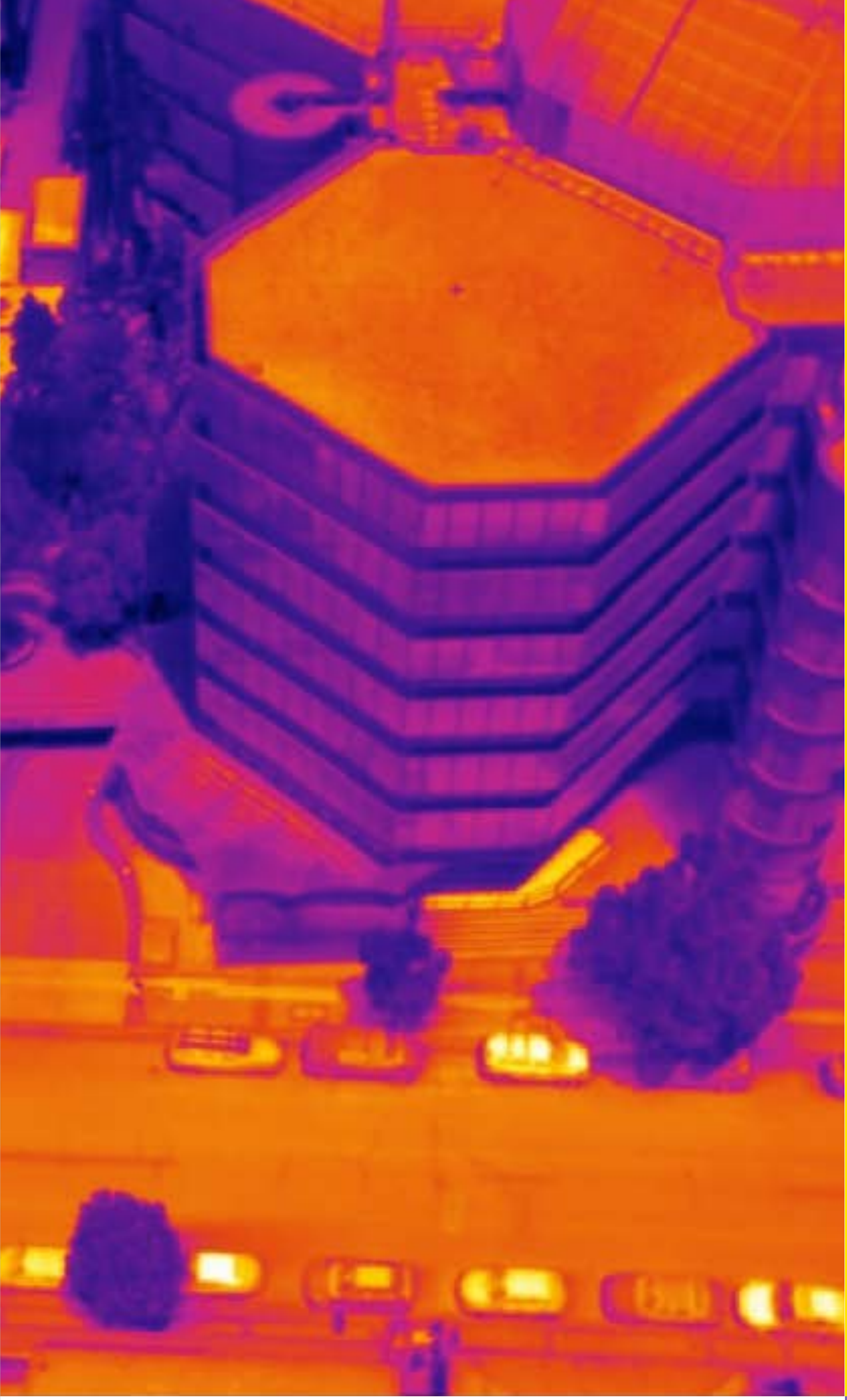

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Retrofit technologies

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Energy Efficiency Training
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Commercial Buildings

Research group

High Performance Architecture research cluster, School of Built Environment, Faculty of Arts, Design and Architecture, UNSW

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Cover image: Infrared aerial orthophoto of a commercial building in Parramatta, Smart Street Project (funded by CRC for Low Carbon Living and City of Parramatta) UNSW Built Environment.

Contents

Executive Summary

The refurbishment of Heating Ventilation Air Conditioning and Refrigeration (HVAC&R) systems in commercial buildings is both a challenge and an opportunity. It is a challenge because commercial buildings, especially the bigger ones, are complex energy systems with high and varying requirements and different operational patterns. It is also an opportunity because commercial buildings are significant, capital-intensive investments that are evaluated with different criteria by different stakeholders. The operation of commercial buildings is also energy-intensive, and there is scope for substantial energy savings.

This short guide provides an overview of mechanical systems, presenting functioning mechanisms and general performance indicators for different technologies available on the market. There is not a direct and univocal match between HVAC&R type and building size and use. For instance, a variable refrigerant volume system or an air-cooled chiller can be both appropriate options for the same office building, depending on the peak cooling load and operation mode. Therefore, a guide presenting the different options can support early decision making by building owners and facility managers, who may then engage consultants in an informed discussion. ■

The operation of commercial buildings is energy-intensive, and there is scope for substantial energy savings

1. Introduction

The role of HVAC&R systems

Improving the energy efficiency of buildings can be achieved by intervening in three major areas:

a. Reducing energy requirements, mainly by refurbishing the building envelope, utilising thermal insulation, cool roofs, advanced glazings and sun-protection systems

b. Upgrading/replacing the HVAC&R systems by using equipment with higher efficiencies, ventilation, waste-heat recovery and free cooling options, and implementing advanced building automation and controls, and

c. Utilising renewable energy sources on or nearby the building

Area (a) is a prerequisite to reducing energy requirements, area (b) is the next step in this chain of interventions to meet requirements in the most efficient way, and area (c) comes as the logical step to cover the reduced requirement in the most feasible and sustainable way.

These three areas are linked to each other and have to be addressed holistically to achieve the best overall results. As this project has shown, heating/cooling and ventilation, in other words, an integrated air conditioning supply accounts for between 40 and 60% of the energy used in commercial buildings. This energy is required to provide the cooling and dehumidification needed in summer, the heating and possible humidification in winter, and the necessary fresh air apply throughout the year, in those buildings at least where a mechanical ventilation system exists.

Development in the HVAC&R technologies has led to doubling the efficiencies of modern chillers compared to 25 years ago, the establishment of highly efficient heat pumps, and efficient heat exchangers for waste heat recovery. Further, sensors, controls and software tools that allow a demand-responsive hardware operation have become widespread. Thus, there is now a significant potential for energy savings while improving indoor air quality and thermal comfort conditions. And this applies even to buildings constructed 20 years ago!

Furthermore, renewable energy systems, like geothermal heat exchangers, can be coupled to heat pumps and hence achieve very high decarbonisation of the HVAC&R operation. State of the art photovoltaics, both Building Applied and Building Integrated, can add to the renewables' share in the building's energy balance.

The design, layout and assessment of HVAC&R systems in refurbished, sustainable buildings, efficiently integrated with the building's envelope and operated in an 'intelligent' way, is well described and quantified by international and national codes, like the ASHRAE standards and the NABERS or the LEED environmental rating system. →

Major components and categorisation of HVAC&R systems

A typical HVAC&R system consists of the following main components:

- Heat generation system: it generates the necessary thermal energy and delivers it in the form of water, air, or refrigerant. Depending on the system, it may use any of the following different heat sources: furnace, boiler, chiller, heat pump, electric resistance or a renewable source (like solar or geothermal energy).

- Heat distribution system: it distributes the thermal energy to the conditioned areas. Depending on the system, this can consist of air ducts, water, or refrigerant lines.

- Heat emission system: it distributes the heat (in the form of conditioned air) to the conditioned areas. Depending on the system, these can be vents (for air), fan-coil units (for water) or terminal units (for refrigerant)

- Sensors & controls: thermostats, CO2 sensors, occupancy controls and other sensors are used to monitor the conditions and provide the input to the control units that steer the flow rates and temperature of the heat distribution and eventually the operation of the heat generation systems.

As discussed in the following sections, HVAC&R systems can be categorised precisely based on which type of components and in what constellation is being used. These components can be found, in varying forms and constellations, in all central HVAC&R systems. Some of these components can be omitted or combined in one entity. For example, electrical infrared heaters do not need a heat distribution system and combine the plant and the emitter in a single piece of equipment. Some systems have thermal energy storage between plant equipment and a distribution system, which acts as a buffer or longer-term storage. Finally, in the case of packaged AC units (room air-conditioners), they are usually integrated into the packaged system.

Still, one can highlight that:

- The plant equipment is characterised by the energy source (e.g. fossil fuels, solar energy) and its form (e.g. chemical, electrical) that is converted into thermal energy in the plant.

- The distribution system is characterised by the transfer heat medium (e.g. air, water, refrigerants).

- The emission system is characterised by its heat transfer mode (e.g. convection, radiation).

Whatever the type and category are, there are principles that apply to all systems to be efficient:

- Appropriate sizing to be able to cope with peak requirements while avoiding over dimensioning.

- Selection of state of the are equipment on all levels. A highly efficient heat pump will not yield the expected savings when combined with inefficient pumps and fans or outdated thermostatic controls.

- Flexibility of the system to cope with partial loads. Most HVAC&R systems operate for over 60% of the year at partial loads of less than 50%. State of the art systems adapt to these conditions; alternatively, one can consider cascade systems.

- Finally, the HVAC&R system, especially as part of a refurbishment, has to select considering the building envelopes properties and the building's operational profile. ■

2. State of the art refrigeration and heat generation, distribution and emission systems

The features of all the components described in the previous section and their integration determine the overall performance of any HVAC&R system. Usually lasting no more than 20 to 25 years, HVAC&R systems will have to be replaced or at least upgraded several times during a building's life of 50 to 100 years. Therefore, it is a given fact that a system that was state of the art 25 years ago may no longer be considered efficient today, even if it is appropriately maintained (which is not always the case) and is still operating without significant malfunctions.

Chillers, heat pumps and boilers

Electricity is used for HVAC&R purposes, lighting, Plant equipment produces thermal energy and delivers it to terminal units. Unlike other plant types, heat pumps, which operate on the same principle as chillers (i.e. a refrigeration cycle), can heat and cool a space.

Electrically-driven vapour compression chillers can be air- or water-cooled. Water-cooled chillers use a condenser and a water circuit to reject heat to a nearby sink such as a lake, a pond or a cooling tower. The lower the temperature of the heat sink, the higher the performance of the chiller.

Water-cooled chillers usually reject heat into ambient air via a cooling tower. They are used in medium to large chillers, consume large amounts of water and require regular maintenance. When outdoor conditions are mild and dry, free tower cooling – using the cool outdoor air as a free cooling source – can be used.

The efficiency of **chillers** and **heat pumps** is characterised by the coefficient of performance (COP) when operating in heating mode. It is characterised by the energy efficiency ratio (EER) when operating in cooling mode, which measures the heat rejected from the building to an ambient heat sink times the energy (usually electricity) used in the compressor to drive the refrigeration cycle. The COP and SEER (i.e., the seasonal EER) are greater than 1.0, so for every electric kWh consumed in the compressor, several thermal kWh are rejected from the building. →

COP is highly dependent on the fluid temperatures that the condenser and evaporator are in contact with. Lower evaporator temperatures result in lower COP, and higher condenser temperatures result in lower COP.

An alternative to the conventional compression chiller is an absorption-based chiller that uses a mixture/solution chemistry and a heat source. These systems are most effective when a “free” or cheap source of heat is available, for example, solar thermal energy or waste heat. The heat source must be hot enough to drive the system.

Absorption chillers typically range from 50 to 6,000 kW, but smaller units are available from some manufacturers. Their COP is usually much lower than those for compression cycle chillers but can be increased by using more complex and sophisticated configurations.

Evaporative cooling, or cooling air through the simple evaporation of water, is an attractive system for dry spaces. It uses no refrigerant and consumes little energy.

There are two types of evaporative cooling: direct and indirect. Direct evaporative cooling (open circuit) puts water into direct contact with air. Warm, dry air is changed to cool, moist air. The outside air heat is used to evaporate the water. Indirect (closed circuit) operates on a similar basis except that it uses heat exchange. The cooled moist air never comes in direct contact with the conditioned environment.

Heat pumps transfer heat by circulating a refrigerant through a cycle of evaporation and condensation. A compressor pumps the refrigerant between two heat exchanger coils. In one coil, the refrigerant is evaporated at low pressure and absorbs heat from its surroundings. The refrigerant is then compressed on the way to the other coil, where it condenses at high pressure. It then releases the heat it absorbed earlier in the cycle.

A heat pump cycle is fully reversible and can provide year-round climate control. Because they use renewable heat sources from their surroundings, heat pumps are a very energy-efficient way to heat and cool spaces and operate most effectively when there is only a small temperature difference between the heat source and heat sink.

Commonly used in air-conditioning and as refrigerants, Hydrofluorocarbons (HFCs) are being phased out because they are potent greenhouse gas, prompting research into safer replacement fluids.

Ambient air is the most common heat source for heat pumps. Air-source heat pumps draw heat from outside air during winter and reject heat outside during summer.

However, they achieve, on average, 10 to 30% lower seasonal performance than water-sourced heat pumps because of the rapid drop in capacity and performance with decreasing outdoor temperature, the relatively high temperature difference in the evaporator, and because of the energy needed to defrost the evaporator and operate the fans.

There are two types of air-source heat pumps, the most common being the air-to-air heat pump. It extracts heat from the air and transfers it indoors. Air-to-water heat pumps are used in buildings with hydronic heat distribution and emitter systems.

Air-to-air heat pumps include single package systems (window and wall systems, packaged units) and split systems (single split systems, multi-split systems and Variable Refrigerant Flow (VRF) systems). A packaged air conditioning system usually refers to a self-contained system fully integrated into one package. Packaged systems can serve a variety of areas, controlling temperature and humidity. They can be designed for internal and external areas that are restricted by size and affected by noise. Ducted systems are popular, with the ductwork distributing the circulated air throughout the areas served. ➔

Split-air conditioning systems are made up of an outdoor and an indoor unit. The outdoor unit is mounted externally and rejects or absorbs heat as the system requires. The two units are connected via small-bore refrigerant pipework and control wiring.

State of the art systems have an inverter that controls cooling and heating by varying the speed of the compressor and fans, making them much more efficient in partial load conditions and also quieter.

Multi-split systems are similar to the single-split system, but they can serve several different rooms by separate indoor units that are matched to one outdoor unit. They can only be used in one mode at a time, heating or cooling, and the outdoor units are fully inverter-controlled, delivering just the right amount of cooling or heating for any room.

An air-to-water heat pump transfers heat from outdoor air to water for space heating or domestic hot water. They are usually all-in-one systems designed to deliver the right temperature for space heating, for domestic sanitary hot water and with the additional advantage of offering air conditioning in the warmer seasons. They have an outdoor unit, an indoor unit (hydrobox) that usually has a backup heater, a domestic hot water tank with an internal electrical heater (optional) and a thermal energy emission system (floor heating and cooling, fan coils, radiators).

As Australia's electrical grid is progressively decarbonised, air-to-water heat pumps are increasingly competitive and environmentally friendly for heating buildings with hydronic (water) heat distribution systems.

Ground source heat pumps (GSHP) are central systems consisting of one or more heat pumps coupled with a condenser loop or a closed-loop ground heat exchanger, with brine as a medium. In a central system, the heat pumps are located in a single mechanical equipment room, providing fluid to hydronic heating and cooling terminal units throughout the building. →

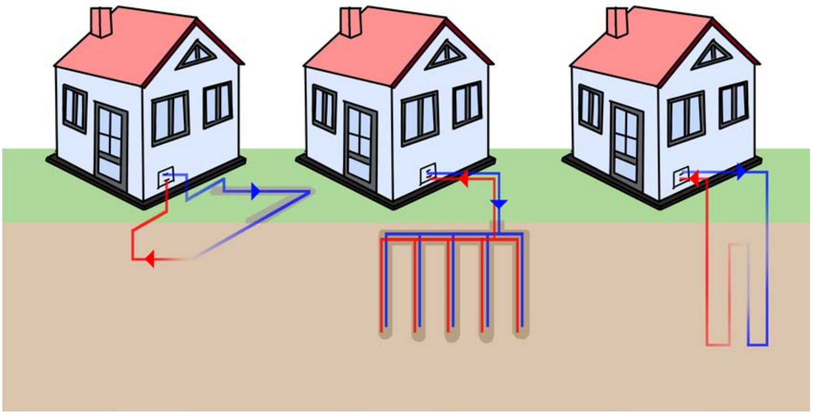

Figure 1. (Left) Horizontal closed-loop system. (Middle) Thermo-active building foundation. (Right) Borehole heat exchanger.

Air Handling Units and waste heat recovery technologies

Air Handling Units (AHUs) are the heart of a central HVAC&R system: They provide all the latent cooling, preheating, and humidification required by a building. Heating is either provided by the main air stream of the central system or locally at specific spaces. They are classified into single- and dual-duct categories as well as constant and variable volume categories.

Conditioning depends on air mass flow rate and temperature difference between supply and room air. The variable volume systems are throttling backflow when less heating/cooling is required, and the reduced flow results in reduced fan energy. Variable temperature systems change supply air temperature as thermal loading conditions change. In general, variable volume systems are considered more energy efficient.

All air systems display a high degree of flexibility in their configuration and can precisely control indoor air temperature and humidity. However, they take up a large amount of space in a building., and their energy performance can be undermined by auxiliary energy consumption from the fan.

Room terminal systems condition spaces by distributing air and water sources to terminal units installed in habitable spaces throughout a building. They allow for more customized zed control of different spaces, while any ductwork is smaller than the all-air systems because it mainly handles fresh air.

Room terminals can be made up of induction units or fan coil units. In an induction unit, centrally conditioned primary air is supplied to the terminals while the secondary flow is drawn into the terminal through a secondary coil for further conditioning.

Heat / Cold emission systems

Heating and cooling terminal units maintain a building's indoor environment at the desired level of thermal comfort. These units can be divided into several groups:

- **Forced air systems** directly control indoor air temperature, although they cannot guarantee comfort in all cases because of variables other than the air temperature.
- **Radiant systems** control surface and air temperatures and have more complex controls but create better comfort at lower air temperatures, in turn, further reducing heat loss via infiltration and ventilation.

Radiant systems – hydronic and electric – supply most of their thermal energy via radiation. They do not centrally mix air, so ventilation needs to be provided mechanically or naturally. Electric radiant systems, which convert electricity to thermal energy, are less efficient than other systems and used only for heating.

Hydronic systems, especially embedded building elements such as heated floors, directly heat and cool buildings and the people in them, and only indirectly heat or cool indoor air. They can also store excess thermal energy, which can be used off-peak. These systems can be difficult to install but have little impact on a building's overall architecture.

These kinds of systems operate at low and medium temperatures so that they can be fed by highly efficient plant equipment, such as heat pumps. They are also quieter because they do not use fans.

Infrared heaters are another kind of radiant system suitable for some niche heating applications. Converting gas or electricity to heat and operating at medium to high temperatures, they do not heat indoor air and can be directed to heat one portion of a building, making them very suitable for large spaces such as aeroplane hangars, factories, warehouses and gymnasiums, and even open areas such as loading docks or stadiums.

Forced air systems include air handling units (AHU), room terminal units, ductless systems, natural convectors and baseboard heaters and fan heaters. ➔

A fan coil unit is a small terminal unit that is often composed of only a blower and a heating and/or cooling coil and is often used in hotels or apartments. Fan coils can draw outdoor air from local apertures, but usually, fresh air is provided by different means. There are many different types of fan coils, as illustrated below, and they can be two-, three- or four-pipe units. A two-pipe unit is a single coil system with one inlet and one outlet pipe, providing heating and cooling with the seasonal changeover. Three-pipe units have two inlet pipes, a common return pipe, and two water coils. They can heat and cool simultaneously, but the common return pipe always undermines energy efficiency. Four-pipe units are a better solution because they have two separate water coils with two inlet and two outlet pipes.

Natural convectors and baseboard heaters heat spaces quicker than radiators can. They are usually placed in entrance halls, foyers, kitchens, bathrooms, small halls or auditoria, and small workshops.

Hybrid systems mainly comprise chilled beams and underfloor air distribution systems. Radiant and forced air systems can be combined and customised for different needs but can be more expensive. Usually, radiant systems heat and cool using a forced-air system, providing fresh air and taking over during cooling when condensation on the radiant systems is likely.

Chilled beams can be passive or active. Passive chilled beams do not have a fan, consisting only of a fin-and-tube heat exchanger contained in a housing suspended from the ceiling. The cooling coil cools warm room air rising to the ceiling, causing it to descend back to the floor. Active chilled beams resemble induction units because they are connected to an integral primary air supply.

In underfloor air distribution (UFAD) systems, an underfloor plenum between the structural concrete slab and the underside of a raised access floor is used to deliver conditioned air directly into the occupied zone of a building. Air is most commonly delivered through floor level supply outlets. UFADs provide better thermal comfort and air quality and use less energy than traditional overhead systems. A system that combines heating, ventilation, air-conditioning, power and data cabling into one easily accessible service plenum under a raised floor is flexible and cheaper than alternatives.

Building Automation and Controls (BAC)

A Building Automation and Control system (BAC) is the centralised automatic digital control of a building's HVAC&R, lighting, security, and other systems. It is also known as Building Management System (BMS) since both terms are usually used interchangeably in the industry, although some references consider BAC as a subset of BMS with a focus on automating HVAC&R and Lighting controls.

BACs are essentially the connection of mechanical and electrical systems and equipment so that they communicate with each other. In addition, the BAC systems can become 'smart' when it has the ability to regulate the building system's function in an optimum way and when networked via the internet to the utilities. In any case, BACs should increase building energy efficiency and reduce maintenance costs compared to buildings without such systems.

The level of a BAC system can be categorised into four classes according to ISO-EN15232, as shown in the following table. Besides, in these standards, efficiency factors for energy use are suggested based on the energy type, i.e. thermal energy or electricity, and on the building type for the four classes (Table 2, page 13).

The aforementioned standard is particularly important because it is the most widely adopted standard, linking BAC systems to a building's energy efficiency by defining four different efficiency classes (A, B, C, D).

The impact of a BAC class on a building's energy efficiency varies across building types and operational patterns. Efficiency factors for thermal energy and electricity in different types of buildings are listed below. Class C is the standard base case.

Upgrading an old, inefficient Class D BAC system in a wholesale and retail building with a new and highly efficient Class A system, without any other retrofit measures, will reduce thermal energy requirements by 60% and electrical energy requirements by 15.7%. The huge reduction in thermal energy requirements is due to the BAC's ability to control the HVAC&R systems, compared with the very basic controls in outdated systems. →

As mentioned above, when a BAC system is integrated with a building's services, it becomes a Building Management System (BMS); Building Energy Management Systems (BEMS) relate to energy efficiency. They control:

- Heating, ventilation and air conditioning
- Lighting
- Smoke detection and fire alarms
- Motion detectors, CCTV, security and access control
- Information and Communications Technology systems
- Lifts
- Industrial processes and equipment
- Shading devices
- Smart meters

They may also be used to monitor and control power distribution, energy consumption and uninterrupted power supplies. Together, those parameters create an integrated and effectively operated building, as shown below.

The phrases' Building Energy Management Systems' and 'Building Management Systems' are being gradually replaced with 'Building Automation and Control' and 'Technical Building Management' systems. But whichever term you use, these systems help managers get the most out of buildings. Alarms and alerts notify a manager when parameters are exceeded or when failures have or will occur. Data collection allows managers to compare the performance of different spaces and buildings and set performance benchmarks. Finally, they provide all the data needed for energy and environmental audits.

But even the best BAC and TBM system depends on the efficiency of the building's various systems, such as its HVAC&R. A BAC system's efficacy also depends on the range and quality of the information it receives from sensors and on how this information is used. In that sense, even a state-of-the-art BAC system needs to be properly commissioned and regularly fine-tuned.

Table 1. Functions and assignment to energy performance classes (ISO-EN15232)

	Heating/Cooling control	Ventilation / Air conditioning control	Lighting Control	Solar protection
A	• Individual room & communication between controllers • Indoor temperature control of distribution network water temperature • Total interlock between heating & cooling control	• Demand/presence dependent airflow control at room level • Variable setpoint with load-dependent compensation of supply temperature control • Room/exhaust/ supply-air humidity control	Automatic • Daylight control • Occupancy detection manual on / auto off • Occupancy detection manual on / dimmed • Occupancy detection auto on / auto off • Occupancy detection auto on / dimmed	Combined light/blind/ HVAC&R control
B	• Individual room control with communication between controllers • Indoor temperature control of distribution network water temperature • Partial interlock between heating & cooling control (dependent on HVAC system)	• Time-dependent airflow control at room level • Variable setpoint with outdoor temperature compensation of supply temperature control • Room/exhaust/ supply-air humidity control	Automatic • Daylight control • Occupancy detection manual on / auto off • Occupancy detection manual on / dimmed • Occupancy detection auto on / auto off • Occupancy detection auto on / dimmed	Motorized operation with automatic blind control
C	• Individual room automatic control by thermostatic valves or electronic controller • Outdoor	• Time-dependent airflow control at room level • Constant setpoint of supply temperature control • Supply-air humidity limitation	Manual • Daylight control • On/off switch + additional sweeping extinction signal • Manual on/off	Motorized operation with manual blind control
D	• No automatic control • No control of distribution network water temperature • No interlock between heating and cooling control	No airflow control at room level No supply temperature control No air humidity control	Manual • Daylight control • On/off switch + additional sweeping extinction signal • Manual on/off	Manual operation of blinds

Table 2. Energy performance factors based on building type for automation and controls used (ISO-EN15232)

Non-residential building types	Electrical efficiency factors			
	D	C	B	A
	Non-energy efficient	Standard (Reference)	Advanced energy efficiency	High energy efficiency
Offices	1.10	1	0.93	0.87
Lecture halls	1.06	1	0.94	0.89
Educational (schools)	1.07	1	0.93	0.86
Hospitals	1.05	1	0.98	0.96
Hotels	1.07	1	0.95	0.90
Restaurants	1.04	1	0.96	0.92
Wholesale and retail	1.08	1	0.95	0.91
Other types – sport facilities, storage, industrial facilities etc.,		1		

3. Typical HVAC&R systems in the considered building groups

Central HVAC systems, providing full air-conditioning

Central HVAC&R systems are typically built around a pre-packaged central air conditioning unit for airflow management (Air Handling Unit, AHU), which consists of one or more fans and combinations of heating and/or cooling coils, filters, humidifiers and control dampers. The control units are connected to a central air duct network which distributes the air to the air-conditioned rooms and can be configured to serve a number of different types of distribution systems.

The basic components that make up a Central Air Conditioning Unit are the following:

- Supply fan
- Return fan
- Heating and/or preheating coils
- Cooling and/or pre-cooling coils
- Filters
- Mixing box
- Control diaphragm (damper)
- Attenuators
- Control system
- Humidifiers →

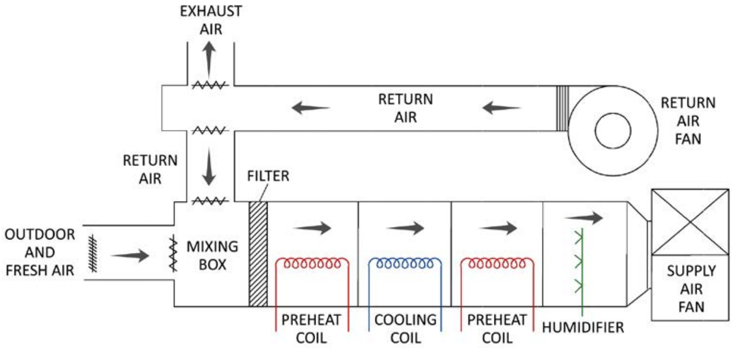

Figure 2. Schematic diagram of typical AHU

CAV systems

Single zone constant air volume (CAV) systems provide a fixed amount of supply air at a suitable temperature to cover indoor thermal loads. The air temperature control is performed by mixing the cold air with hot or directly reheating the cold air. These systems can not provide adequate control for the different thermal zones.

The main categories of CAV systems are:

- CAV systems with terminal reheating
- CAV systems with indoor reheating and peripheral induction units or fan-coils
- Induction systems with peripheral reheating

VAV systems

Variable volume air (VAV) systems provide a variable amount of constant temperature air to cover thermal loads. They can provide adequate temperature control in different zones by varying the amount of air supplied to each zone via outlets, inlet valves or inverter motors. The air temperature control is performed by reheating the air in each room.

The most widely used VAV systems are:

- VAV systems with terminal reheating
- VAV systems with peripheral reheating →

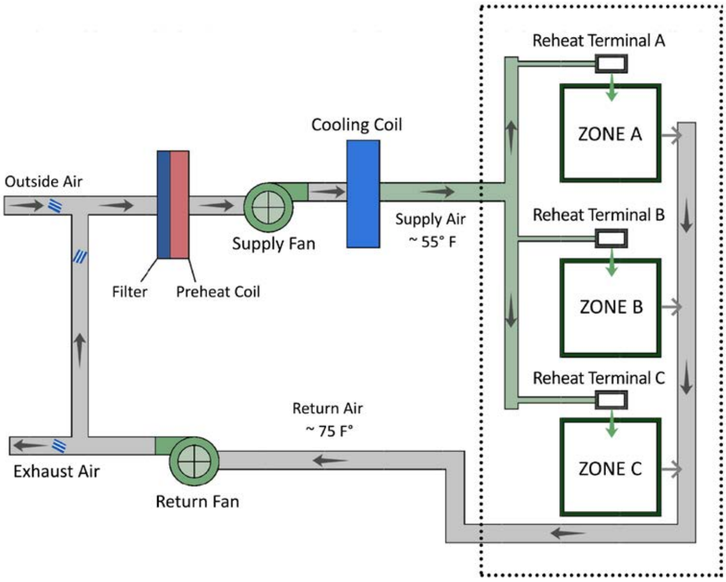

Figure 3. CAV system schematic diagram

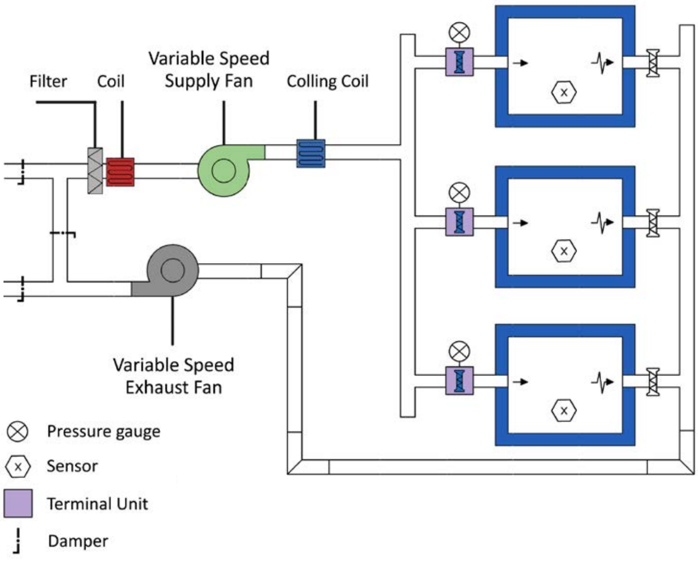

Figure 4. VAV system schematic diagram

VRV/VRF systems with mechanical ventilation

VRV (Variable Refrigerant Volume) or VRF (Variable Refrigerant Flow) systems are more complex and larger variants of ductless multi-split systems. They have several compressors, a large number of evaporators, and sophisticated oil and refrigerant management and control systems. Variable refrigerant flow refers to the ability of the system to control the amount of refrigerant flowing to each of the evaporators, allowing for the use of multiple evaporators of varying capacities and configurations, individualised comfort control, simultaneous heating and cooling in different zones, and heat recovery from one zone to another.

Two-pipe or three-pipe systems are available. A two-pipe inverter is similar to a multi-system inverter in that it has multiple indoor units of various sorts and sizes. One or more outdoor condensing units serve the inside units, all of which are connected by a single refrigerant piping system.

Multiple interior units are connected to one or more outside units via one set of refrigerant pipework in the three-pipe system, which is identical to the two-pipe system. It employs three independent pipelines between all of the units, rather than two, as the name implies.

VRF systems have numerous advantages and are often regarded as one of the best solutions for commercial building heating and cooling. They can serve many zones, each with its own setpoint control.

VRF systems can maintain precise temperature control because they use variable speed compressors with large capacity modulation capabilities. Duct losses, which are often estimated to be between 10% and 20% of total airflow in a ducted system, are almost eliminated with the VRF.

Each condensing unit in a VRF system normally has two to three compressors (one of which is variable speed), allowing for a wide range of capacity modulation. Because HVAC&R systems normally operate at 40-80% of maximum capacity, this results in high part-load efficiency, which translates to great seasonal energy efficiency.

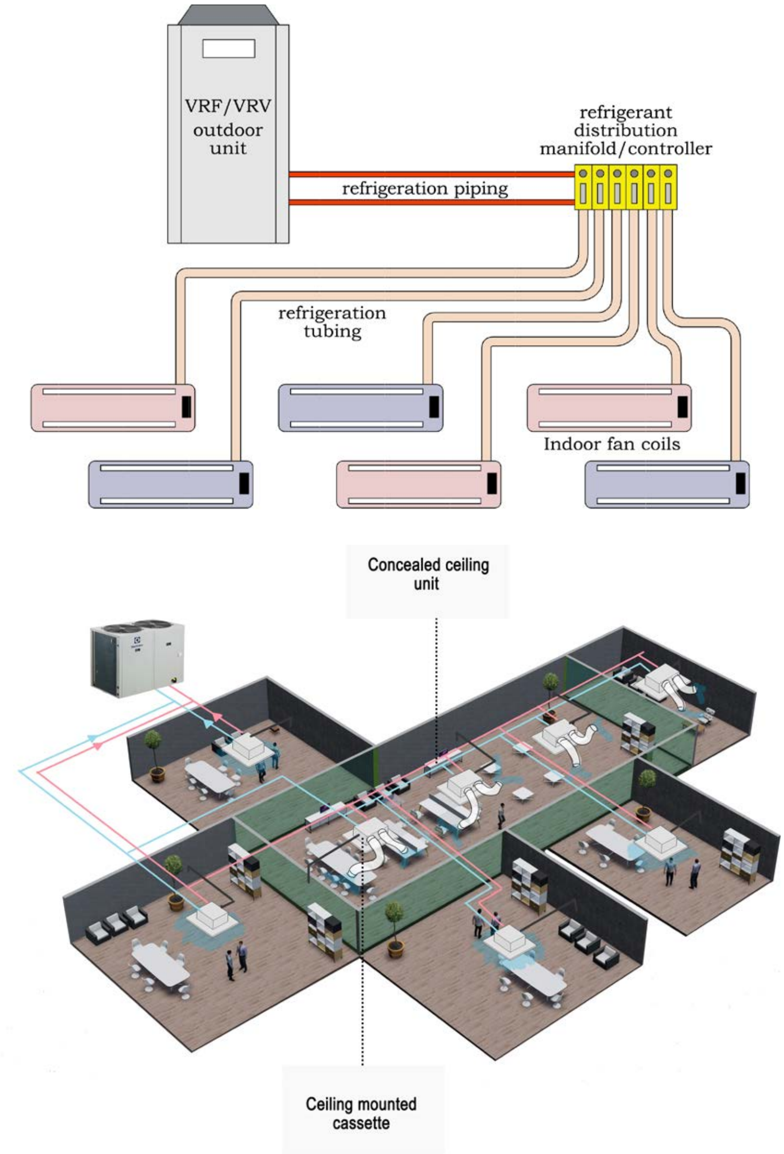

Figure 5. VRF/VRV system schematic diagram and typology

Local HVAC&R systems providing cooling/heating

Multiple zones or a big, single zone can exist in some buildings, necessitating the use of central HVAC&R systems to serve and meet the thermal requirements. Other structures, such as houses and residential apartments, may have a single zone that requires equipment to be located within the zone. This type of system is referred to as a local HVAC&R system since each piece of equipment only serves its own zone and does not cross into adjacent zones (e.g., using an air conditioner to cool down a bedroom or using an electrical heater for the living room). As a result, to activate the local HVAC&R system, a single zone only requires one point control point attached to a thermostat. Multiple local HVAC&R systems serve particular single zones in some buildings and are controlled by the single-point control of the desired zone. These local systems, on the other hand, are not connected to or integrated with central systems, but they are still part of a larger full-building HVAC&R system.

Local air-conditioning systems

Unitary air conditioner

From an equipment standpoint, it is comparable to window air conditioners. It's mounted on the building's external wall, usually near the floor-to-wall intersection. Every room will have a single unitary air conditioner or a central packaged air conditioner that covers different rooms that can be installed. ➔

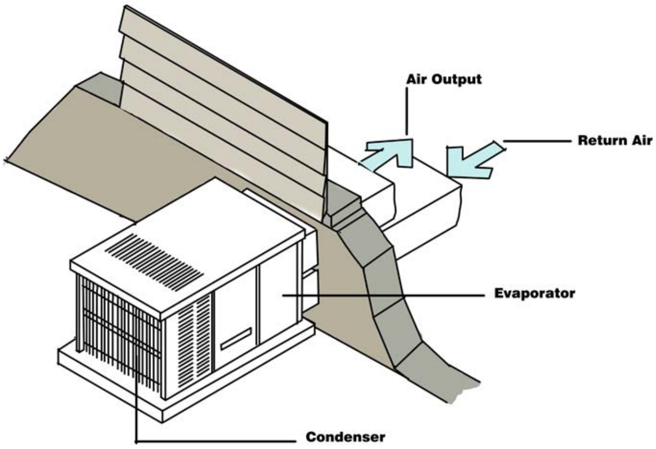

Figure 6. Unitary air-conditioner

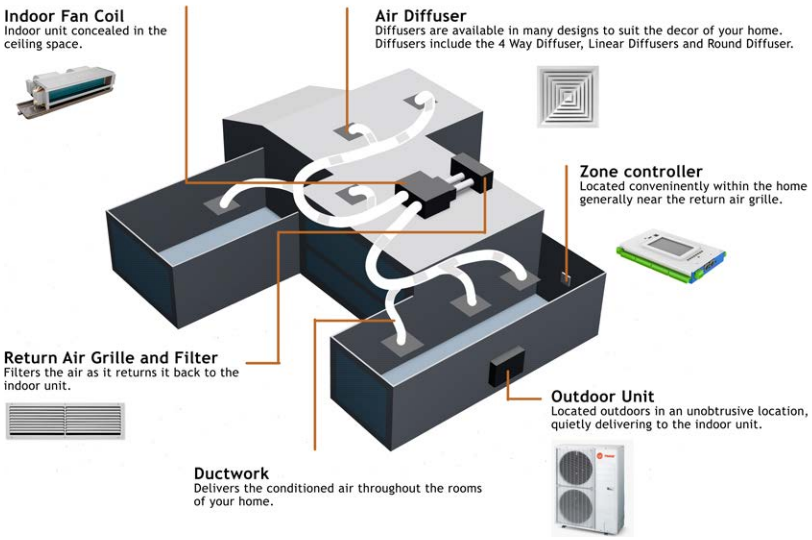

Figure 7. Ducted split air-conditioner

Packaged rooftop air-conditioner

It consists of a vapour compression refrigeration cycle, a heat source such as a heat pump or electric resistance, and an air handler with dampers, filters, fans, and control devices. This technology can be connected to ductwork and used to cool a big single zone that unitary or window air conditioners couldn't reach.

Split systems

The condenser, which is positioned outside, and the evaporator, which is located inside, are the two central components in split systems. A conduit for refrigerant lines and wires connects the two devices. Because the location and installation of window, unitary, or rooftop air conditioners might affect the aesthetic value and architectural design of the building, this system addresses several concerns with small-scale single-zone systems. One condenser unit can be coupled to many evaporator units in a split system (multi-split) to service as many zones as possible under the same or different climatic conditions. →

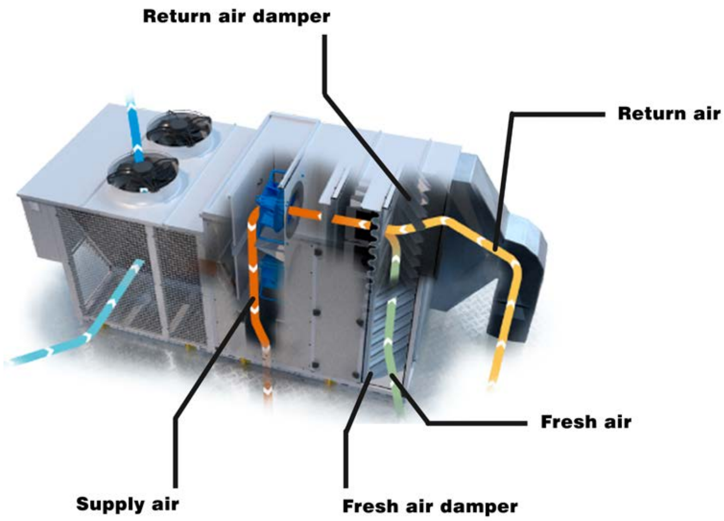

Figure 8. Packaged rooftop air-conditioner

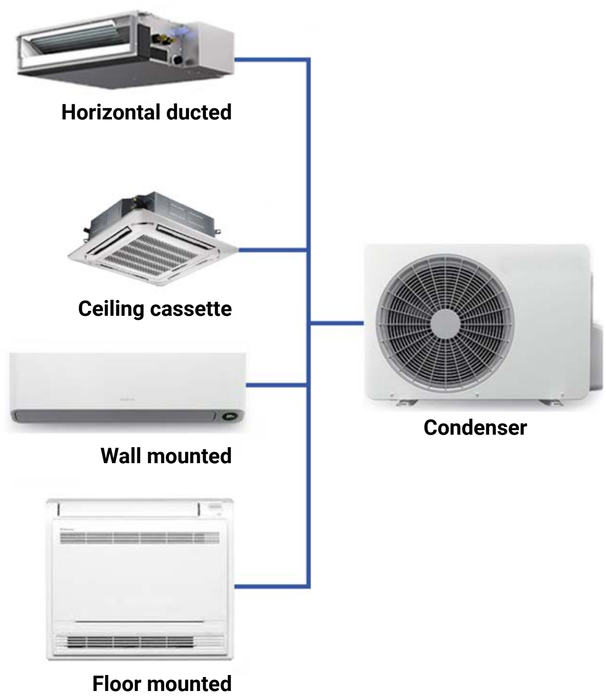

Figure 9. Multi-split system air-conditioner

Ventilation systems

Mechanical Extract Ventilation (MEV)

Simple and efficient to install, MEV systems actively extract air from 'wet rooms' (kitchens, bathrooms, utility spaces) via ducting to a central ventilation unit. This then removes the stale air through an exhaust point.

The systems are typically dual speed, providing low-speed continuous trickle ventilation and high-speed boost flow when needed. Replacement fresh air is drawn into the property via background ventilators located in the habitable rooms and through air leakage.

Decentralised Mechanical Extract Ventilation usually offers continuous low levels of ventilation to a single room.

Mechanical Ventilation with Heat Recovery (MVHR)

MVHR systems combine supply and extract ventilation in one system - working on the principle of extracting and reusing waste heat from wet rooms.

MVHR systems use the waste stale air by pre-warming the fresh air drawn into the building using a heat exchanger; this mechanism can recover up to 95% of waste heat. The filtered, pre-warmed air is then distributed around the space, helping share the heating loads throughout the zone.

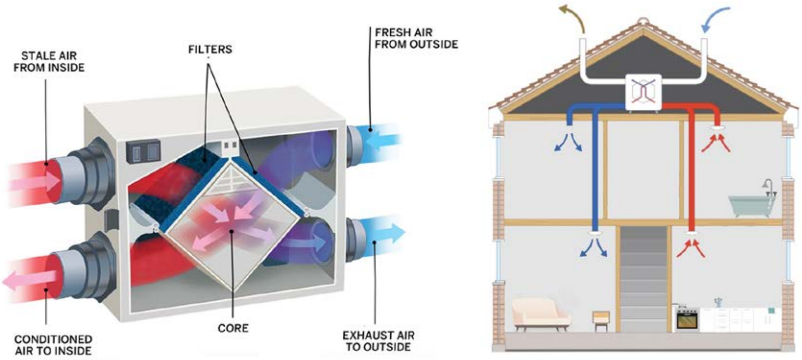

Figure 10. Centralised Mechanical Ventilation with Heat

4. Refurbishment strategy

A series of aspects can determine the refurbishment strategy for a commercial building: the wish to reduce operational expenses, the improvement of indoor conditions, and the reduction of the environmental impact are the main ones, and they are to be weighted by the building's owners and/or users.

Still, every refurbishment project is foremost driven by the technical nature of the process and its implications on costs, time and achieved results. Since these aspects are by and large affecting each other, a common approach is to distinguish three categories of interventions that serve different strategic goals:

- a "minimalistic" low-cost option
- a medium level or "Mid-life modernisation" option
- a "deep renovation" option

Typical interventions that can be implemented in each category are presented in Table 3. →

Table 3. Refurbishment strategies and the respective interventions

Cases	Description
Minimalistic low-cost option	- Maintenance, operational patterns, and settings - Improve operational attitudes (educating and training the users) - Installation of ceiling fans - Internal shading
Medium level or Mid-life modernisation option	- Replacement of outdated or damaged components and subsystems - Improvement of the lighting systems - Installation of automation and control systems (HVAC&R and lighting) - Installation of mechanical ventilation systems with waste heat recovery
Deep renovation option	- Refurbishment of the roof, fitting thermal insulation under the existing roof - Replacement of the windows - Applying insulation on external walls - External shading systems - Improvement of the lighting systems - Replacement of the whole HVAC&R system, if necessary - Installation of Building Management System (B.M.S.) - Integration of renewable energy systems • Solar thermal systems for DHW production • Photovoltaics • Ground source heat pumps • Air source heat pumps

Depending on the different buildings' typologies, construction years as well as climatic conditions, there is a variety of interventions that can be considered. It is well–known that choosing the most suitable ones is a challenging process since they must be technically applicable, efficient and cost-effective. Towards this direction, the three refurbishment strategies are presented.

Minimalistic low-cost option

In this option, minor interventions as part of the regular operation of the building are suggested. It is important to upgrade maintenance schemes so as to ensure that the infrastructure is kept in its optimal condition. For example, HVAC&R diffusers, grilles and filters should be cleaned in order to improve air quality and reduce losses. Also, the operational patterns and settings of the HVAC&R systems should be changed to reduce energy consumption and improve thermal comfort. It is also very important to educate the users of the buildings to raise their awareness about how to save power and energy and reduce waste. Moreover, the installation of ceiling fans, as well as window shadings, can significantly reduce the cooling loads of the building, which is crucial for many cities in Australia.

The minimalistic option includes no- and low-cost interventions, which can achieve nevertheless achieve savings of between 5 and 7%.

Medium level or Mid-life modernisation option

In this option, more advanced and sometimes complex interventions are proposed, which result in lower energy consumption and more energy-efficient buildings. First of all, the replacement of any outdated or damaged component and subsystem of the HVAC&R infrastructure is suggested. In this way, the energy efficiency of the existing HVAC&R systems can be significantly increased.

In addition, the replacement of the existing lighting system with a more efficient one can reduce the energy consumption as well as improve the thermal and visual comfort of the users. The efficacy (lumens per watt), the colour temperature, the colour rendering index, life and lumen maintenance, the dimming capability, and the cost are the main aspects that should be considered when choosing a new lighting system.

Furthermore, it would be beneficial to install automation and control systems concerning both the HVAC and the lighting systems, according to ISO-EN15232. Even HVAC&R systems of the highest efficiency cannot run optimally if they do not consider variations in ambient air temperature and solar radiation, the presence of users in the various rooms and the thermal response of the building's envelope. For example, sensors for efficiently mixing natural and artificial lighting, presence sensors, and a smart lighting control system can maximise light and minimise energy consumption.

Finally, the incorporation of night ventilation patterns into the HVAC&R system's operation can significantly reduce the cooling loads and, as a result, reduce the energy consumption regarding cooling.

The medium level interventions can achieve savings of between 20 and 40%. →

Deep Renovation option

In this option, a more holistic approach is taken into consideration. The idea is to upgrade the whole building, both the building envelope and the HVAC&R systems, integrate renewable energy systems and install a Building Management System.

More specifically, the refurbishment of the roof by fitting thermal insulation under the existing roof can reduce both heating and cooling loads. In the same context, applying thermal insulation on the external wall will also lead to the reduction of thermal losses, resulting in the reduction of energy consumption. Moreover, another intervention concerning the building envelope is the replacement of the windows with new aluminium framed, double glazed ones of high energy efficiency to reduce thermal losses in winter and solar loads in summer and achieve airtightness throughout the year. In this approach, replacing the whole HVAC&R system and the distribution network with a more efficient one is also suggested. In addition, implementing the Building Management System in accordance with the automation and control systems to interlock the use of HVAC&R, DHW and lighting systems with both the weather conditions and the operational requirements will contribute to the reduction of energy consumption.

Finally, the integration of renewable energy systems is essential in this approach. Photovoltaics can be installed on the rooftops to cover a part of the electrical needs of the building. Concerning the production of DHW, the installation of solar thermal collectors is suggested. The solar thermal system can be either autonomous (the well-known solar water heaters) or a central one with the main storage tank. Moreover, the implementation of heat pumps (ground or air source) for heating, cooling and DHW purposes can be considered.

The deep renovation option, which is clearly the one with the highest initial investment costs, can turn existing buildings into nearly zero-energy ones. ■

5. Criteria for selecting a refurbishment strategy & the interventions

One of the reasons why it is difficult to promote refurbishment projects in commercial buildings, despite the very appealing feasibility of energy savings, is their operational status: the complexity of leasing arrangements, the varying lengths of tenure and the fact that the expected benefits are not always shared in a fair and effective way between the owners and the tenants, make the implementation of otherwise sound and feasible retrofits more difficult than in singly-occupied buildings. Especially when it comes to HVAC&R systems, their refurbishment is linked with works that have to be examined with respect to their technical and financial feasibility, along with their energy and environmental impact. Finally, since such interventions, as a rule, disrupt the HVAC&R's, and hence the building's operation, it is essential to consider the duration of works and the disruption they cause.

According to the procedure of developing an effective and sustainable decision-making framework related to interventions, the following criteria should be considered, as they are presented in Table 4. →

Table 4: Criteria for selecting refurbishment interventions for buildings.

Categories	Parameters examined/Input Data	Tools
Technical	Type and age of the building Structural parameters Functional parameters Occupancy patterns Location and accessibility	Energy Audit Technical Feasibility Study
Energy efficiency	Climate Type of HVAC&R systems (size, type, capacity, energy coefficient, lifespan) Thermal comfort Indoor air quality Renewable Energy Systems Building Automation and Controls	Energy Audit HVAC&R Study Energy Study Energy Rating
Environmental impacts	Technical parameters mentioned above Energy consumption Transportation Water use Waste production Lifespan	Carbon Footprint Analysis, NABERS, LEED, BREEAM Life Cycle Analysis
Economic Feasibility	Investment costs Operational and maintenance costs Replacement costs Capital cost rate Energy prices Service lifetime of the equipment Circularity (dismantling, recycling, reuse costs)	Life Cycle Cost Analysis, Internal Rate of Return, Net Present Value, Payback period

Especially concerning the HVAC&R system, the following criteria should be examined and evaluated:

- Selection of main HVAC&R components: Efficiency, Coefficient of Performance and Energy Efficiency Ratio (EER) of equipment
- Selection of auxiliary components (Fans, pumps, heat exchangers etc.): Efficiency
- Air volume of the system according to the rate of air changes and the dimensions of the conditioned areas.
- Terminal units (air diffusers, fan-coils etc.) selection to ensure the optimum performance and conditions.
- Noise rating level. The sound rating of HVAC&R is an important criterion for occupants.

The correlation between efficiency (expressed by the various indices) and feasibility is easily comprehensible: the more efficient the HVAC&R system the lower the running energy expenses, and this should be by itself reason enough to justify the refurbishment. Still, with growing environmental awareness and with Corporate Social Responsibility becoming more and more important, property developers and owners are beginning to appreciate the sustainability aspect of buildings. The assessment may be expressed in monetary terms, like in longer acceptable payback periods, and in more qualitative terms, for example, in the improved public profile of the developer or in the higher marketability of the property.

In that sense, the aforementioned criteria are related to the HVAC&R system's technical quality, but they go beyond the "business as usual" approach since they are related to the building's living/working quality, the life span of the systems and their carbon footprint.

According to environmental certification schemes like NABERS and LEED, the HVAC&R contribution to the building's final rating depends on each main component's rating: the higher the rating, the more efficient the system and, consequently, the HVAC&R equipment will influence the final score of the building certified. Furthermore, the HVAC&R system also impacts the scoring categories related to Energy and Atmosphere (EA) and Indoor Environmental Quality (IEQ). The requirements the HVAC&R systems have to fulfil according to the NABERS rating system are presented in Table 5. →

Table 5: HVAC&R requirements according to the NABERS rating system

HVAC&R parameter	Requirement
System type	Describe the system that has been modelled and any differences between the design and modelled systems. For shopping centres and offices, the description should address whether or not the area is centrally serviced.
Hours of operation	Describe the hours of operation of the HVAC&R plant.
After-hours	Describe the representation of after-hours operation used and why this figure has been used.
Plant	Describe the plant sizes used and specifically note any areas where the simulation was allowed to default rather than use data from the design. Describe the chiller and boiler efficiencies. Describe any miscellaneous plant items (e.g. toilet exhaust systems). Describe how any limitations of the selected system/s have been modelled. Describe how low loads have been modelled.
Zoning	Describe the zoning of the HVAC systems and identify any differences between the design and the model. For offices and shopping centres, describe how HVAC zoning has been considered when modelling AHAC / extended hours for a NABERS rating.
Control	Describe the differences between the known or likely control methodologies of the actual system and those modelled.
Commissioning	Describe any known commissioning plans or strategies.
Infiltration	The sensitivity of the model should be tested to a range of infiltration scenarios in recognition of the difficulty of infiltration to predict. This is due to the possibility of infiltration increasing if façade construction is poor, doors are left open, or exhaust fans are left running longer than expected.

Eventually, one should consider a final criterion, namely marketability, which refers to the potential of a property to be rented fast and at a higher rate and is one of the strongest arguments for an appropriate renovation leading to an efficient, sustainable building. This marketability applies not only to the commercial value of office or hotel buildings but also to the appeal of nurseries and kindergartens to local communities.

Commissioning performed by a third party, including testing and tuning, has an essential role in ensuring the performance of an HVAC&R system and its operation as designed. From “startup”, to “testing, adjustment, and balancing” and then commissioning, are different stages of the whole commissioning process, that lead to an efficient operation of the HVAC&R system, delivering thermal comfort to the building. Without measurements, testing and commissioning, it is difficult to achieve high efficiency, especially for complex systems.

6. Conclusions: Elaborating the 'best' strategy

The quest for a 'best' refurbishment strategy for HVAC systems cannot lead to a uniform "one size fits all" solution since there are neither uniform buildings nor uniform HVAC&R systems.

The building as such defines the boundary conditions for the HVAC systems that can be considered, and two 'extreme' examples may help in demonstrating the applicability of this approach:

A small, low-rise kindergarten with a relatively low internal height can be heated and cooled by packaged air-conditioners. The idea of installing a central HVAC system, which would, in theory, enable mechanical ventilation with waste heat recovery and night cooling, may be appealing from an energy efficiency aspect, but it is technically not feasible and, given the overall rather low energy demand, financially not feasible. Replacing the old, packaged air-conditioners with new, highly efficient ones and installing ceiling fans to improve thermal comfort limits is more than adequate to achieve energy savings, improve thermal comfort conditions, reduce the carbon footprint, and all this at reasonable investment costs. A modest photovoltaic system can contribute to covering a reasonable part of the reduced electricity consumption.

At the other end of the scale, a big, high-rise office or apartment building with a central air-conditioning system is, almost by definition, a significant energy consumer. Such a building will need major interventions such as state-of-the-art chillers or a cascade of heat pumps, high efficiency heat distribution system and sophisticated Building Automation and Controls to reduce energy requirements drastically. When combined with ground heat exchangers to utilise geothermal energy, one can eventually transform the wasteful building into a nearly zero-energy one, not forgetting the necessary interventions on the building's envelope and the lighting system. It is clear that such a deep renovation strategy calls for high initial investment costs. It is also clear that a well-executed deep renovation leads to an entirely different building, efficient, sustainable, highly livable and eventually also marketable.

These two 'extreme' examples, which in reality are very common and representative of big clusters of buildings, demonstrate that the 'best' strategy is eventually determined on the one hand by the building itself and on the other by the goals set by the building's owners.

The refurbishment of HVAC systems in commercial buildings is a challenge and an opportunity. It is a challenge because commercial buildings, especially the bigger ones, are complex energy systems with high and varying requirements and different operational patterns. It is an opportunity because commercial buildings are significant, capital-intensive investments that are evaluated with different criteria by different stakeholders.

On the market, there are excellent technological solutions that enable the refurbishment of highly efficient, intelligent HVAC&R systems. Hence engineers and consultants have a great array of tools to tackle the challenge.

Finally, commissioning, including testing and tuning, has an essential role in ensuring the performance of an HVAC&R system.