Cool Net Zero

350PPM
Capitalist Solutions to Climate Change

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Introduction

This report provides an introduction to one of the least-discussed aspects of climate change mitigation strategies - cooling. We focus in particular on how Cold Thermal Energy Storage (CTES) can help in the decarbonisation of the cooling and electricity sectors - amongst others - by decoupling the generation of cooling from its consumption. Electrochemical batteries can do a similar thing for electricity but not precisely this for cooling.

Cooling is more important, energy-intensive and polluting than many appreciate. It's vital to many aspects of people's lives - preserving food, vaccines, etc. - but at the same time consumes about a fifth of electricity and accounts for roughly a tenth of greenhouse gas emissions, globally. These emissions are due both to the energy consumed by, and to the chemicals used in, cooling equipment. Any strategy to reduce these emissions must contend with an inevitable increase in cooling demand over the coming decades; inevitable because of a very robust set of drivers - global population and income growth, urbanisation and, of course, climate change itself amongst them. Cooling is both driving climate change as well as being one of things we most need to adapt to it.

The first section of this report, 'Cooling Basics', provides some elementary background - what, why and how we cool, as well as the factors that influence cooling demand.

The section 'Current Cooling Demand' covers a few basic statistics about the current demand for cooling, both globally and in the UK.

The section 'Net Zero Cooling' looks at the greenhouse gas emissions associated with cooling and the strategies by which these could potentially be eliminated.

The final section, 'Cold Thermal Energy Storage (CTES)', explains what CTES is, the various types that exist, as well as its potential benefits. This section concludes with a case study about an innovative version of CTES being developed by UK company Organic Heat Exchangers Ltd.

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Cooling Basics

In this section, the first of four, we cover the fundamentals of cooling - what, why and how we cool, as well as the factors that affect cooling demand. [Skip this section](#).

What Do We Cool?

The need for cooling is wide-ranging, both in terms of the types of things that need cooling and the types of end-users who rely on cooling, often critically so. This is illustrated in **Figure 1**, split between this page and the next.

The combined **Figure 1** divides cooling applications into two high-level categories: air-conditioning and refrigeration. From a basic science viewpoint these are fundamentally very similar processes, though they are somewhat different in their purpose and implementation. Loosely speaking, **refrigeration** involves removing heat from a confined space in order to keep physical goods at a fixed temperature, usually well below room temperature; while **air conditioning (AC)** involves controlling the temperature of the air in an enclosed space such as a building or vehicle, usually to keep the people inside comfortable (it also controls other properties of the air such as humidity and air quality). As illustrated in **Figure 1**, these categories both have applications across wide swathes of the economy. For example, refrigeration is used in these settings:

Domestic - home fridges and freezers;

Commercial - fridges and freezers in supermarkets, stores and restaurants;

Industrial - refrigeration for cold storage and for specific industrial processes, such as the processing of foods such as cheese;

Transport - refrigeration to prevent the spoilage of products en route to consumers, including fresh foods and pharmaceuticals.

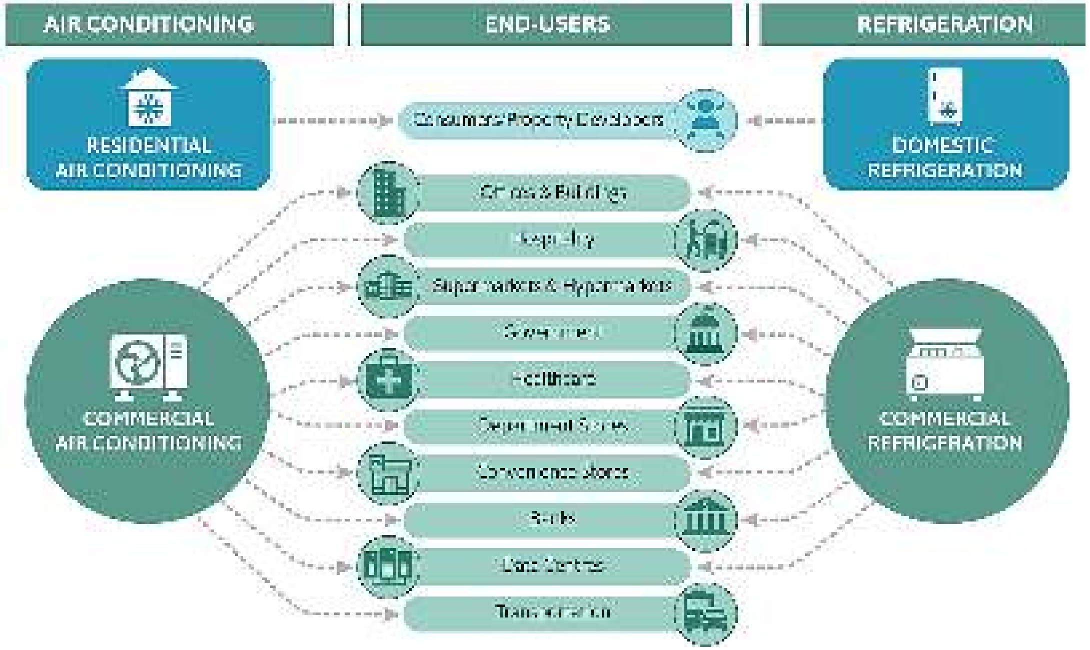


Figure 1 - end-users of air-conditioning and refrigeration, first part. Source shown on the next page.

And air conditioning (AC) is used in these settings:

Residential - peoples' homes;

Commercial - large commercial spaces such as supermarkets, offices and hotels;

Industrial - manufacturing facilities, workshops, warehouses and laboratories;

Mobile - cars, buses, lorries, etc.

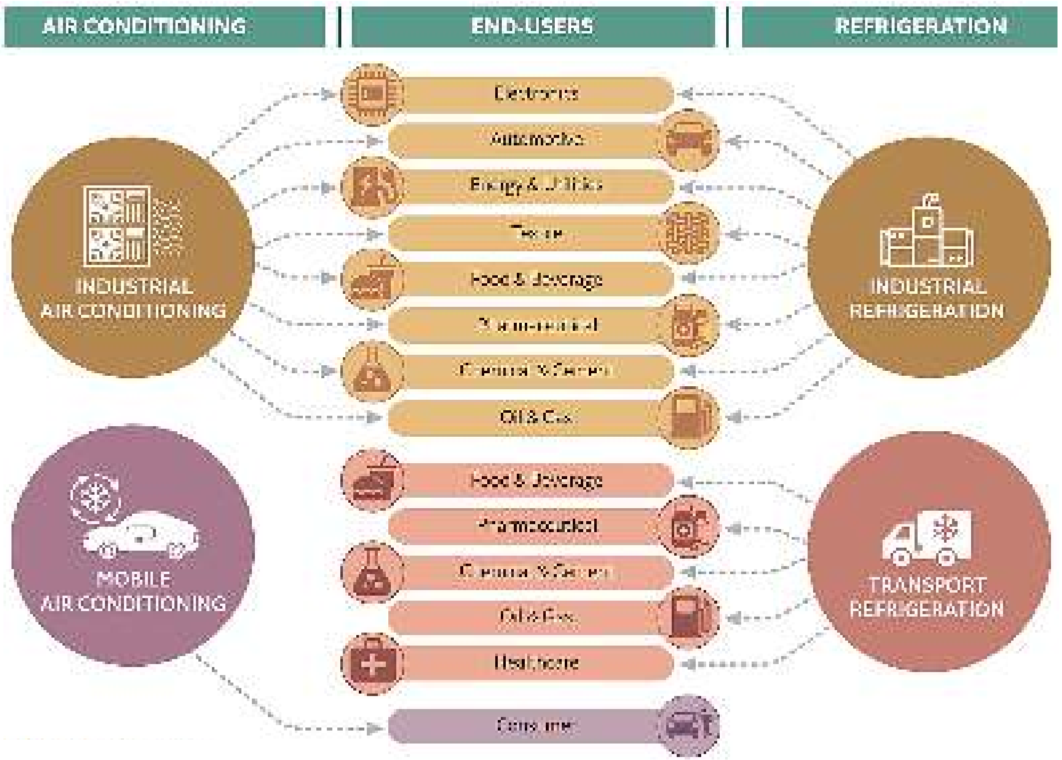


Figure 1 - end-users of air-conditioning and refrigeration, second part. Source: [‘The Cooling Imperative: Forecasting the size and source of future cooling demand](#)’, the Economist Intelligence Unit, 2019.

How is Cooling Beneficial?

As suggested by **Figure 1**, cooling impacts people’s lives in a myriad of ways. These are often underappreciated, especially in developed countries such as the UK where access to cooling is high. To highlight a few of these (stats come from [Figure 1’s source](#)):

Improving food security - without the existence of **cold chains**, which store and transport food from farm to fork at a reduced temperature, perishable foods can only be eaten locally, for a limited time. This is bad both for food suppliers and buyers. In the UK, 70% of food moves through the cold chain; worldwide this percentage is just 10%. This lack of cold chain capacity, especially in developing countries, is responsible for a loss of 14% of the world’s food supply, more than enough to deal with world hunger.

Preventing spoiled pharmaceuticals - in the absence of refrigeration, high temperatures quickly ruin some medicines and vaccines. The World Health Organisation (WHO) estimates that more than half of freeze-dried vaccines, and 25% of liquid vaccines, are wasted every year due to intermittent power supplies and a lack of effective cooling.

Preventing heat-related illness and death - human bodies do not tolerate high temperatures well, especially in the absence of sufficient water. For example, in the absence of cooling, heatwaves today kill an estimated 12,000 people every year. Owing to the effects of climate change the WHO forecasts that, without an increase in access to cooling, deaths could rise to 255,000 by 2050.

Improving people’s ability to learn and work effectively - thermal conditions affect people’s cognition, engagement, mood and comfort, especially children. For this (and other) reasons, a lack of cooling can therefore negatively impact education outcomes and work productivity. The International Labour Organisation has warned that a 1.5°C increase in global temperature by the end of the century would result in the loss of 2.2% of working hours, or 80m jobs by 2030, at a cost of USD$2.4 trn.

The impact of cooling extends well beyond these points, including providing wealth to those who work and invest in the sector ([we look at the value of the market later](#)). A list of how cooling impacts *seventeen* of the UN’s Sustainable Development Goals is included in this [report from the University of Birmingham](#).

How is Cooling Generated?

Cooling can be generated either actively or passively.

Active cooling involves the expenditure of energy - consuming electricity, burning fossil fuels, etc. - to artificially bring about a reduction in temperature. Powered refrigeration and AC are both examples of active cooling. The energy expenditure is often significant - obviously more so the lower the target temperature - as active cooling involves working against the laws of thermodynamics; these dictate that energy naturally flows from hot to cold until everything becomes the same temperature.

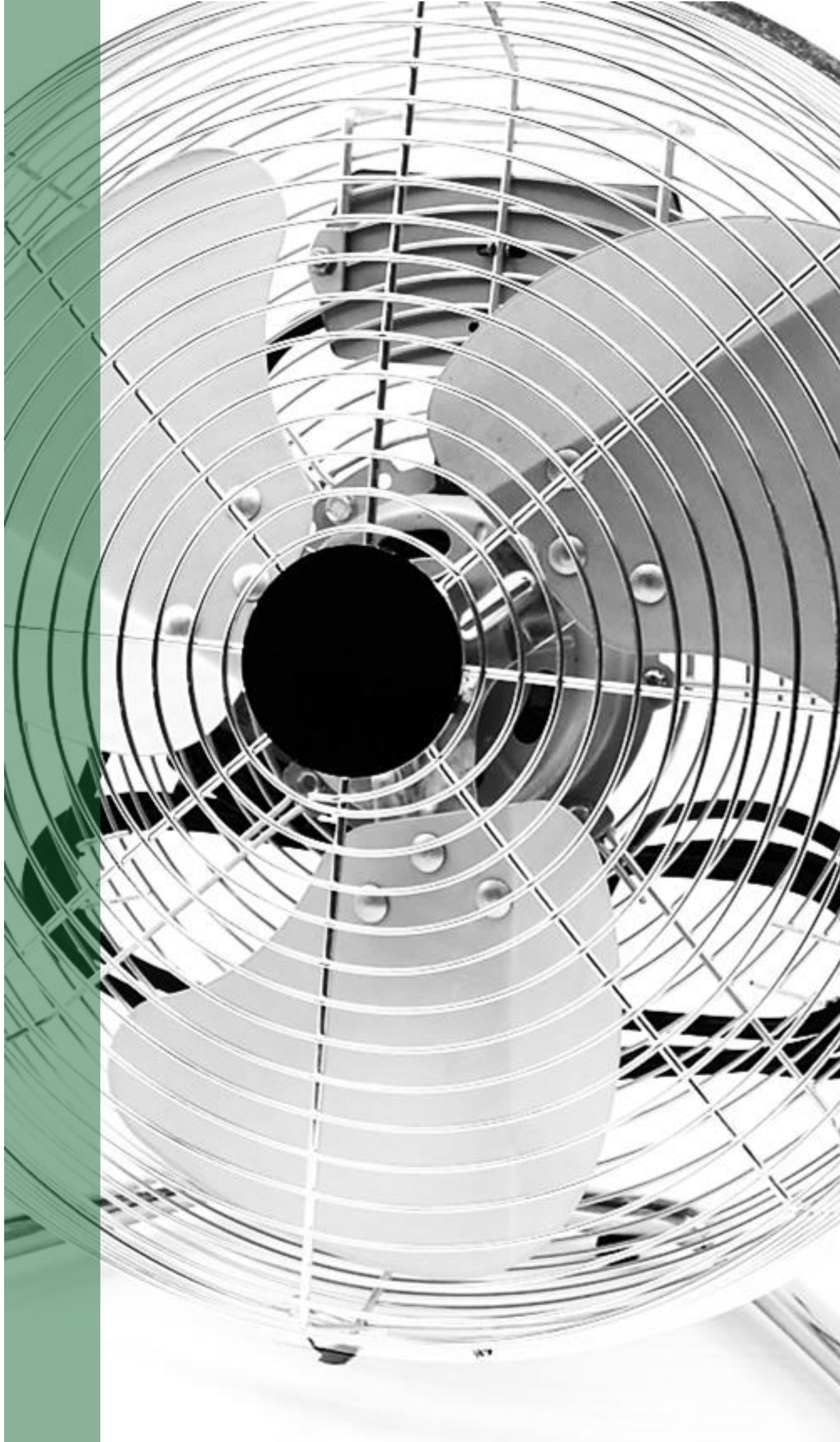
Passive cooling aims to avoid or reduce the need for active cooling by designing a thermal enclosure - a building, for example - such that it keeps naturally cooler, without the need for an ongoing expenditure of energy, though there is an initial energy cost to install passive cooling measures. Examples of passive cooling measures applicable to a building include optimising the building's location, orientation and form; use of natural ventilation and thermal insulation; shading of windows, internally or externally; use of reflective surfaces, e.g. white paint; and deploying vegetation and water in surroundings or on roofs. More about passive cooling can be found in the UK government's 'Cooling in the UK' report.

Types of Active Cooling

There are a handful of fundamental processes by which active cooling can be brought about. We outline some of the more common ones below. Practical cooling technologies often employ several of these processes in combination.

Moving Air

The conceptually most straightforward way of cooling something is simply to use a fan to move ambient air across it. Heat is exchanged from the something to the air, then the air moves away, taking the heat with it. Used on its own this type of cooling is inherently limited as it can only be used when the desired low temperature is above the ambient air temperature. It is therefore more often used for ventilation, or in combination with other cooling processes, though it does have standalone cooling applications - for example, to cool process fluids in industrial settings. It's a simple process but not the most energy efficient.



Non-cyclic Evaporation

Following on from our last section, small fans are often used to cool human beings. In this case there is an additional process happening that makes the overall cooling more effective - the flow of air increases the evaporation rate of sweat from the skin. This causes cooling as a significant amount of energy, known as the **latent heat**, is required to change the state of matter of the water in the sweat from a liquid to a gas. This latent heat is drawn from the skin, causing the skin to cool. Latent heat absorption is a general feature of solid->liquid and liquid->gas phase changes, as is latent heat release when going in the opposite direction.

In hot and dry climates the process of evaporative cooling can be used to cool from a few degrees to 50% below ambient air temperatures - the hotter and less humid the air the better - though a continuous supply of water is needed. Although this makes its applications fairly limited, the process has better heat exchange compared to moving air, meaning it typically has a lower energy consumption (lower also than all the other conventional forms of active cooling covered in this section). Mainly for this reason, evaporative cooling is deployed in niche commercial and industrial settings. For example, it is increasingly popular in data centres; these have gigantic electricity and cooling demands. As is also the case with moving air, evaporative cooling is a relatively simple process, with no need to employ any potentially damaging chemicals, neither of which apply to our next cooling process, the granddaddy of cooling processes - the vapour compression cycle.

Vapour Compression Cycle

The notion of latent heat, central to non-cyclic evaporative cooling, is also at the heart of vapour compression cooling, used in the overwhelming majority of refrigeration and AC equipment worldwide. With vapour compression cooling a fluid known as a **refrigerant** is forced to evaporate and condense repeatedly in a closed loop of coils, removing the need to continually supply something to evaporate. Manmade fluorinated gases, including hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), are the most commonly used refrigerants today. Unfortunately, these are extremely potent greenhouse gases. We look at potential solutions to this problem later.

Figure 2, overpage, shows the basic components and operating principle of an AC system that uses a vapour compression cycle (and moving air). As shown here, a vapour compression cycle is implemented using four main components: an **evaporator**, **compressor**, **condenser** and an **expansion valve**.

The basic steps of the cycle are as follows:

Compression - the gaseous refrigerant is compressed under adiabatic conditions (no heat transfer to the surroundings), which raises both the temperature and pressure of the refrigerant. This process is conventionally a mechanical process, driven by an electrical or fossil-fuelled motor, and is the main reason vapour compression is so energy-intensive compared to other cooling processes.

Condensation - the gaseous refrigerant passes into the condenser and condenses back to a liquid. This releases latent heat, which is typically rejected to the outside air, though it is preferable from an overall energy efficiency standpoint if this heat is recovered.

Expansion - the now-liquid refrigerant passes through an expansion valve. As a result, the refrigerant drops in temperature and pressure.

Evaporation - the liquid refrigerant enters the evaporator, which acts as a heat exchanger between the refrigerant and a source of heat (e.g. ground, air or water). When heat is transferred to the refrigerant, it boils and evaporates into a gas; in so doing, the refrigerant absorbs latent heat, cooling the ground, air or water. The cycle then repeats.

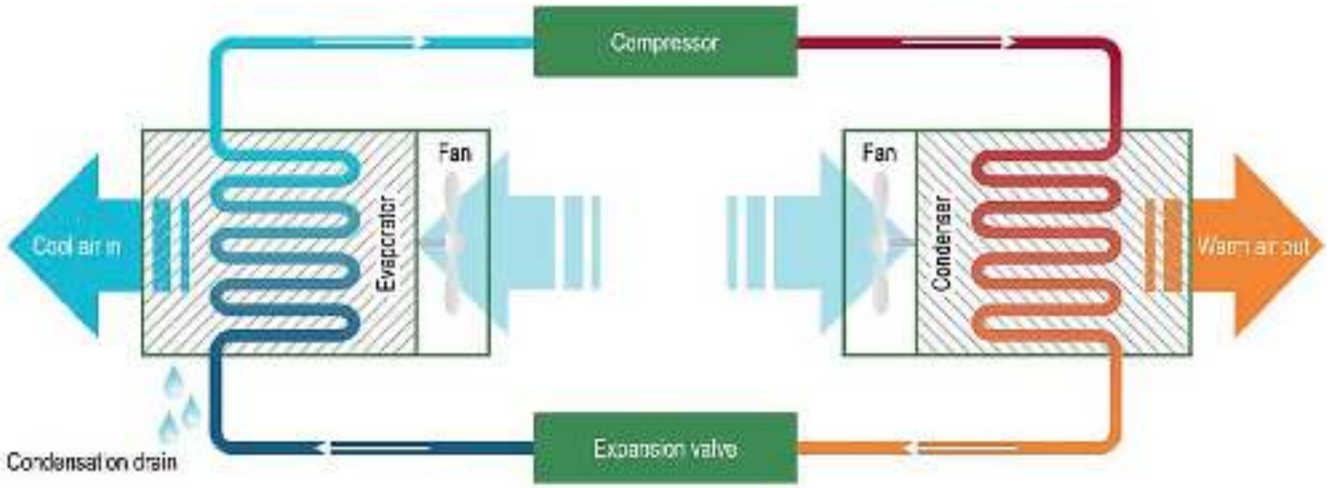


Figure 2 - illustration of the main components and operating principle of an AC system that uses a vapour compression cycle. Source: 'The Future of Cooling', International Energy Agency (IEA), 2018.

By picking an appropriate refrigerant, vapour compression systems can achieve cooling down to any temperature you might want to use in everyday applications (for example fridges operate at about 5°C and freezers at -18°C); you are not limited by the ambient air temperature as you are with the moving air and non-cyclical evaporation processes. It is not, however, the most energy-efficient process, especially when the target cold temperature is low and rejection temperature high.

Note that heat pumps also typically employ a vapour compression cycle - just in reverse - so this cycle is vital to the entire heating and cooling sector, and will become more so as heating shifts from fossil fuels to heat pumps as it electrifies and decarbonises. As well as providing heat, some heat pumps can be dynamically reversed so as to also provide cooling.

Absorption Cycle

Vapour compression is not the only way of producing cooling using a repeatable cycle. For example, an absorption cycle is similar to a vapour compression cycle but the refrigerant vapour is pumped to a higher pressure via a thermo-chemical interaction instead of a mechanical one. As the name suggests this interaction is driven by heat, rather than electricity. This heat can be supplied by burning natural gas or in some other way, such as by utilising waste industrial heat or solar thermal energy. Although it is counter-intuitive to use heat to produce cooling, absorption refrigeration is apparently the most common type of thermally-driven equipment worldwide. A lithium bromide and water solution is typically used as the refrigerant, though other refrigerants exist, such as lithium chloride and water, or ammonia and water, which are often used to produce chilled water at temperatures below 0°C. Vapour absorption systems are, in general, much less efficient than vapour compression systems, though with

with fewer moving parts. For this (and other) reasons they are not widely deployed, with use mostly limited to large commercial and industrial applications where an ability to utilise an otherwise wasted source of heat and/or to reduce electricity consumption may counteract lower efficiency.

Other Cooling Processes

In addition to those cooling processes already described, there are several less conventional ones that, although still at a comparatively early stage of R&D and/or market penetration today, do have the potential to accelerate the decarbonisation of the cooling sector, the subject of our third section. These include:

Electrochemical compression - pumping refrigerant vapour to a higher pressure via an electro-chemical interaction instead of a mechanical or thermo-chemical one. Electrochemical compressors work using specialised ion-permeable membranes to transport gas from an area of low concentration to one of high concentration when an external voltage is applied. This type of compression is potentially more efficient than mechanical cooling and can use climate-friendly refrigerants.

Solid-state (caloric) cooling - applying a magnetic or electric field, or a mechanical force, to specialised materials that change their thermal state as a result. This process has no moving parts (except in the mechanical case) or refrigerants, and can potentially provide both heating and cooling.

Radiative sky cooling - emitting thermal infrared radiation to the cold universe via rooftop panels. This is done at specific wavelengths that are not absorbed by the atmosphere. New materials have made this process, which was previously only possible at night, possible during the day as well. Radiation consumes no electricity - it's a passive process - though you still have to actively pump a fluid to the radiative panels. This process is illustrated in **Figure 3**.

Evaporative cooling coupled with solid or liquid desiccants - a form of non-cyclic evaporative cooling in which the air is dehumidified by secondary technologies, such as desiccants or specialised membranes, prior to evaporation. This theoretically extends the geographical applicability of evaporative cooling to more humid regions.

Further details on these and other innovative processes can be found in the previously referenced 'Cooling in the UK' report, and for radiative sky cooling from manufacturer SkyCool Systems.

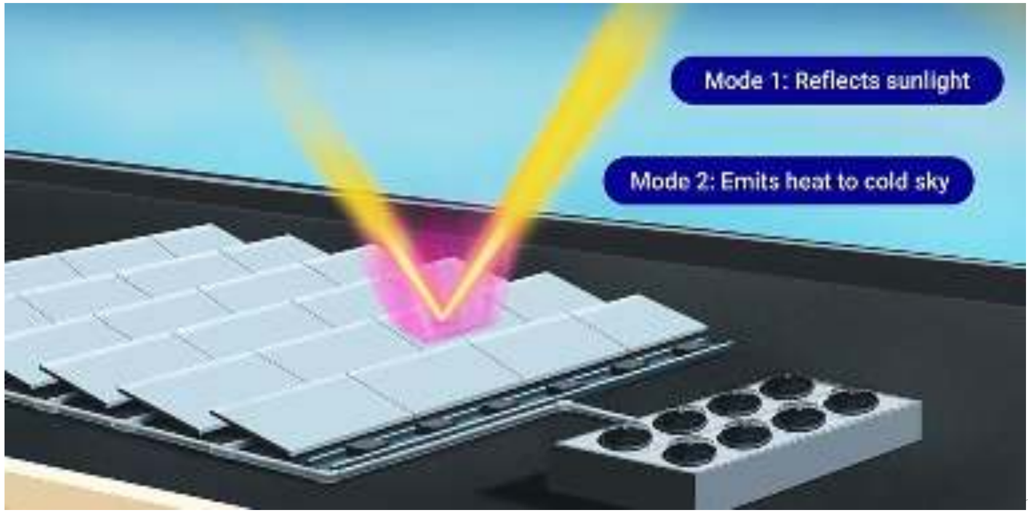


Figure 3 - radiative sky cooling principle of operation. Source: SkyCool Systems.

Active Cooling Equipment

The active cooling processes outlined in the previous section are physically realised in a bewildering array of equipment. This equipment comes at all sorts of scales and in all sorts of forms.

To illustrate this, let's have a look at the type of equipment that falls under the general heading of stationary AC. At one end of the scale spectrum are handheld and portable fans, used to cool a single person or room. At the other are devices called **chillers**, see the bottom of **Figure 4** for an illustration. These are used in a broad range of larger-scale AC and refrigeration applications, mainly in the multi-residential, commercial and industrial sectors. Between these two extremes come numerous devices, some of the more common types of which are also illustrated in **Figure 4**. As well as scale, these devices vary in other fundamental ways - for example, whether the equipment is packaged (contained in one unit) or split (contained in multiple units), and whether refrigerant, air, water or other heat transfer fluid is ultimately used to deliver cooling inside.

Chillers are central to our later case study, so it is worth saying a few more words about them. A chiller's purpose is to provide a chilled liquid, such as a water-glycol mix, into a network of pipes. This network can vary in scale from feeding cooling around, for example, a single high-end apartment or industrial process, to feeding cooling around an entire **district cooling network**, which provides cooling for many buildings, typically in a densely populated urban area. A chiller has two circuits - a primary circuit that commonly contains a refrigerant undergoing a vapour compression cycle, and a secondary circuit that contains the chilled liquid. A heat exchanger transfers heat from one to the other. **Figure 4** illustrates the two main types of chiller - air-cooled and water-cooled.

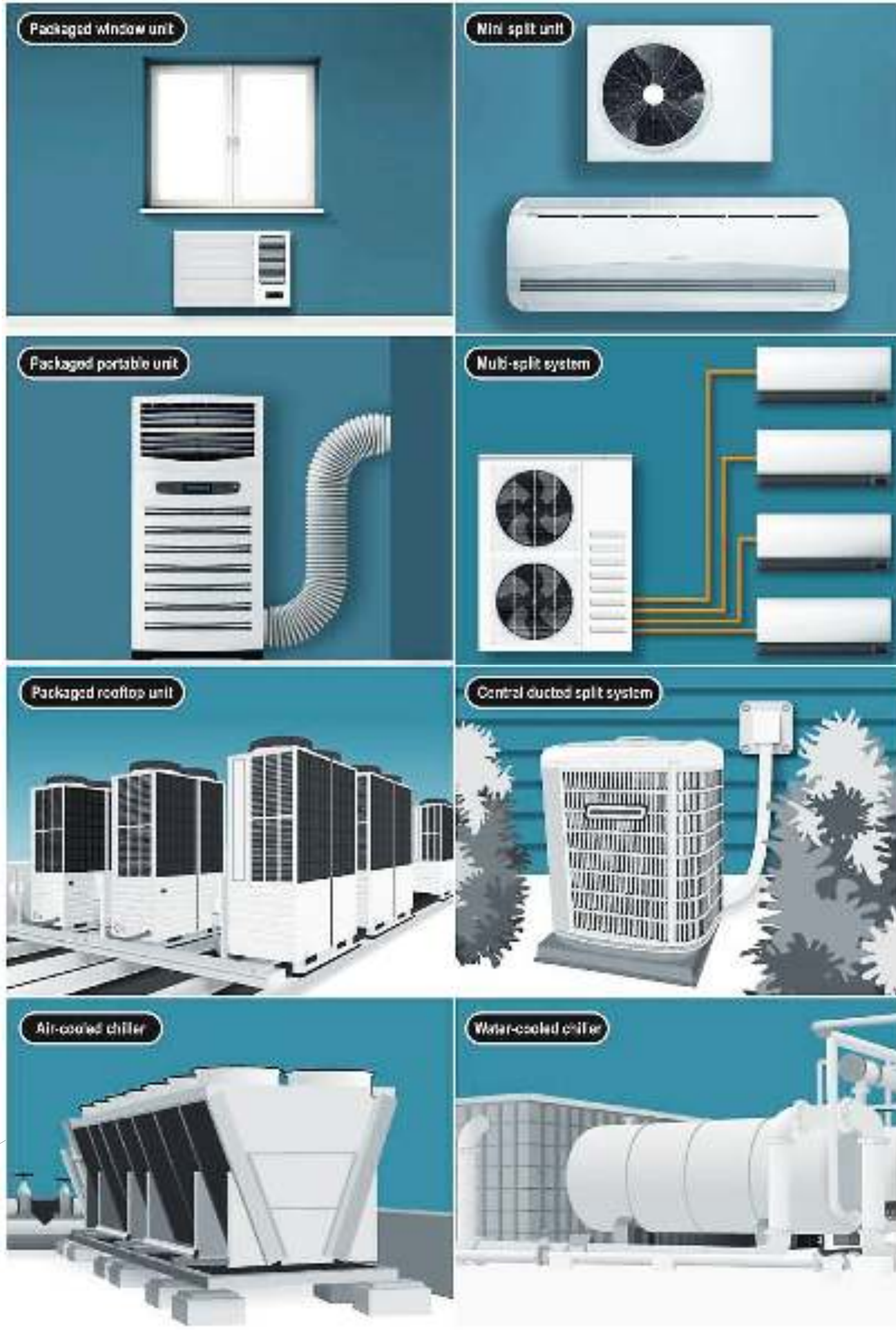


Figure 4 - common types of AC equipment. Descriptions available at the source.
Source: 'The Future of Cooling', International Energy Agency (IEA), 2018.

What Influences Cooling Demand?

Cooling demand is influenced by a complex web of factors, with each cooling application, the set of which we showed back in **Figure 1**, having a unique but overlapping set of factors. We will not go in to great detail - see 'The Cooling Imperative: Forecasting the size and source of future cooling demand' by the Economist Intelligence Unit for more - but it is useful to point out the most important factors.

Looking first at those factors that influence *unit sales* of cooling equipment in a given region, these include:

Population size. Clearly, more people and households equals more cooling demand potential, both directly in a residential setting, and in the broader economy too.

Affordable cooling access. Individuals and companies must be able to afford cooling equipment and have access to affordable, reliable energy - meaning electricity in most cases - to run it. While this factor is not universally relevant, an estimated 470 million people in poor rural areas lack access to safe food and medicines due to inadequate electricity and refrigeration, and an estimated 630 million people in hot, poor urban slums have little or no access to cooling due to inadequate power supplies. This is according to Sustainable Energy for All, quoted in the above-referenced report by the Economist Intelligence Unit.

Climate. Although some types of cooling applications are not optional and are therefore climate insensitive, the demand for discretionary cooling - residential AC in particular - is highly correlated with the local climate. The relevant climatic variables are the air temperature, humidity, prevalence of heatwaves, as well as how these are varying due to climate change. **Figure 5** shows how one common metric used to quantify the need for cooling varies across the world - red areas most needed. As you might expect, the need is highly concentrated in areas lying within a narrow band running roughly parallel with the equator and covering the tropics and sub-tropics. These areas,

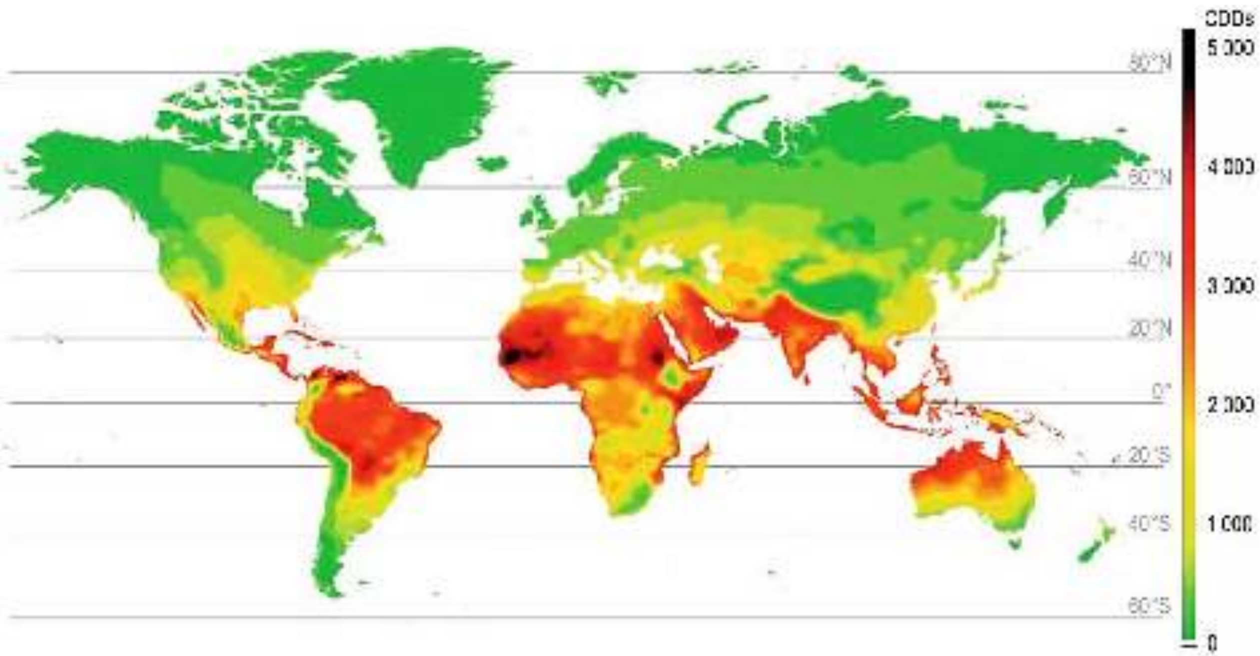


Figure 5 - global cooling need, as quantified by the average cooling degree days (CDD) metric from 2007-17. CDD measures the positive deviation of temperatures from a reference point in a given location over a specified period, see the source for more detail. Source: 'The Future of Cooling', IEA, 2018.

areas that experience hot weather for at least several weeks or months of the year are where AC is common. In cooler countries, mainly in the northern hemisphere, AC is simply unnecessary most of time, with electric fans generally sufficing during heatwaves.

Microclimate. Cities - or 'urban heat islands' as they are sometimes known - raise temperatures by trapping heat and preventing its dissipation into the lower atmosphere. Typically, the annual air temperature of a city with more than 1 million people can be between 1 and 3°C warmer than its surrounding areas, according to the National Geographic. The more densely populated a city and the bigger the land area it covers, the bigger the effect. The majority of people live in cities today.

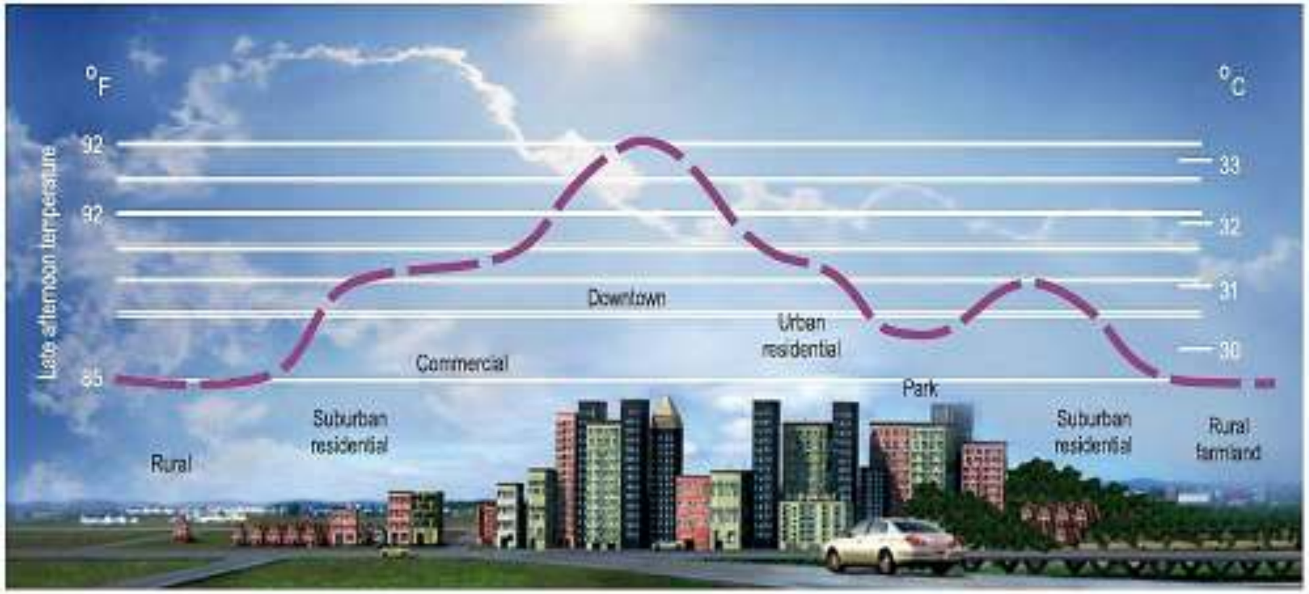


Figure 6 - illustration of the heat island effect in cities. Source: 'The Future of Cooling', IEA, 2018.

Product-specific factors. In addition to the broader factors discussed above, each commercial product that relies on cooling in its production, storage or operation has its own market dynamics that will impact demand for cooling related to that product. For example, when a large fraction of the planet joined social media platforms, the demand for data centres went up, as did the need to cool them. And, of course, when the billions of Covid-19 vaccines started being rolled out, the demand for vaccine cooling systems took off.

Turning now to the *amount of energy* needed to run the cooling equipment in a region, this depends on another set of factors, the most important of which are the:

Number of operational cooling units. Duh.

Size, type and **efficiency** of operational units. Cooling equipment varies considerably in its scale and inherent ability to convert input energy into output cooling.

Operation and **maintenance** of units. Energy usage goes up the more equipment is used, the less efficiently it is used - for example setting an AC's setpoint temperature ridiculously low, or cooling rooms not in use - and if it is not properly maintained.

Size and **thermal efficiency** of the enclosure being cooled. Smaller, more airtight and better insulated enclosures require less energy to cool.

Climate. It obviously takes more energy to cool to the same temperature in a hotter climate than in a colder one.

We quantify current cooling demand starting overpage. And in a later section we explore future cooling demand.

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