The history of refrigerants goes back to 1830 as shown in Figure 27. With the discovery of vapor-compression air-conditioners, refrigerants were used as a heat transfer medium in the vapor-compression cycle. Naturally available fluids like ammonia, water, CO$_2$, sulfur dioxide, ethers, hydrocarbons, and air were used as refrigerants. Due to the toxicity and flammability of natural refrigerants, in 1930, synthetic refrigerant CFCs were invented and began to be used globally. In 1950 another synthetic refrigerant HCFCs was developed, which were partially chlorinated.

The harmful effect of CFC and HCFC on the ozone layer was identified in 1970, CFC has a higher ozone-depleting potential (ODP) than HCFC, but both refrigerants can cause significant damage to the environment. Therefore, the Montreal Protocol—the global phase-down mechanism on substances that deplete the ozone layer—was established in 1987. This protocol aimed to phase down the use and
production of harmful chemicals to ozone layers in developed and developing countries. CFCs have been phased out under this protocol, and HCFCs are scheduled to be entirely phased out by 2030.

HFCs were developed as an alternative to CFCs and HCFCs as they have negligible or zero ODP, but they have higher global warming potential (GWP) 4,000 times higher than CO₂. Overall, HFC emissions are growing at 8% per year, and annual emissions are projected to rise to 7%–19% of global CO₂ emissions by 2050 (About the Montreal Protocol, UNEP 2014). Therefore, uncontrolled growth in HFC emissions challenges efforts to keep global temperature rise at or below 2°C this century. Efforts have been made to control the use of HFCs; in October 2016, the Parties to the Montreal Protocol adopted the Kigali Amendment. HFCs were added to the list of controlled substances and approved a timeline for their gradual reduction by 80%–85% by late 2040 [17].

![Figure 27: History of refrigerants.](image)

EU=Europe

Source: [18].

6.1.2 Type of Refrigerants

Based on the working principles, refrigerants can be classified into two categories: primary and secondary.

1. **Primary refrigerants.** Primary refrigerants go through all the processes of the refrigeration cycle and are used as a heat transfer medium. They transfer heat by utilizing the latent heat of vaporization. Examples are CFC, HCFC, HFC.
2. **Secondary refrigerants**. Secondary refrigerants do not take part in the refrigeration cycle directly. They do not go under the phase change like primary refrigerants; they are used as a storage medium to transfer energy from one place to another. They are also popularly known as brines or antifreeze. Water is an example.

**Classification Of Refrigerants**

**Hydrocarbons and inorganics**
This class of refrigerants includes ammonia, CO₂, water, and hydrocarbons; they are often known as “natural refrigerants” with zero ODP, low-GWP, and low toxicity. These refrigerants are not suitable for small cooling applications. The refrigerants of this class are ethane, propane, butane, and isobutene. The drawback of these refrigerants is their high flammability which makes them unsuitable for use in refrigeration systems.

**Halocarbons**
They are organic compounds consisting of compounds of carbon and fluorine and halogen compounds, primarily chlorine or hydrogen. They are responsible for the destruction of the ozone layer and contribute to the increase in the greenhouse effect.

**Chlorofluorocarbons**
In 1928, freon was developed to substitute for toxic natural refrigerants by Thomas Midgley in cooperation with Albert Leon Henne and Robert Reed McNary. They are molecules composed of carbon, chlorine, and fluorine. CFCs are colorless, odorless, nonflammable, non-corrosive gases, or liquids. Owing to the above properties, it reduced the risk of the leakage of refrigerants and within a few years became standard refrigerant used in almost every domestic application. CFCs are stable fluids. They can easily reach the stratosphere and destroy the ozone layer.

**Hydrochlorofluorocarbon**
In 1973, Prof. James Lovelock reported finding trace amounts of refrigerant gases in the atmosphere, and in 1974, Sherwood Rowland and Mario Molina predicted that CFC refrigerant gases would reach the high stratosphere and cause damage to the ozone layer. HCFCs were developed as synthetic compounds containing hydrogen, chlorine, fluorine, and carbon. HCFC production increased significantly after countries agreed to phase out CFCs in the 1990s, although they have been used for more than 60 years. HCFCs have a much lower ODP than CFCs, but they have a relatively high-GWP, albeit generally lower than CFCs.

**Hydrofluoro olefin**
These are unsaturated organic molecules having carbon, hydrogen, and fluorine. They are unstable molecules with low-GWP and a short atmospheric lifetime due to double bonds. Hydrofluoro olefins (HFOs) differ from traditional HFCs by being derivatives of alkenes rather than alkanes. There are two types of refrigerants in this class: HFO-1234yf (2,3,3,3-tetrafluoropropene) and HFO-1234ze (trans 1,3,3,3-tetrafluoropropene) HFOs, HFO-1234yf and HFO-1234ze are now considered as the most promising fourth-generation refrigerants

**Mixture of Refrigerants**

**Azeotropic Refrigerants**
These are stable mixtures of two or several refrigerants whose composition does not change from liquid to vapor. An azeotropic blend is a mixture of two or more refrigerants in such a ratio that it forms a vapor with the same concentration as the solution and distills without a change in concentration.

**Zeotropic Refrigerants**
A zeotropic mixture is one whose composition in the liquid phase differs from that in a vapor phase. Zeotropic refrigerants, therefore, do not boil at constant temperatures, unlike azeotropic refrigerants. Refrigerants blended in zeotropic blends do not boil at the same temperature, so during the phase transfer process, one of the more refrigerant blends will transfer to another phase than the rest. This will change the composition of the blend and cause the boiling point temperature to shift as well. The overall shift of temperature from one side of the heat exchanger to the other is called the temperature glide. A single pressure-temperature relationship cannot define zeotropic blends. The temperature glide will cause different values for the temperature at a given pressure, depending on how much refrigerant are liquid and vapor.

**6.1.3 Introduction of Hydrofluorocarbon**
The harmful effects of CFC and HCFC on the ozone layer were realized by 1980. This has led to the requirement to completely phase out all ozone-depleting substances, which led to the development of other non-ozone-depleting refrigerants, particularly hydrofluorocarbons (HFCs). They are organic compounds with molecules of carbon, hydrogen, and fluorine. HFCs are manufactured refrigerants and are produced synthetically. They are relatively nonflammable, chemically stable, and nonreactive gases. Most of them are colorless and odorless. Once they are released into the atmosphere, they decompose faster than CFCs, and they are broken down in the troposphere by the reaction with hydroxyl (OH). Within the atmosphere, the carbon-fluorine bond are HFCs that trap the solar radiation, especially infrared, and redirect that radiant energy to the earth's surface. This is called the positive radiative forcing effect, which is responsible for global warming.

After the Montreal Protocol, they have been widely used worldwide as an alternative to CFCs and HCFCs. HFCs have zero ozone depletion potential, but they are potent greenhouse gases, and they can be 3,000
to 4,000 times more damaging to the environment than CO₂. This was added to the list of controlled substances in the Kigali Amendment of the Montreal Protocol to control the use of HFCs. The countries under this amendment have committed to cutting HFC production and consumption by more than 80% by 2040 to avoid more than 70 billion metric tons of CO₂ equivalent emission by 2050 [19].

### 6.1.4 Types of Hydrofluorocarbons

#### Single-component Hydrofluorocarbon Refrigerants

HFC-134a has evolved globally available and can be used for refrigerating at around 4°C in commercial refrigeration. HFC-134a is suitable for high ambient temperatures, operates at pressures similar to CFC-12, and is compatible with most materials in CFC-12 systems. Since 1993 it has been used widely to replace CFC-11 and CFC-12 for low to medium-pressure applications in centrifugal and screw-type chillers. Equipment that uses HFC-134a has similar energy consumption as HCFC-22 equipment, while greenhouse gas (GHG) emission is less because of lower GWP, lower pressures, and lower risk of pressure oscillations in the tubing. However, different HFC-134a dryers are required, and other minor system changes may be necessary.

#### Hydrofluorocarbon Blends

Several HFC blends have emerged as replacements for HCFC-22 in air-conditioning applications. HFC blends are zeotropic or azeotropic compositions of HFC-32, HFC-125, and HFC-134a and many more. The two most widely used HFC blends are R-410A and R-407C.

### 6.2 Climate Impact of Refrigerants

#### 6.2.1 Ozone-Depleting Potential

Ninety percent of ozone exists in the stratosphere. When an oxygen molecule is broken into a single oxygen atom by the ultraviolet (UV) rays, it combines with another oxygen molecule, and ozone O₃ is formed. Ozone is essential to life on earth. It absorbs the most harmful UV-B radiation from the sun and filters out lethal UV-C radiation.

The ozone-depleting potential is a relative measure and describes how harmful a substance is relative to one of the most used ozone-depleting substances when the Montreal Protocol came into being. This benchmark chemical is chlorofluorocarbon, CFC-11, assigned an ODP of 1.0. The ozone-depleting potentials of all other chemicals are assessed in terms of ozone destruction compared to the same unit mass of CFC-11.

CFCs are stable compounds and can reach the stratosphere without many problems. The UV radiation breaks down the CFC compound, and the free chlorine atom gets separated from the parent compound. The detailed chemical reaction is presented in the equation:
The free chlorine atom again takes part in the reaction with another ozone molecule. One chlorine atom separated could destroy 100,000 ozone molecules.

6.2.2 Global Warming Potential

Ozone depletion is not interchangeable with global warming or climate change issues. These are two separate issues. The earth is surrounded by a thin layer of gases that forms the atmosphere. The atmosphere regulates the earth's temperature by trapping some of the heat that radiates from the sun but allowing most of it to radiate back into space. The composition of the atmosphere has changed over geological time but at a prolonged rate. Global warming can be defined as the increase in earth's temperature observed since the pre-industrialization period (between 1850 to 1900) due to human activity, mainly because of burning fossil fuels which have increased the amount of heat-trapping greenhouse gases. Since the pre-industrial period, human activities are estimated to have increased the earth's global average temperature by about 1°C, a number that is currently increasing by 0.2°C per decade [20].

The impact of greenhouse gas emissions is assessed by comparing different compounds' GWPs. The GWP index is a relative measure like the ozone-depleting potential, using carbon dioxide as the benchmark. CO₂ has been assigned a GWP of 1. Another factor in comparing the impact of different greenhouse gases is that they break up in the atmosphere at different rates. ODP and GWP values of some of the most used refrigerants are presented in Table 5.

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>ODP</th>
<th>GWP</th>
<th>Atmospheric lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>0</td>
<td>&lt;1</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>&lt;1</td>
<td>-</td>
</tr>
<tr>
<td>CO₂</td>
<td>0</td>
<td>1</td>
<td>&gt;50</td>
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<td>CFC-11</td>
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<td>5160</td>
<td>52.0</td>
</tr>
<tr>
<td>Refrigerant</td>
<td>GWP</td>
<td>ODP</td>
<td>2010 ppmv</td>
</tr>
<tr>
<td>------------</td>
<td>-----</td>
<td>-----</td>
<td>------------</td>
</tr>
<tr>
<td>CFC-12</td>
<td>0.82</td>
<td>10300</td>
<td>102.0</td>
</tr>
<tr>
<td>HCFC-22</td>
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</tr>
<tr>
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</tr>
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</tr>
<tr>
<td>R-410A</td>
<td>0</td>
<td>2100</td>
<td>-</td>
</tr>
<tr>
<td>HFO-1234yf</td>
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<tr>
<td>HC-600a</td>
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<tr>
<td>HC-290</td>
<td>0</td>
<td>20</td>
<td>0.034</td>
</tr>
</tbody>
</table>

R=Refrigerant

Source: [21].

6.3 Phasing Out of Refrigerants

6.3.1 Montreal Protocol

In 1985, scientists discovered a hole in the stratospheric ozone layer above the Antarctic. This discovery raised concerns among the international scientific community. The ozone layer over the Antarctic was weakening, and in 2003, the size of the hole in the ozone layer was around 28 million square kilometers. A treaty was formalized called the Vienna Convention on 22 March 1985.

The Montreal Protocol was signed by 24 countries and by the European Economic Community to control the substances that deplete the ozone layer. It came into force in 1989. It is the only United Nations (UN) treaty that all the countries globally have signed (all 198 UN nations). The Montreal Protocol sets a progressive target for developed and developing countries to phase out ozone-depleting substances. It includes the 96 ozone-depleting chemicals in thousands of applications across more than 240 industrial sectors.

However, the Parties to the Montreal Protocol recognized the difficulties faced by developing countries regarding the cost of phaseout and the availability of suitable alternative technologies. To tackle these difficulties, the Multilateral Fund was established in London’s Second Meeting of the Parties in 1990. The
Multilateral Fund (MLF) started operating in 1991, its main objective being to assist developing country Parties to comply with the control measures set out in the protocol. The criteria for assessing a country’s technical and financial assistance eligibility are set out in Article 5 of the Montreal Protocol. Developing countries whose annual per capita consumption and production of ozone-depleting substances (ODS) is less than 0.3 kilograms (kg) are deemed eligible for assistance [22]. Currently, 147 of the 191 Parties to the Montreal Protocol meet these criteria. They are referred to as Article 5 countries. Contributions to the MLF from industrialized countries, or non-Article 5 countries, are assessed according to the UN scale of assessment [22].

6.3.2 Kigali Amendment
Phasing out of CFCs and HCFCs under the Montreal Protocol led to another group of substances, HFCs. After the Montreal Protocol, they have been widely used worldwide as an alternative to CFCs and HCFCs. HFCs have zero ozone depletion potential, but they are potent greenhouse gases with GWP ranging from 12 to 14,800.

Replacing high-GWP HFCs with low-GWP alternatives could avoid 0.1°C of warming by 2050 [23]. HFC emissions are growing at a rate of 8% per year, and annual emissions are projected to rise to 7%–19% of global CO₂ emissions by 2050 [21]. Therefore, uncontrolled growth in HFC emissions challenges efforts to keep global temperature rise at or below 2°C this century.

The Parties to the Montreal Protocol reached an agreement shown in Table 6 at their 28th Meeting of the Parties on 15 October 2016, in Kigali, Rwanda, to phase down HFCs. It was added to the list of controlled substances in the Kigali Amendment of the Montreal Protocol to control the use of HFCs. The countries under this amendment have committed to cutting HFC production and consumption by more than 80% by 2040 to avoid more than 70 billion metric tons of CO₂ equivalent emissions by 2050.

<table>
<thead>
<tr>
<th>Ozone-depleting substances</th>
<th>Developed countries</th>
<th>Developing countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorofluorocarbons (CFCs)</td>
<td>Phased out end of 1995</td>
<td>Phased out end of 2010</td>
</tr>
<tr>
<td>Halons</td>
<td>Phased out end of 1993</td>
<td>Phased out end of 2010</td>
</tr>
<tr>
<td>CCl₄ (Carbon tetrachloride)</td>
<td>Phased out end of 1995</td>
<td>Phased out end of 2010</td>
</tr>
<tr>
<td>CH₃CCl₃ (Methyl chloroform)</td>
<td>Phased out end of 1995</td>
<td>Phased out end of 2015</td>
</tr>
<tr>
<td>Hydrochlorofluorocarbons (HCFCs)</td>
<td>Freeze from the beginning of 1996 35% reduction by 2004 75% reduction by 2010</td>
<td>Freeze in 2013 at a base level calculated as the average of 2009 and 2010 consumption levels</td>
</tr>
<tr>
<td>Hydrobromofluorocarbons (HBFCs)</td>
<td>90% reduction by 2015</td>
<td>Total phase out by 2020</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-----------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Phased out end of 1995</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|-----------------------------------------------|-----------------------------------|-----------------------|-----------------------|-----------------------|------------------------|-----------------------------------------------|-----------------------|------------------------|

<table>
<thead>
<tr>
<th>Hydrofluorocarbons (HFCs)</th>
<th>10% reduction by 2019</th>
<th>30% reduction by 2024</th>
<th>70% reduction by 2029</th>
<th>80% reduction by 2034</th>
<th>85% reduction by 2036</th>
<th>Freeze in 2024</th>
<th>10% reduction by 2029</th>
<th>30% reduction by 2035</th>
<th>50% reduction by 2040</th>
<th>80% reduction by 2045</th>
</tr>
</thead>
</table>

Source: [24].

6.3.3 Kyoto Protocol

Global warming due to the greenhouse effect has become a major environmental issue. The Intergovernmental Panel on Climate Change (IPCC) agrees that global warming is primarily due to human activity, which has occurred since the Industrial Revolution. To control global warming, the UN Framework Convention on Climate Change (UNFCCC) was established in 1992. The Kyoto Protocol, under UNFCCC, which came into force in 2005, set out more specific and binding commitments to abate the use and emissions of greenhouse gases. 192 Nations have ratified the Kyoto Protocol. The Kyoto Protocol follows the principles and provisions of the UNFCCC Convention and its annex-based structure. The protocol binds the developed economies in transition to limit and reduce greenhouse gas emissions in conjunction with agreed individual targets. The protocol binds only developed countries based on the principle of “common but differentiated responsibility and respective capabilities” because they are significant contributors to current high levels of GHG emissions in the atmosphere.

6.4 Phasing Out of Hydrofluorocarbons

Global efforts have been made to limit and reduce the consumption of HFCs. In October 2016, the global HFC phase-down steps were agreed upon and became part of the Montreal Protocol under the Kigali Amendment, which came into force on 1 January 2019. This section of the report will cover the regulations
limiting HFCs’ consumption apart from the Kigali Amendment around the world. Figure 28 presents the main HFC phase-down that has already been imposed on the industry.

Figure 28: Hydrofluorocarbon Phase-Down Scenario

Source: [18].

6.4.1 F-Gas Regulation (European Union)

Fluorinated gases (F-gases) are a range of powerful greenhouse gases that trap heat in the atmosphere and contribute to global warming. The most common F-gases are HFCs, which are typically used in refrigeration and air-conditioning applications. The F-gas emission almost doubled in Europe from 1990 to 2014. To take regulatory action against the emission of F-gases, the F-gas regulation was implemented on 1 January 2015. By implementing F-gas regulation, cumulative emission saving of 1.5 gigatons of CO₂ equivalent by 2030 and 5 gigatons by 2050 will be achieved [16]. These targets will be achieved by:

1) Limiting the sales of F-gases in Europe from 2015 onwards and phasing them down in steps of 1/5 of 2014 sales in 2030. This could be a significant driver for the development of climate-friendly technologies.

2) Using the less harmful low-GWP alternatives and restricting the use of F-gases in the new types of equipment.

3) Preventing emissions of F-gases from existing equipment by regular checks, proper servicing, and recovery of the gases at the end of the equipment's life.
Given that climate-friendly alternatives are available for many products and equipment in which F-gases are commonly used, this ambitious reduction is achievable at a relatively low cost. It also offers opportunities for driving innovation in the refrigeration and air-conditioning sector.

### 6.4.2 United States Hydrofluorocarbon Phase-Down

In late 2020, the AIM Act authorized the Environmental Protection Agency (EPA) to phase down HFCs following the Kigali Amendment’s schedule seeking to reduce the usage of HFCs by 85% in 15 years. The AIM Act directs the EPA to address HFCs to phase down the production and consumption of listed HFCs, manage these HFCs and their substitutes, and facilitate the transition to next-generation technologies.

The Significant New Alternative Policy (SNAP) Program was developed by the EPA to implement the ODP phaseout in 1989. The SNAP concept is to accept or eventually ban specific refrigerants for safe usage in defined applications. There are three steps in accepting and introducing a new refrigerant in the market:

1. The first step is for the EPA to list the new refrigerant as an acceptable substitute through its SNAP rules.
2. The second step is to establish safety standards for design and usage.
3. The final step is to establish building codes to accept the usage of the new refrigerant which can harmonize with safety standards.

Under the SNAP rule, high-GWP HFCs were excluded from use and low- or medium-GWP HFC/HFOs (and even HCs) received acceptance for specific applications. One of the most used HCFC, R22, have been phased out and cannot be produced for new equipment, and all production and import of R-22 ended in 2020. HFCs; R-404A, R-134a, R-410A, and R-407C were used as a replacement for R-22 and will not be used in new chillers after 1 January 2024.

**California**

California is going beyond the SNAP ruling and imposes a GWP-based phase-down plan. This plan is often regarded as the trendsetter for new marketing and technology.

The following targets have been set for air-conditioning:

- Single-speed and variable-speed air-conditioners will not be produced using refrigerants whose GWP is greater than 750 from 2026.
- A GWP limit of 750 for new chillers used for air-conditioning, effective 2024.

### 6.5 Life-Cycle Assessment Approaches

#### 6.5.1 Total Equivalent Warming Impact

The concept of total equivalent warming impact (TEWI) was developed to measure the combing the global warming impacts of the refrigerant losses to the atmosphere and the CO₂ emissions from fossil fuels to generate power to run the refrigeration air-conditioning systems. There are two components of TEWI:
The direct emissions component of TEWI is a way to capture the climate impact of all the refrigerant emissions over the system's lifetime. At the same time, the indirect component captures the CO\textsubscript{2} generation because of electricity consumption throughout the lifetime of the AC. It can be calculated as:

$$\text{TEWI} = (\text{GWP} \times L_a \times n) + (E_a \times B \times n)$$

Where:

- GWP = global warming potential
- $L_a$ = leakage rate (kg) per annum
- n = number of years
- $E_a$ = energy consumption (kWh per annum)
- B = CO\textsubscript{2} emissions per kWh

TEWI calculations' accuracy depends on many assumptions related to equipment performance and use patterns, refrigerant properties, and electricity generation efficiencies.

### 6.5.2 Life-Cycle Climate Performance

One of the limitations of the TEWI approach is that it does not consider the energy consumed and other emissions related to the manufacture and transportation of refrigerants. The life-cycle climate change performance (LCCP) addresses the TEWI approach's limitation and provides a holistic method for estimating all greenhouse gas emissions associated with the system's lifespan. LCCP could be useful for comparing the climatic impact of different alternative refrigerants for a given application. LCCP incorporates all the TEWI factors, and in addition, it accounts for the GWP of emitted chemicals used in manufacturing the operating fluids. LCCP also accounts for energy used to produce the operating fluids. The embodied energy is expressed in CO\textsubscript{2e}.

LCCP can be applied to all HVAC&R applications ranging from commercial refrigeration systems to residential heat pumps, and chillers. Like TEWI there are two emission categories of LCCP: Direct and Indirect. LCCP can be calculated as:

$$\text{LCCP} = \text{Direct Emissions} + \text{Indirect Emission}$$

**Direct Emissions**

$$\text{Direct Emissions} = C \times (L \times \text{ALR} + \text{EOL}) \times (\text{GWP} + \text{Adp.GWP})$$

**Indirect Emissions**

$$\text{Indirect Emissions} = (L \times \text{AEC} \times \text{EM}) + \sum (m \times \text{MM}) + \sum (mr \times \text{RM}) + (C \times (1 + L \times \text{ALR}) \times \text{RFM}) + (C \times (1 - \text{EOL}) \times \text{RFD})$$
Where:

- \( C \) = Refrigerant Charge (kg)
- \( L \) = Average Lifetime of Equipment (yr)
- \( ALR \) = Annual Leakage Rate (% of Refrigerant Charge)
- \( EOL \) = End-of-Life Refrigerant Leakage (% of Refrigerant Charge)
- \( GWP \) = Global Warming Potential
- \( Adp. \ GWP \) = GWP of Atmospheric Degradation Product of the Refrigerant
- \( AEC \) = Annual Energy Consumption (kWh)
- \( EM \) = \( CO_2 \) Produced/kWh (kg \( CO_2e \)/kWh)
- \( m \) = Mass of Unit (kg)
- \( MM \) = \( CO_2e \) Produced/Material (kg \( CO_2e \)/kg)
- \( mr \) = Mass of Recycled Material (kg)
- \( RM \) = \( CO_2e \) Produced/Recycled Material (kg \( CO_2e \)/kg)
- \( RFM \) = Refrigerant Manufacturing Emissions (kg \( CO_2e \)/kg)
- \( RFD \) = Refrigerant Disposal Emissions (kg \( CO_2e \)/kg)

There are several tools for calculating LCCP, like the AHRI tool for residential heat pumps; the ORNL LCCP tool is a web-based and open-source tool for all air-conditioning and refrigeration applications. Like TEWI, LCCP calculations are dependent on many assumptions about the system performance, manufacturing emissions, typical system characteristics, and energy generation emissions. These values are all subject to a certain amount of uncertainty.

### 6.6 Refrigerants Management System in Centralized Air-conditioning

This section will cover the methods of refrigerant management in CACs and ways by which one could avoid the harmful impact of refrigerants on the environment. Figure 29 represents five ways of management of refrigerants in CASs.
6.6.1 Reducing Capacity of CAC Systems

The first step of any sustainable solution would be to reduce consumption. Earlier, the projected increase in the demand for air-conditioners was discussed, which will also increase the demand for refrigerants. Hence, reducing the capacity of the CAC system by designing high-performance buildings becomes a necessary step. The capacity reduction can be achieved in many ways such as mentioned in Figure 30.
6.6.2 Increasing Refrigeration Efficiency

After optimizing the capacity of the CAC system, the next step is to increase the refrigeration system efficiency. The selection of a refrigeration system depends on various parameters like climate zone, equipment availability, and cost apart from the building loads. The efficient design of the refrigeration loop can reduce the volume of refrigerant by optimizing the length, diameter, and location of components. For example, the length of the piping within the system can be reduced by shifting some components closer rather than bypassing the condenser by adding parallel pipes with check valves, or another approach could be to construct reversible heat pump systems with bi-flow expansion valves. Reducing the diameter of the liquid line and the related increase in pressure loss will not affect system performance if the refrigerant stays liquid before reaching the expansion valve and the valve has the appropriate capacity.

Together with the higher efficiency system, the control system of CAC also plays a vital role in increasing the refrigeration system's efficiency. Figure 31 represents the way by which refrigeration efficiency can be increased.

![Figure 31: Strategies for Increasing Refrigeration Efficiency](image)

Source: Author.

6.6.3 Refrigerant Life-cycle in Centralized Air-conditioning

The life-cycle of a refrigerant is presented in Figure 32. Refrigerant emission begins from the production step only. To minimize the climate impact of refrigerants, it is necessary to reduce the emission of refrigerant in all the steps of its life-cycle. Each step of the refrigerant’s life-cycle and its management approaches are discussed in this section.
6.6.3.1 Reducing Leakage Rate in CAC Through Maintenance

The possibility of refrigerant is always associated with the refrigerant throughout its lifetime, from production to installation to operation and maintenance of the CACs. Non-Article 5 countries are now targeting minimum refrigerant charge and zero leakage during the system's life-cycle. The limitation of refrigerant emissions depends on an efficient recovery policy for end-of-life equipment, careful refrigerant handling by the original equipment manufacturer (OEM), and efficient leak fixing during operation and maintenance by the service sector. Figure 33 presents approaches to reduce the leak of refrigerants in CAC.
6.6.3.2 Recovery and Destruction of Refrigerants for Centralized Air-conditioning

For the sake of sustainability, there has been an increasing emphasis on the conservation of refrigerants and the reduction of emissions through recovery, recycling, reclamation, and destruction. Maintenance, recovery, and recycling of refrigerants are crucial to minimizing climate impact.

**Recovery.** This is a process to remove a refrigerant in any condition from a system for further processing. The CAC system employs a large capacity of refrigerants and recovering refrigerants from such a system could benefit economically and environmentally.

**Recycling.** Extracted refrigerant from the recovery process could be recycled using oil separators and filter driers to reduce moisture, acidity, and particulate matter. Recycling is usually carried out at the field site. Since the quality of recycled refrigerants cannot be proven by analysis, some restrictions are imposed on recycled refrigerants in some countries. Currently, the MAC industry reuses recycled refrigerants.

**Reclamation.** This is to reprocess used refrigerants to virgin product specifications. Chemical analysis of the refrigerant is made to ensure that certain specifications are met. Reclamation extends the lifespan of
the refrigerant and decreases the dependency on virgin refrigerants. Small portable refrigerant reclamation systems have varying features, capable of reclaiming about 80 kg of refrigerant per hour. Reclamation is typically carried out in a designated facility.

**Destruction.** Converting used refrigerants into harmless chemicals is beneficial to the environment. There is a worldwide need to destroy ODS refrigerants because of the environmental benefits of the avoided emissions. There are several approved destruction facilities, in both non-Article 5 and limited in some Article 5 countries, including India.

![Figure 34: Recovery and Destruction of Refrigerants in Centralized Air-conditioning](image)

Source: Author.

### 6.7 Summary

This chapter provided an overview of refrigerants, from history to the type of refrigerants and their environmental impacts and metrics to quantify the environmental impact of refrigerants. Technological developments, together with recognized safety standards, have finally made it possible to begin moving toward real long-term solutions with zero ODP, and low-GWP refrigerants. Under the Montreal Protocol, developed countries have started phasing out the HFCs, and developing countries are planning an 80% reduction by 2045.

This chapter also covers the global HFC phasing out initiatives like F-gas regulation in the European Union, SANP rules in the US, and how they stopped production of R-22 in 2020. The US has banned the use of R-404A, R-134a, and R-410A by 2024, which were the most used HFC blend in CAC systems, and they are
moving toward low-GWP refrigerants like HFOs. Developing countries can use this as a case study and efficiently utilize the multilateral fund provided to them under the Montreal Protocol. TEWI and LCCP calculations can be useful in understanding the environmental impacts of CAC systems and can be useful in managing refrigerant use in CAC systems. The final part of this chapter gives an understanding of refrigerant management approaches in CAC systems.
7. References


