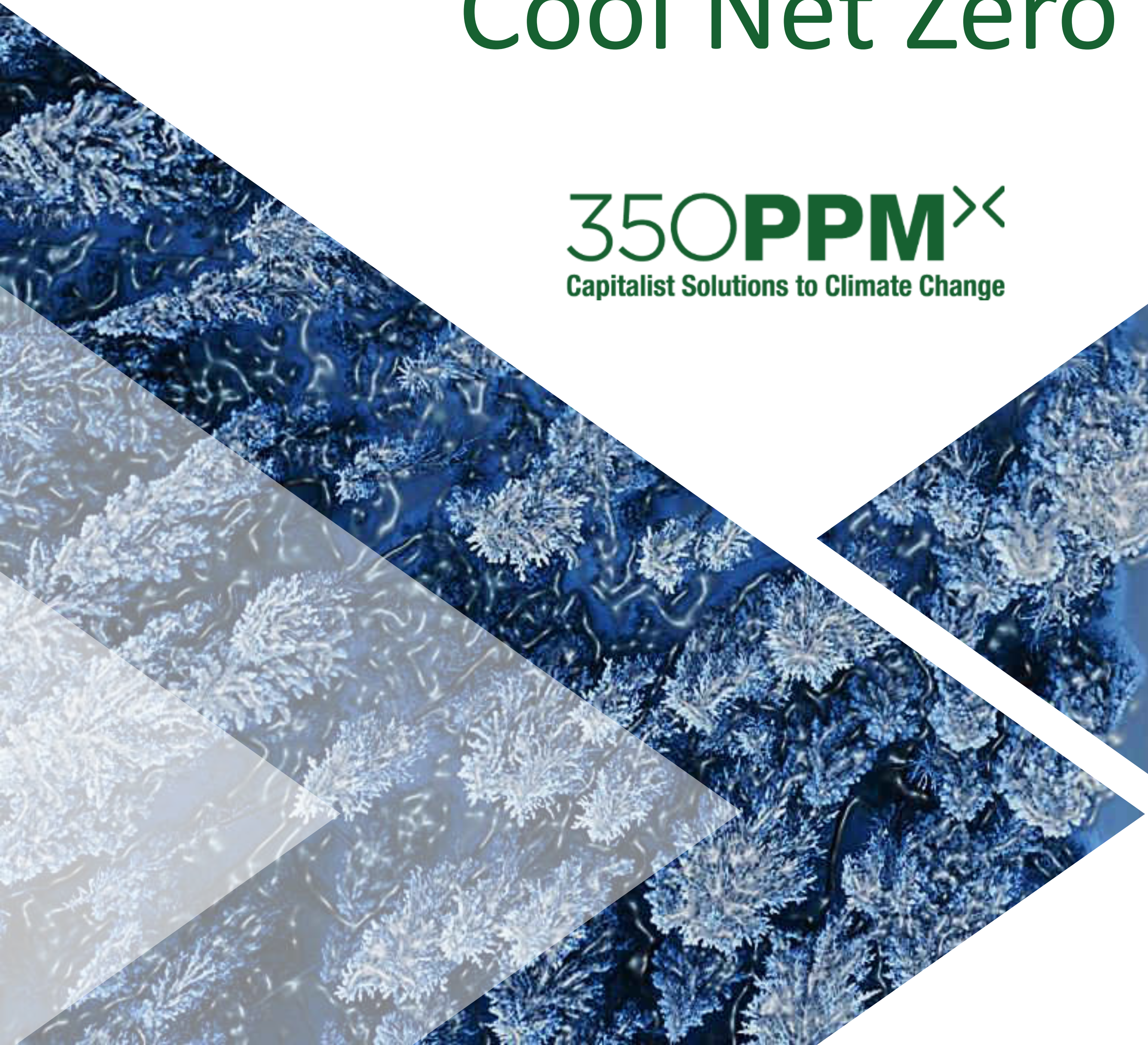
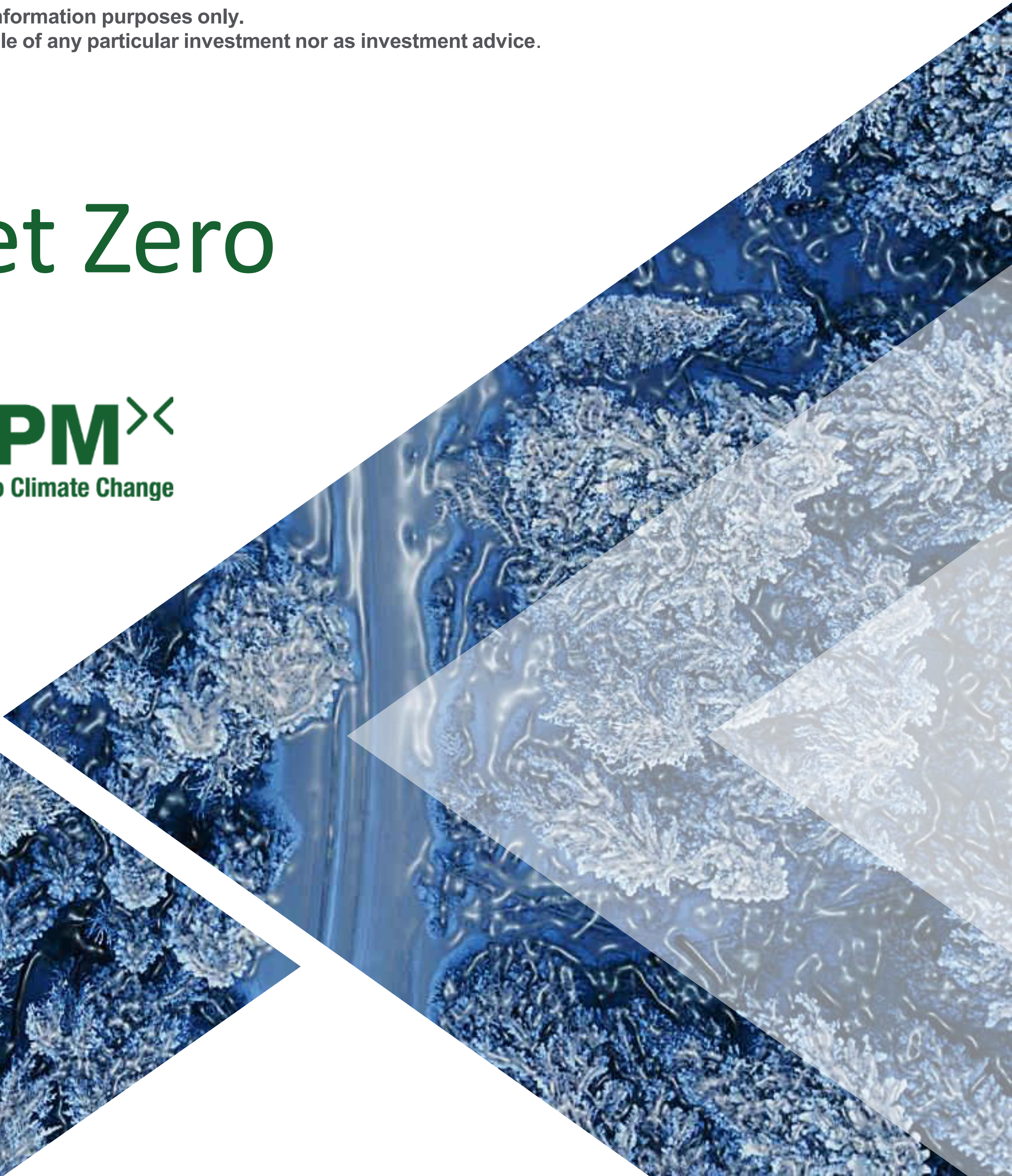
Cool Net Zero

350PPM
Capitalist Solutions to Climate Change





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Written January 2022.

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 - keeping people thermally comfortable, 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 the 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.

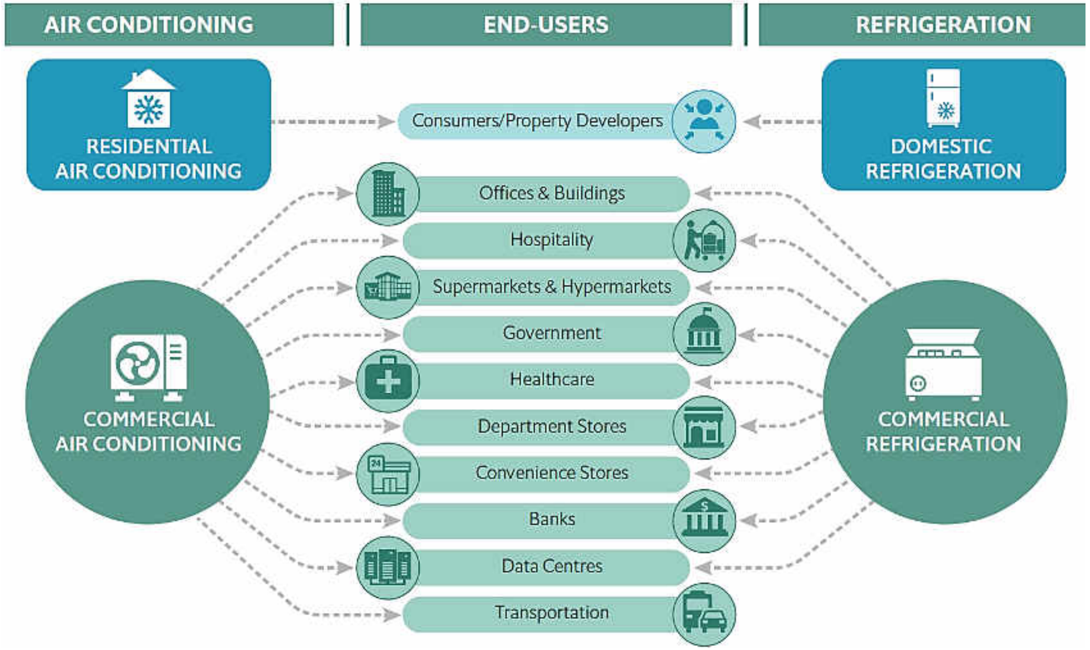


Figure 1 - end-users of air-conditioning and refrigeration, first part. Source shown on the next page.

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.

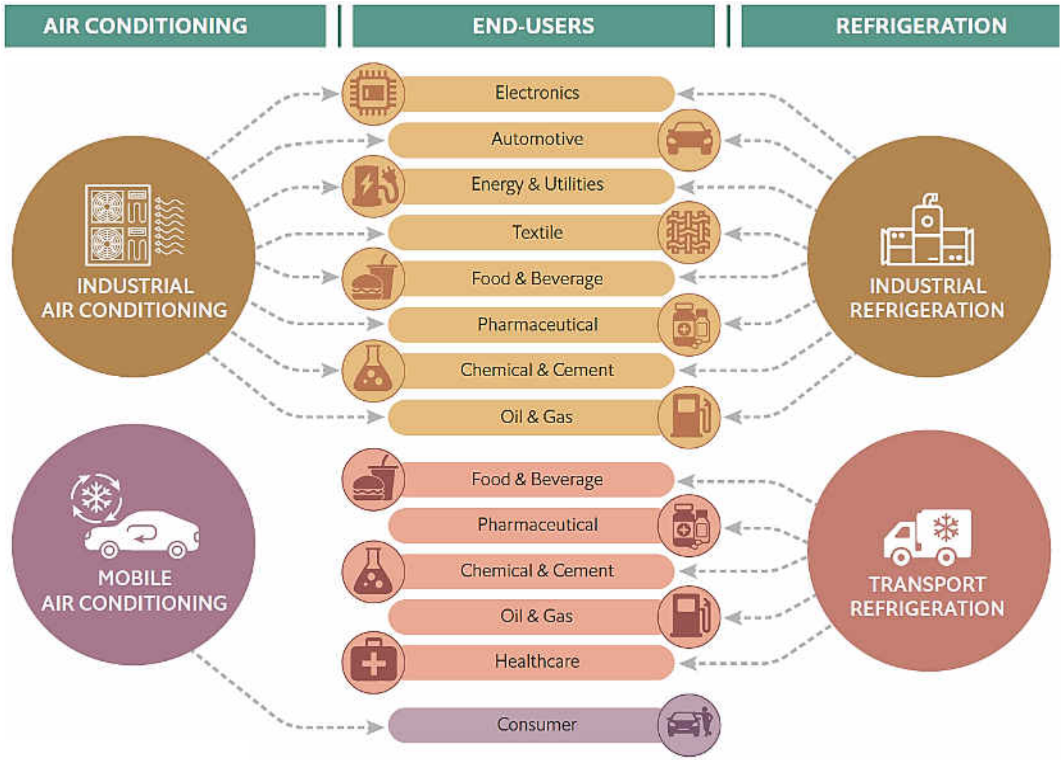


Figure 1 - end-users of air-conditioning and refrigeration, second part. Source: 'The Cooling Imperative: Forecasting the size and source of future cooling demand', the Economist Intelligence Unit, 2019.

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.

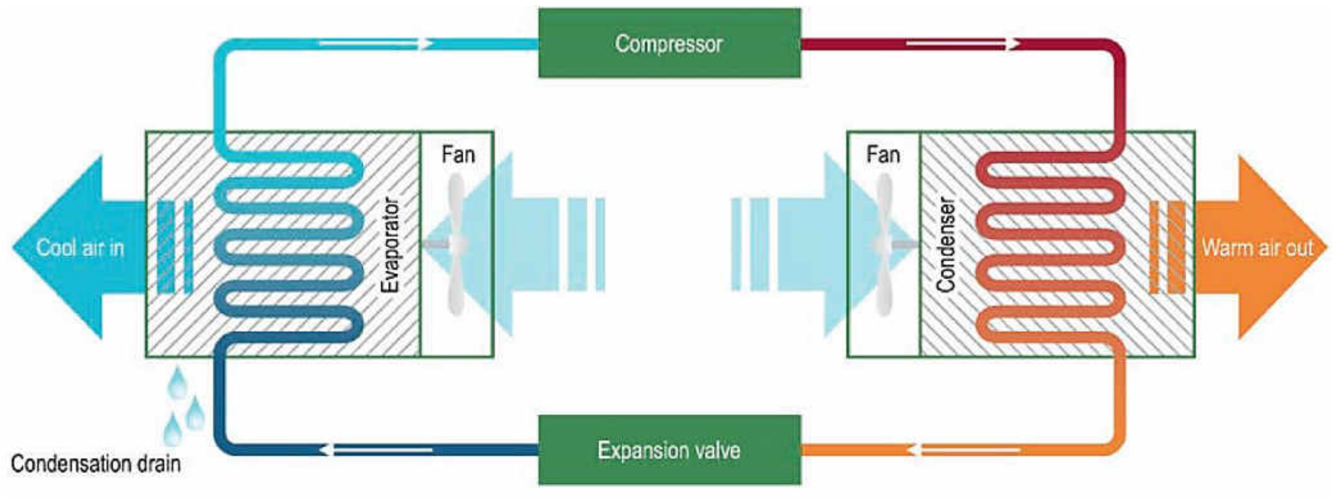


Figure 2 - illustration of the main components and operating principle of an AC system that uses a vapour compression cycle. Source: 'The Future of Cooling', International Energy Agency (IEA), 2018.

Vapour compression systems can achieve cooling down to any temperature you might want to use in everyday applications (for example fridges operate at about 4°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.

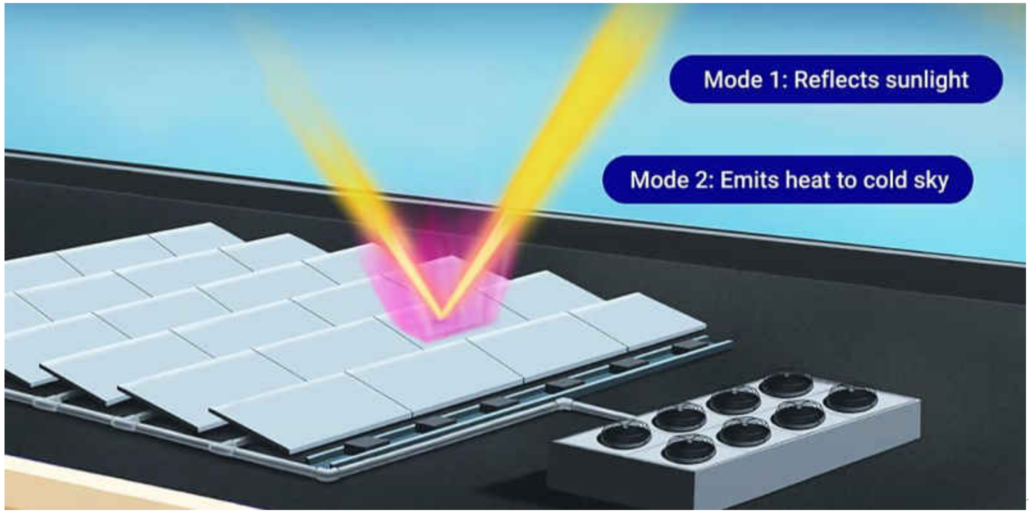


Figure 3 - radiative sky cooling principle of operation. Source: SkyCool Systems.

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.

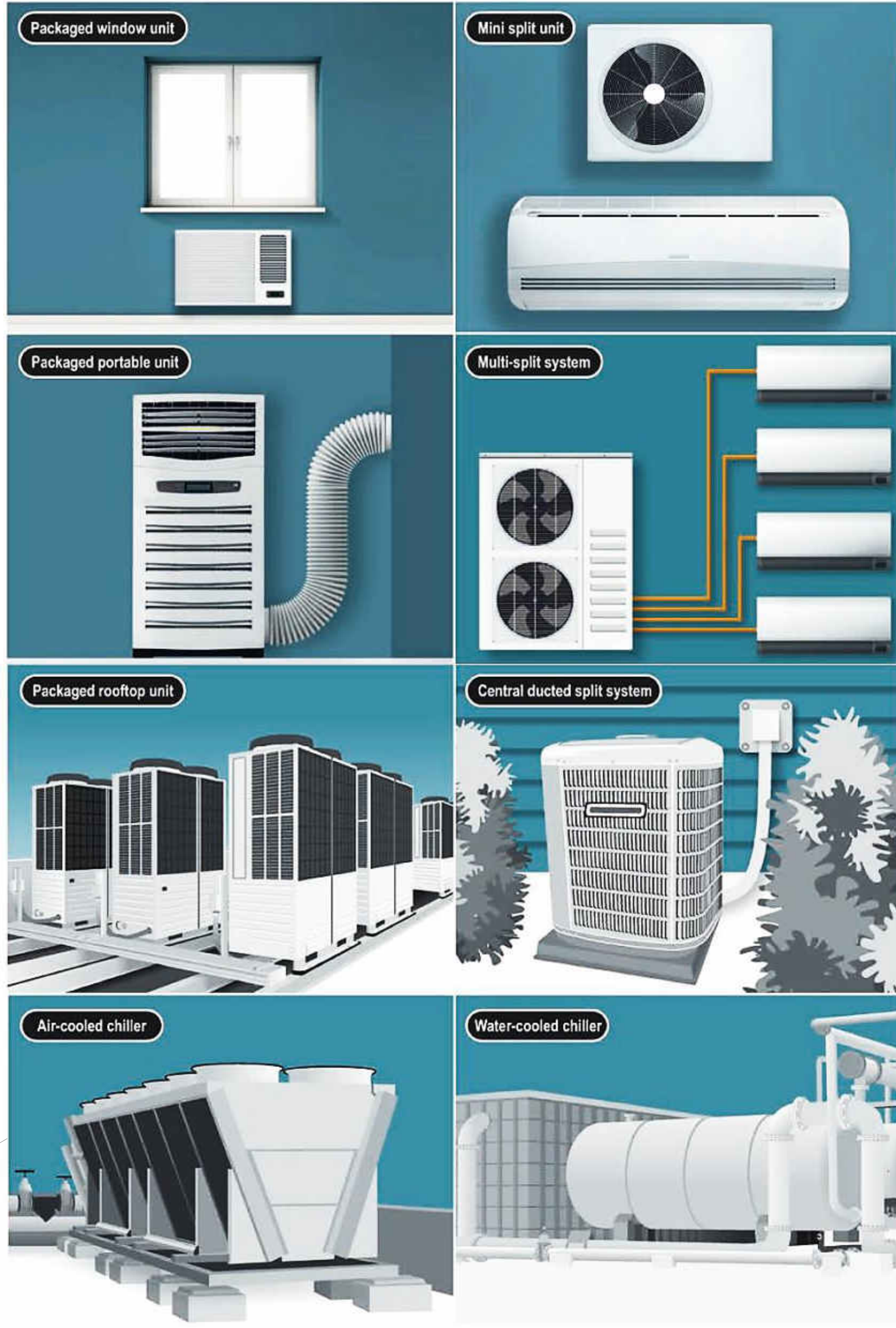


Figure 4 - common types of AC equipment. Descriptions available at the source. Source: 'The Future of Cooling', International Energy Agency (IEA), 2018.

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,

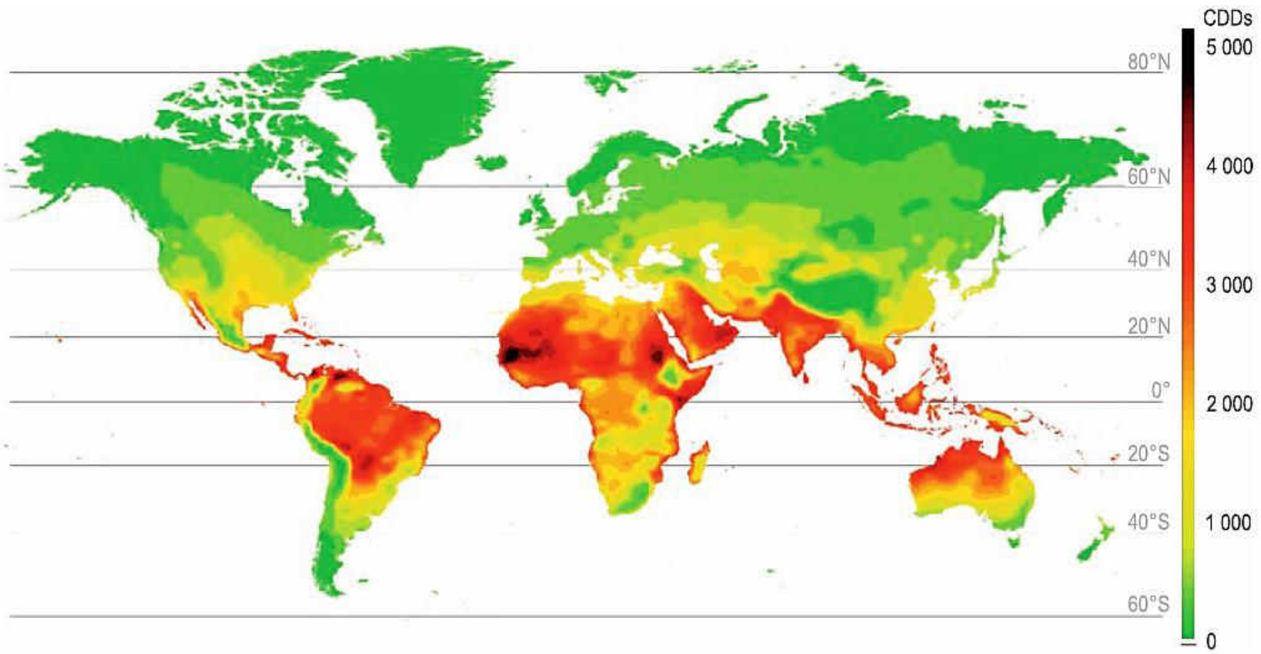


Figure 5 - global cooling need, as quantified by the average cooling degree days (CDD) metric from 2007-17. CDD measures the positive deviation of temperatures from a reference point in a given location over a specified period, see the source for more detail. Source: 'The Future of Cooling', IEA, 2018.

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.

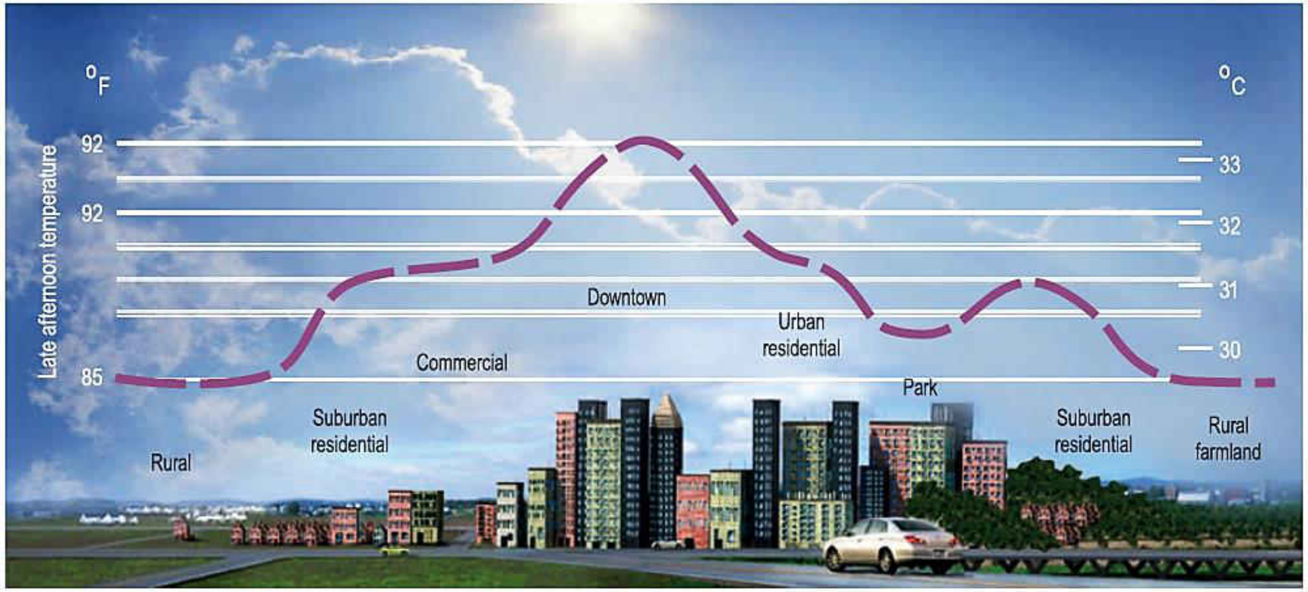


Figure 6 - illustration of the heat island effect in cities. Source: 'The Future of Cooling', IEA, 2018.

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.

Current Cooling Demand

In this section, the second of four, we provide an assortment of statistics about the current demand for cooling, both globally and in the UK. Skip this section.

Global Stock

An astonishing **4 billion pieces of cooling equipment** - or thereabouts - are in use today, extrapolating from 2018 figures from the University of Birmingham, see **Figure 7**, right. Stationary refrigeration accounts for ~50% of these units, ~90% of which are domestic fridges or freezers. The remaining ~50% of units is evenly split

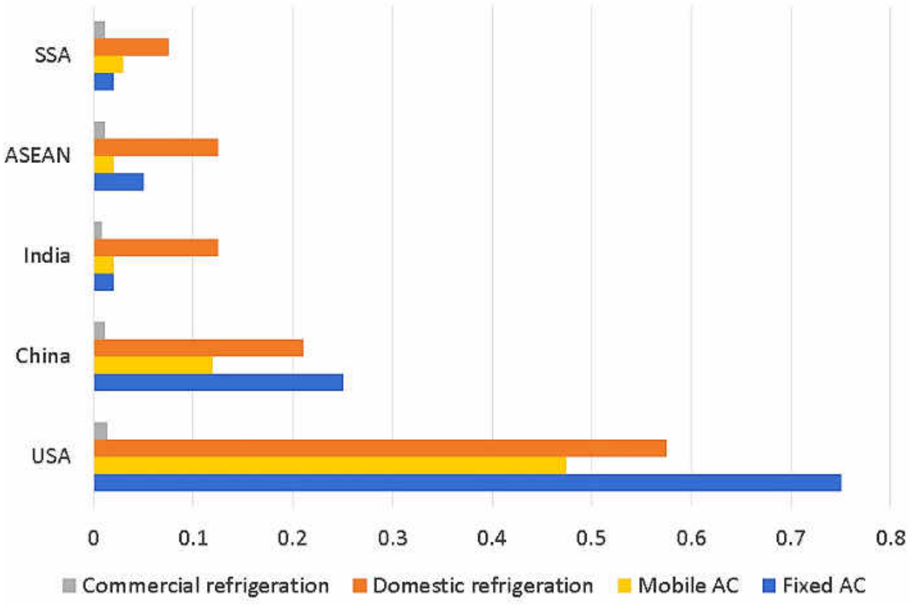


Figure 8 - per capita geographical distribution of cooling equipment stock, by sector, 2018 (number of units per capita). SSA - Sub-Saharan Africa; ASEAN - Association of Southeast Asian Nations. Data source: same as **Figure 7**.

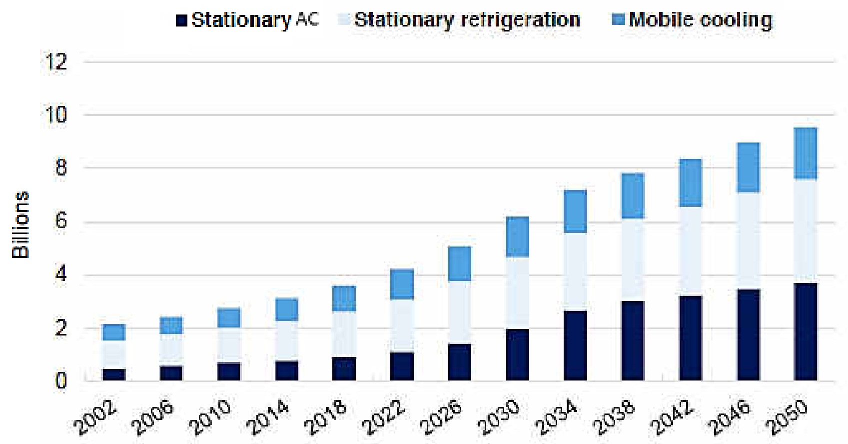


Figure 7 - stock of cooling appliances globally, by sector (number of units). Forecasts from 2022 onwards. Source: 'A Cool World: Defining the Energy Conundrum of Cooling for All', University of Birmingham, 2018.

between stationary AC (provided by buildings' ACs) and mobile cooling (provided by vehicle AC and mobile refrigeration).

As well as telling us about 2018, **Figure 7** also shows how the global stock of cooling equipment has evolved over the past two decades. Very roughly, the number of units has doubled over this timeframe. And **Figure 7** also gives a prediction of how the global stock might evolve over the next three decades, based on a single scenario provided by the Green Cooling Initiative. This prediction implies more than another doubling in the number of units by 2050.

Figure 8, left, provides some insight about where these billions of cooling units are located. It shows the number of units per capita for the most cooling-dependent geographical regions in 2018, split by more granular application categories than those used in **Figure 7**. The transport and industrial refrigeration categories were left off this graph as the bars would be tiny. **Figure 8** demonstrates that there is significant disparity across regions in terms of cooling access, though this does not seem to be obviously related to the region's need for cooling (compare **Figure 5**); wealth is likely the key factor here. **Figure 8** is another indicator that there is a considerable unmet demand for cooling - AC in particular - in poorer regions.

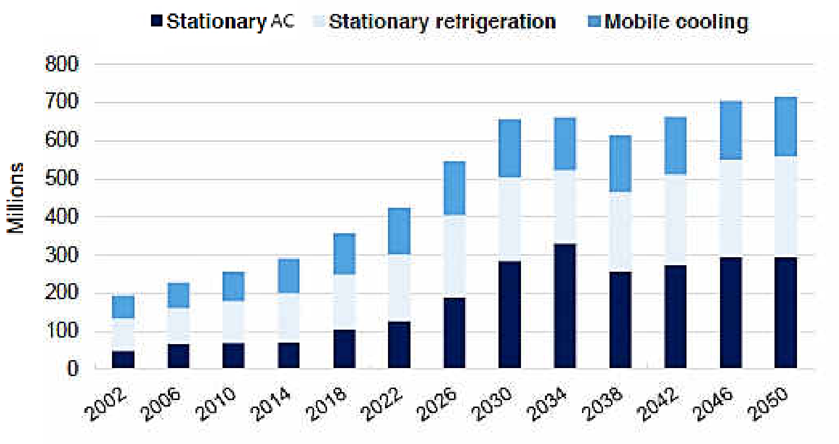


Figure 9 - annual sales of cooling appliances globally, by sector (number of units). Forecasts from 2022 onwards. Source: same as **Figure 7**, on previous page.

Global Annual Market

As shown in **Figure 9**, left, more than **350 million pieces of cooling equipment** were sold globally in 2018. This estimate, again from the University of Birmingham, ties up reasonably well with another estimate from the Economist Intelligence Unit, who also bravely put a monetary value on this market - **US$135 billion**. This makes the cooling market about the same size as the digital games market and larger than the solar PV (photovoltaic) market at the time. **Figure 9** shows that the annual cooling market has grown steadily for the past two decades, roughly doubling over this period, and is predicted to accelerate in the 2020s to roughly double again by 2030, before settling at this higher level. The Economist Intelligence Unit is more conservative, forecasting growth of about a third from 2018-2030, to an annual market size of US$170 billion in 2030.

Figure 10, right, provides more granularity than **Figure 9** about the relative sales between cooling applications. It shows that 92% of global annual cooling sales come from domestic refrigeration, residential AC and mobile AC combined. Note, however, that although smaller in number, commercial and industrial AC and refrigeration units - all categories relevant to chillers - are typically orders of magnitude larger, more expensive and power-hungry than residential and domestic units. See **Figure 10**'s source for additional figures, split by region and business type.

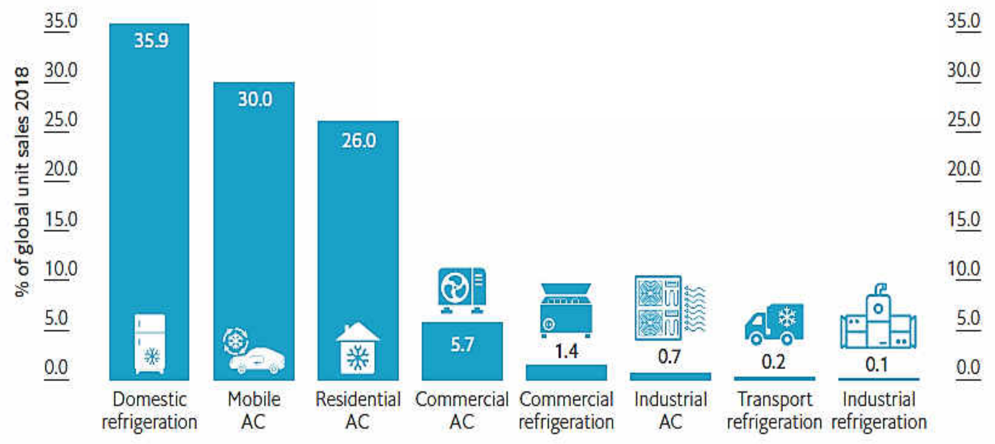


Figure 10 - annual sales of cooling appliances globally, by subsector, 2018 (% of unit sales). Source: 'The Cooling Imperative: Forecasting the size and source of future cooling demand', the Economist Intelligence Unit, 2019.

Global Energy Usage

As we pointed out earlier and explore in detail later, cooling is a significant contributor to climate change, in large part due to its energy use. We quantify this here.

In summary, cooling equipment consumes **4TWh of energy annually worldwide** - or thereabouts - based on 2018 figures from the University of Birmingham. This is ~3.5% of the world's total energy demand. Stationary AC is the most power-hungry application (41%), followed by stationary refrigeration (34%) and then mobile cooling (25%), see the left part of **Figure 11**, below. If we compare **Figure 11** with **Figure 7** it is clear there is not a direct correlation between the number of units and their energy consumption; it's only one of several relevant factors, outlined earlier. Stationary AC is the most extreme example of this, using 41% of energy but accounting for only 25% of units. Tying in with the loosely related **Figure 8**, the right side of **Figure 11** illustrates that China, the US and India dominate global cooling energy usage.

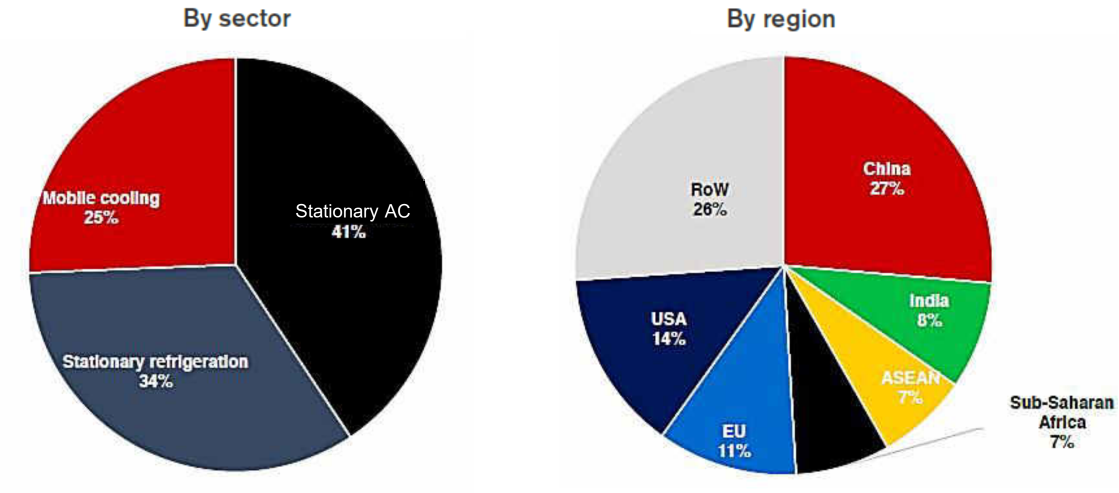


Figure 11 - global cooling energy consumption, by sector and region, 2018 (%). Source: 'A Cool World: Defining the Energy Conundrum of Cooling for All', University of Birmingham, 2018. ASEAN - Association of Southeast Asian Nations; RoW - Rest of World.

Electricity Usage

The stationary AC and refrigeration sectors are powered overwhelmingly by electricity, while the mobile cooling sector is powered primarily by fossil fuels. Making the simplifying assumption that stationary AC and refrigeration are powered entirely by electricity implies that these two sectors combined consumed up to 12% of the world's electricity in 2018. Lumping heat pumps in with AC and refrigeration, you can find estimates of this group consuming **25-30% of the world's electricity**. Clearly then, cooling, and vapour compression more broadly, is very important to the electricity sector and vice versa.

Peak Demand

In most countries with significant seasonal cooling demand, cooling's contribution to peak electricity demand is markedly higher than to total demand throughout the year. For example, in 2016 the peak demand due to AC in the US reached 30% of the total demand on a national basis, even though annually it only uses 15% of the total demand, according to the International Energy Agency's (IEA) 'Future of Cooling' report. This report highlights that peak AC demand can be far more extreme than this on occasions, especially on a local basis, citing the example of 74% of total peak demand in Philadelphia on a particularly hot day in July 2011. Such high and variable peak demand due to cooling is problematic as it places considerable strain on electricity grids. As we explore later, Cold Thermal Energy Storage (CTES) can potentially help to flatten these demand peaks (and earn itself some money in the process). This is one of the main benefits of CTES to the electricity system.

UK Energy Usage

The government provides detailed energy consumption statistics, from which it is possible to extract some useful insights about cooling in the UK. In these statistics the economy is split into service, industrial, domestic and transport sectors. We have assumed that the 'cooling and humidification', 'cooled storage', 'fans' and 'refrigeration' consumption categories are relevant to this report - this is debateable. For simplicity we are going to call the combined set of these categories 'cooling', though they include aspects beyond simply reducing temperature.

The main findings are that for the UK in 2019:

Cooling was **98% powered by electricity**; 2% powered by fossil fuels.

Across the service and industrial sectors, cooling accounts for **17% of total electricity use** and 7% of total energy use. Figures for the other sectors are not given.

In the service sector, cooling accounts for 28% of electricity use and 11% of total energy use, while in the industrial sector, cooling accounts for 6% of electricity use and 2% of total energy use.

In the service sector the top users of cooling are in terms of:

- Total amount of energy, by subsector, in descending order - retail, offices, storage, hospitality, health and arts, leisure and community.
- Cooling's share of total *electricity* use, by business type, in descending order - cold stores, large food shops, clubs and community centres, theatres, small shops, hotels, pubs, large distribution centres, law courts and leisure centres. The percentage shares are shown in **Figure 12**.

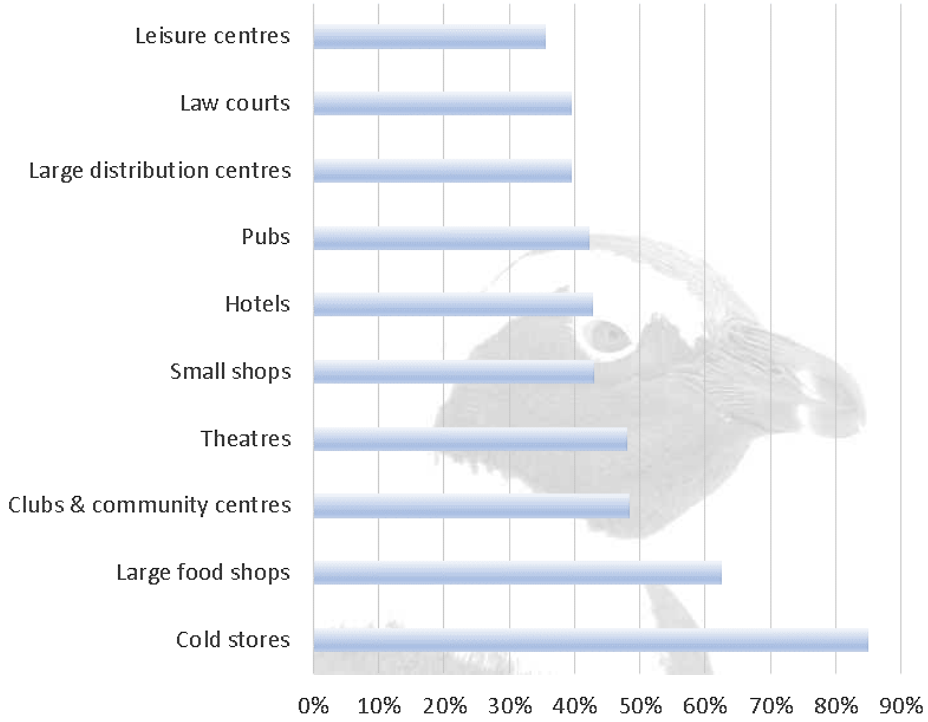


Figure 12 - cooling's share of total electricity consumption in the UK's service sector, by business type, 2019 (%). Data source: 'Energy Consumption in the UK 2020', UK government, 2020.

- Cooling's share of total *energy* use, by business type, in descending order - cold stores, large food shops, small shops, clubs and community centres and museums. **Cold stores have the one of the highest energy costs of any industry**; energy expenditures are usually second only to payroll, according to GreenTech Media.

In the industrial sector the only recorded users of cooling are, by cooling's share of total electricity or energy, in descending order - manufacturers of food and beverages, manufacturers of tobacco, and manufacturers of chemicals and chemical products (this last type of manufacturer has the highest absolute energy use).

UK Market

We end this section of the report with a somewhat idiosyncratic selection of stats about the UK cooling and then chiller markets. It is not easy to find high quality data on these areas, or it is hidden behind paywalls.

Domestic Market

According to the ONS (Office for National Statistics), there were 27.8 million households in the UK in 2020, so it is reasonable to guess there are a similar number of domestic fridges-freezers in operation. The domestic refrigeration market is estimated at up to £1 billion per annum, according to the ACRIB (Air Conditioning and Refrigeration Industry Board), the industry body for the RACHP (the Refrigeration, Air Conditioning and Heat Pump) industry, see **Figure 13**. **Figure 13** is dated but other sources suggest the refrigeration and wider cooling markets are relatively slow changing, so this may remain a reasonable estimate.

The picture is very different if we look at domestic AC. The previously referenced 'Cooling in the UK' report estimates that only 3-5% of homes have some form of portable or fixed cooling unit, with fixed units in the minority, and that sales of AC units in the domestic sector numbered just ~6,500 in 2019.

Non-domestic Market

Non-domestic buildings in the UK are far more likely to have AC than domestic ones. This is reflected in the annual sales figures, which show the non-domestic sector sold ~150,000 units in 2019, 23 times the domestic AC market (same source as domestic figures above). Combined, the domestic and non-domestic AC *and heat pump* markets are estimated at £0.7 billion annually, according to **Figure 13**, which also suggests the commercial refrigeration market is around the same size, with transport refrigeration coming in at £0.2 billion, and industrial refrigeration unknown in size. Therefore, the overall cooling and heat pump market is estimated at **£2.7 billion per annum**. In addition, the refrigeration market is estimated to support a value of goods and services way beyond this - approaching £100 billion per annum.

Sector	Value £ billion
Air Conditioning	0.7
Commercial refrigeration	0.5-0.7
Industrial refrigeration	Not known
Transport refrigeration	0.2
Domestic refrigeration	0.7-1.0

Figure 13 - annual market value estimates for the main sectors of the UK cooling and heat pump industry in 2013. Definitions of sectors at source. Source: ACRIB industry overview webpage, accessed Jan 2022.

Chiller Market

We introduced the concept of a chiller earlier and they feature in our later case study. In the UK, air-cooled chillers sold an average of 2500 units and water-cooled chiller sold an average of 400 units per annum from 2013-2019. Chillers range in size from providing kW to MW-scale output, with prices ranging from thousands into the millions of pounds. Although the precise value of this annual UK market is unknown, the market for chiller units above 50kW in the EU (including the UK) stood at €1.1 billion in 2020, according to Eurovent Market Intelligence. One estimate (of uncertain quality) suggests the worldwide annual market is roughly ten times this size, at **~US$10 billion**, with commercial and industrial sectors accounting for 75% of the market.

Net Zero Cooling

In this section, the third of four, we look at the greenhouse gas emissions associated with cooling and the strategies by which these could potentially be eliminated. Skip this section.

Current Cooling Emissions

As vital as it is, cooling is responsible for considerable harm to the environment. A few decades ago the focus was primarily on the harm the refrigerants in use at the time - particularly chlorofluorocarbons (CFCs), which have since been progressively phased out - were doing to the ozone layer. More recently the focus has shifted, somewhat belatedly, to the effect that cooling has on climate change, through its associated greenhouse emissions, which are substantial. Estimates for **cooling's contribution to global greenhouse gas emissions range from 7-10%**, which is three times more than aviation and shipping combined, according to the Economist Intelligence Unit. Cooling creates emissions both directly, from the release of refrigerants (and insulation foam gases) into the atmosphere, the most common of which - HCFCs and HFCs - have a very high global warming potential (GWP) (explained overpage), and indirectly, though the energy used to power the equipment. These emissions occur during manufacturing, operation and disposal. On average, direct emissions account for ~30% of cooling equipment's climate impact, according to the Environmental Investigation Agency (EIA); indirect emissions, 70%.

Figure 15 breaks down the global cooling sector's emissions by sector and region. Looking first at the sector split, if you compare this with **Figure 11**, three pages back, it is clear there is not a direct correlation between energy use and emissions. Mobile cooling is particularly problematic emissions-wise, accounting for 31% of emissions despite only consuming 25% of the sector's energy. This is because, in contrast to other cooling applications, it consumes primarily fossil fuels and is characterised by a higher share of emissions from refrigerant leakage and equipment manufacture and disposal (37%; 27% is the equivalent share for the other applications).

There is also not a direct correlation between energy use and emissions in a region. For example, China accounts for 33% of emissions despite only consuming 27% of world's energy related to cooling. This is because China is heavily reliant on coal. It therefore has relatively higher emissions than regions with a cleaner electricity supply.

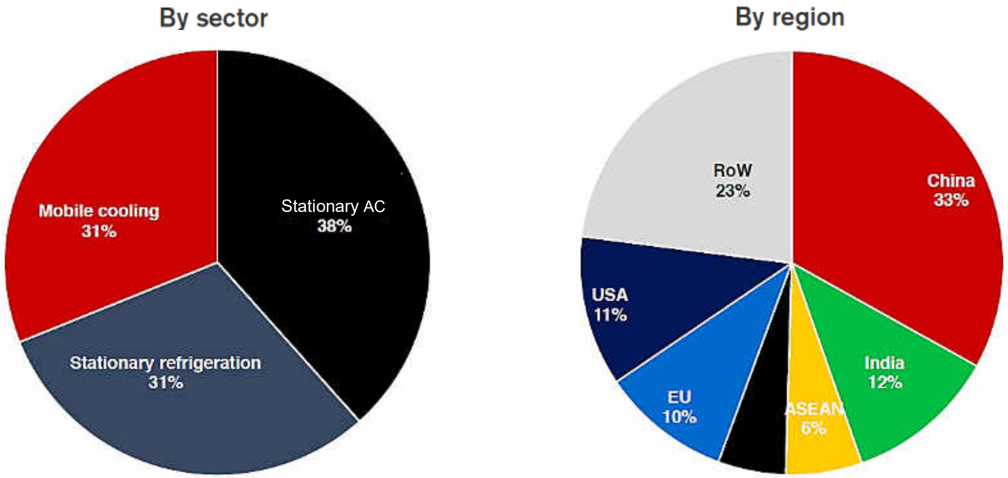


Figure 15 - global cooling sector greenhouse gas emissions, share by sector and region, 2018 (%). Source: 'A Cool World: Defining the Energy Conundrum of Cooling for All', University of Birmingham, 2018.

Getting to Net Zero Cooling

The basic idea of ‘net zero cooling’ is to reduce the greenhouse gas emissions associated with the cooling sector as much as possible, and if unavoidable emissions remain, to offset them by taking emissions permanently out of the atmosphere (by direct carbon capture, for example). Of course, the cooling sector cannot be considered in isolation as it intricately linked to the electricity, heat and buildings sectors, amongst others. Any strategy to decarbonise cooling will therefore influence and be influenced by parallel decarbonisation strategies and progress in these sectors.

To date, cooling does not seem to have been a big priority for governments in the context of their overall net zero strategies, despite its high emissions (though there are some signs this is starting to change, as evidenced by an increase in the number of countries including cooling in their Paris Agreement climate pledges). This is certainly the case in the UK, where heating has taken most of the limelight. This is understandable to some extent as heating has higher levels of emissions (37% of total UK emissions) and is mostly powered by fossil fuels. This requires more radical change and hence government intervention, governments would argue, to decarbonise. While there is relevant regulation around energy efficiency and refrigerant use in place in many countries, current progress towards net zero cooling is arguably now being driven more by cooling equipment manufacturers and installers seeking new business opportunities as their customers become increasingly climate-conscious.

Reducing Direct Emissions

It is possible - if wildly impractical - to imagine completing eliminating cooling’s direct emissions. These are caused by the release of refrigerants and insulation foam gases (though we will not discuss the latter further here). In practice, the goal will be to greatly reduce emissions while taking equipment energy efficiency (covered separately later), safety, affordability and other relevant factors into account. The main strategies include:

Minimising Lifetime Refrigerant Leakage

Most cooling equipment is based on vapour compression and therefore uses gaseous refrigerants. These can leak during equipment manufacture, operation - 24hrs a day whether the equipment is on or off - and disposal. The majority of direct emissions occur when equipment is being disposed of and leakage spikes. Multiple sources suggest that it is perfectly feasible to substantially reduce lifetime leakage by improving leak prevention and detection features on equipment, and with more careful disposal of equipment, including re-use or destruction of refrigerant gases. In theory, significant progress can be made in this area without massive capital investment, relatively quickly.

Shifting to Low-GWP Refrigerants

On the assumption that some degree of refrigerant leakage is inevitable, a parallel strategy is to reduce the global warming potential (GWP) of the refrigerants in use. The GWP is a measure of the potency of a greenhouse gas compared to carbon dioxide, which is given a GWP of 1. The most common refrigerants in use today have a GWP 2 to 4 orders of magnitude higher than this. Ideally, we should be using 'ultra-low' GWP refrigerants, meaning with a GWP of less than five.

In general, an existing cooling system cannot simply have its refrigerant swapped out for a lower-GWP one - the system has to be completely replaced with one designed to work with a low-GWP refrigerant, or undergo a major refit. This means that without massive expense, the shift to low-GWP refrigerants will have to happen slowly, over decades, as systems are naturally replaced at end-of-life.

The good news is that ultra-low GWP refrigerants, including natural (not man-made) ones - such as ammonia and, somewhat ironically, carbon dioxide - do exist across nearly all - but not all - cooling applications, each of which has unique requirements. The extent to which efficient, low-GWP equipment is already available and deployed varies greatly by application and region. This is summarised nicely in the 'Key Findings' section of Environmental Investigation Agency's 'Pathway to Net-Zero Cooling Product List'. The bright spots include domestic refrigerators, with 75% of all new manufacturing using natural refrigerants, and commercial refrigeration, where CO_2 systems are gaining significant traction.

Overall though, low-GWP solutions are not widely deployed, and there remain significant barriers to their deployment, such as safety concerns (some low-GWP refrigerants are flammable, e.g. propane), building codes (that prevent you using flammable refrigerants), and lack of a skilled workforce (with the skills and knowledge to safely handle these refrigerants).

On the policy side of things there are already international agreements in place to phase down and out high-GWP refrigerants, including HCFCs and, most recently, HFCs. These include the Kigali Amendment to the Montreal Protocol (first brought in to deal with the hole in the ozone layer), which has been ratified by over 100 countries, and regional frameworks such as the EU's F-Gas Regulation. These provide an important policy framework for action, though the ambition of such policies will need to be ratcheted up to deliver net zero cooling on a timescale compatible with overall net zero ambitions, according to the Carbon Trust et al.

Increasing the Penetration of Non-Refrigerant Cooling Methods

As we highlighted earlier, there are a number of cooling processes and associated technologies that do not use refrigerants at all. Some of these are already in common use, if in niche applications, while others are promising but early-stage technologies, yet to be fully developed or commercialised but with the potential for wide applicability.

The extent to which it will be possible to shift to non-vapour-compression systems, and when, is a complicated one, with cost a key consideration. The IEA has stated an ambition for non-vapour-compression systems to achieve the same cost as vapour compression under mass production, something that is crucial for the technologies to be adopted at scale (quoted in 'Cooling in the UK'). However, wider deployment is not expected until the 2030s onwards, though I'm sure companies like SkyCool Systems, mentioned earlier, would disagree with this timescale. In short, yes these technologies might help at some point but relying on this happening is not a sound strategy.

Reducing Indirect Emissions

As most cooling systems are electrically powered, and as grid-supplied electricity is rapidly decarbonising due to the switch to renewables, it might be tempting to say that these indirect emissions will take care of themselves, without any action on the part of the cooling industry or its customers. While this is true to some extent, the speed of the cooling, electricity and overall net zero transitions could be increased and their cost reduced using the most proactive approach possible. One estimate is that meeting future cooling needs sustainably could reduce the costs of the renewable energy build-out by up to **US$3.5 trillion by 2030** and accelerate the net zero transition by up to **eight years**, according to the Economist Intelligence Unit. Such a proactive approach involves a combination of: (a) reducing the need for active cooling; (b) using the most inherently efficient equipment, as efficiently as possible, to supply this need; (c) powering this equipment with 100% zero-carbon energy; (d) using energy storage to improve both the operational efficiency of equipment and, while grid-supplied electricity remains non-zero-carbon, the carbon intensity of electricity inputs.

Reduce Active Cooling Need

The inherent need for active cooling can be reduced by incorporating passive cooling measures, introduced earlier, into the design of buildings and other thermal enclosures. A simple example of this is to locate, for example, a data centre in a cool climate, or even floating on water. This is best done at the design stage but certain measures can be retrofit into or around existing enclosures. Governments can influence or dictate the use of passive cooling measures in buildings through incentives and building codes. It is also possible to plan towns and cities - which are naturally hotter than out in the countryside, as we saw earlier - such that there is a slightly reduced need for cooling.

Use Efficient Cooling Equipment, Efficiently

Parallel to reducing the inherent need for active cooling, the energy required for active cooling can be minimised by selecting the most energy-efficient equipment for a specific cooling application, and then using it as efficiently as possible.

Efficiency can be quantified using several metrics. The most straightforward measure is the Coefficient of Performance (COP), which is the ratio of the refrigerating capacity of the system to the energy consumed. The Seasonal Energy Efficiency Ratio (SEER) is related to the COP and reflects the efficiency of a product over an entire year/season, thus accounting for the variations in ambient temperatures.

Efficiency improvement opportunities are greatest during the equipment selection and installation phase, rather than once operational. The installation of a district cooling network provides a good example of this. As introduced earlier, district cooling involves the centralised production and delivery of cooling to multiple buildings. This is typically only done in a a region with a hot climate and high density of buildings. Due to efficiencies of scale, this has the potential to cool multiple times more efficiently than each building having its own cooling system. In addition, district as well as smaller-scale cooling systems can potentially reduce their energy usage by utilising waste cold. One possible source of this is the liquified natural gas (LNG) industry, which uses very low temperatures to convert natural gas to a liquid for transport purposes. However, waste industrial heat tends to be more common than waste cold and, as we saw earlier, there are cooling processes, such as absorption, which can utilise waste heat. On the flip side, cooling systems typically generate appreciable amounts of waste heat. If this is recovered into a heating system, this will boost the efficiency of the combined heat and cooling system.

Having established the basic type of system, selecting for efficiency then involves picking equipment: (a) suitable for the application; (b) at an appropriate scale relative to anticipated demand; (c) that is market-leading in efficiency for its type. This is all subject to other constraints such as cost, reliability, etc. This equipment then has to be installed according to best practices, with cooling being transferred to end-users in an optimal manner.

The efficiency of functionally interchangeable equipment is influenced by many technical factors. These include the selection of the refrigerant and related refrigeration cycle, and of the key components that bring this cycle to life, i.e. compressors, heat exchangers, materials, controls, etc. In general, equipment that is more flexible - able to adjust its output, and to do so selectively - and smarter - able to collect data from internal and external sources, process it, and then adjust operation intelligently - is likely to be more efficient. We give an example of a smart, flexible cooling setup in our later case study.

As shown in **Figure 16**, cooling efficiency has been improving at a more or less steady pace for the past three decades and, even without a step-change in cooling equipment, this is expected to continue. **Figure 16** highlights that, due to this march higher in efficiency, in-use equipment quickly becomes highly inefficient relative to the start-of-the-art. For example, existing state-of-the-art vapour compression systems can be up to five times more efficient than average systems, so the potential for improvement in this area is significant.

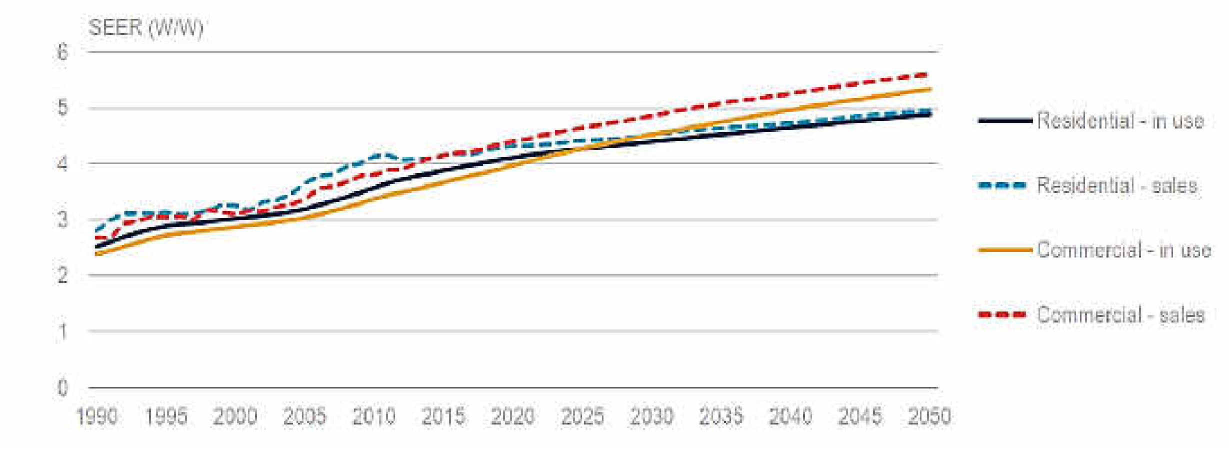


Figure 16 - historic and future trends in cooling efficiency, based on the weighted average world Seasonal Energy Efficiency Ratio (SEER) in a 'Baseline' scenario. Source: 'Cooling in the UK', BEIS, the department for Business, Energy and Industrial Strategy, 2021.

Turning briefly to policy, many governments around the world already have Minimum Energy Performance Standards (MEPS) in place which ban the sale of the most inefficient cooling (and other) equipment. To get to net zero cooling, these standards will inevitably need to be strengthened and better enforcement undertaken. Adopting standards equivalent to the most efficient AC available on the market could halve 2050 energy demand for cooling buildings, according to the IEA.

Although the best that can be achieved is set by the choice of equipment, how a system is monitored, controlled and

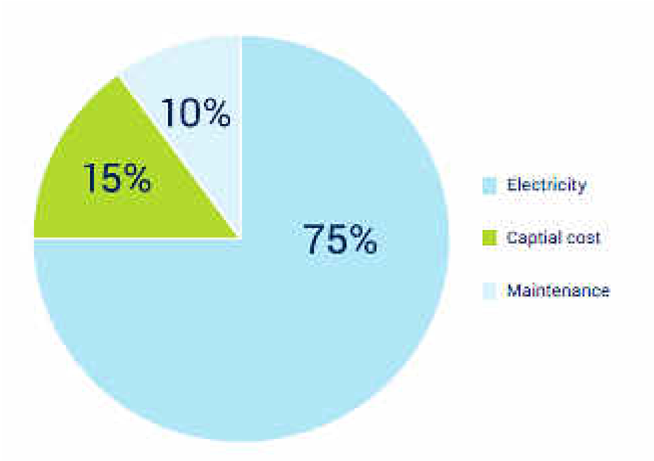


Figure 17 - example RACHP (refrigeration, air conditioning and heat pump) lifecycle costs. Source: [‘The Importance of Energy Efficiency in the Refrigeration, Air-conditioning and Heat Pump Sectors](#)’, UN Environment Programme, 2018.

maintained while in use is what ultimately determines the achieved efficiency. To give one example, chillers operate inefficiently at the wrong combination of operating temperature of the chilled fluid and cooling load (partial load is inefficient), and when rejection temperatures are high. Although smarter systems aim to reduce the extent to which this depends on humans behaving sensibly, this is often what it comes down to, especially for basic systems. Humans often set controls inappropriately, though a lack of understanding or laziness, often without realising the impact this has on energy use. Training is one partial solution to this.

Efficiency is closely related to cost. As the cost of energy dominates the lifecycle cost of most cooling (and heat pump) equipment, as illustrated in **Figure 17**, left, improving efficiency usually goes hand-in-hand with saving money. Installing more efficient equipment does tend to cost more initially, and making adjustments to operation and maintenance can have minor cost implications, but this extra cost is paid back through energy savings. Many efficiency opportunities have payback periods in the range of one to three years, [according to the UN Environment Programme](#).

Efficiency is also related to the refrigerant that is used. It only makes sense to use low-GWP refrigerants if you are not creating more indirect emissions than you are saving in direct emissions. Thankfully, the low-GWP refrigerants being used to replace high-GWP refrigerants are at least as efficient, if not more, in most cases.

Use Clean Energy Inputs

Any emissions that remain after parallel strategies to reduce passive and active energy expenditure can only be removed if all energy inputs come from zero-carbon sources. For systems that only consume electricity this involves generating renewable electricity on-site and/or securing an external supply of zero-carbon electricity. Externally, a zero-carbon supply can be procured using an electricity supplier’s green tariff, or, for larger companies, by signing a Power Purchase Agreement (PPA) with a remote renewables project. Where a system uses heat or cold inputs, these should also be generated by zero-carbon means, or be waste heat. For example, the heat necessary for an absorption system can come from solar thermal or an industrial process.

Figure 18, right, gives some idea of the scale of the efficiency improvement potential from some of the measures discussed in this section.

MINIMIZING COOLING LOAD (30–60%) Building design Shading Insulation Doors on retail displays	**EQUIPMENT AND CONTROL (30–70%)** High efficiency heat exchangers High efficiency compressors Optimized refrigeration cycle Good controls (e.g. variable speed drives)
OPERATION AND SERVICING (15–30%) Managing existing stock Timely servicing Performance measurement / fault diagnosis	**REFRIGERANT SELECTION (5–10%)** Choice of most appropriate refrigerant

Figure 18 - potential for RACHP (refrigeration, air conditioning and heat pump) efficiency improvements, with indicative savings ranges. Source: same as **Figure 17**.

Use Energy Storage

Integrating energy storage into a cooling system can potentially reduce some of the challenges associated with the last two strategies just described for reducing indirect emissions. These challenges can be summed up by saying that without energy storage cooling equipment has to run to meet cooling demand, *even when conditions are not optimal*. By separating when energy is imported, or when cooling is generated, from when cooling is sent out to be consumed, energy storage enables conventional cooling equipment to be run under non-optimal conditions less of the time.

For example, one challenge is that electrically-powered cooling equipment has to provide cooling output even when the input electricity is not coming from the preferred source in terms of carbon intensity or price. One relevant circumstance is when using variable on-site generation to power cooling equipment. **Figure 19** illustrates the challenge in the case of solar PV. The yellow line shows how the output from a solar PV system typically changes during the day. Overlaid on this are two modelled cooling demand profiles - assumed to be building AC - one domestic and one non-domestic. While the match is OK early in the day, by the evening there is no solar PV output but considerable cooling demand, especially in the domestic case. The demand cannot be covered by the preferred source of input electricity, so will instead have to imported from the grid. Energy storage can potentially solve this problem by charging when the sun is out, and then discharging in the evening to cover the cooling load. The traditional way of doing this is to store solar electricity in an electrochemical battery and then later to power the cooling equipment using this stored electricity. The exact same outcome can also be achieved by the subject of our next section - **Cold Thermal Energy Storage (CTES)** - this time by storing and supplying cold instead of electricity.

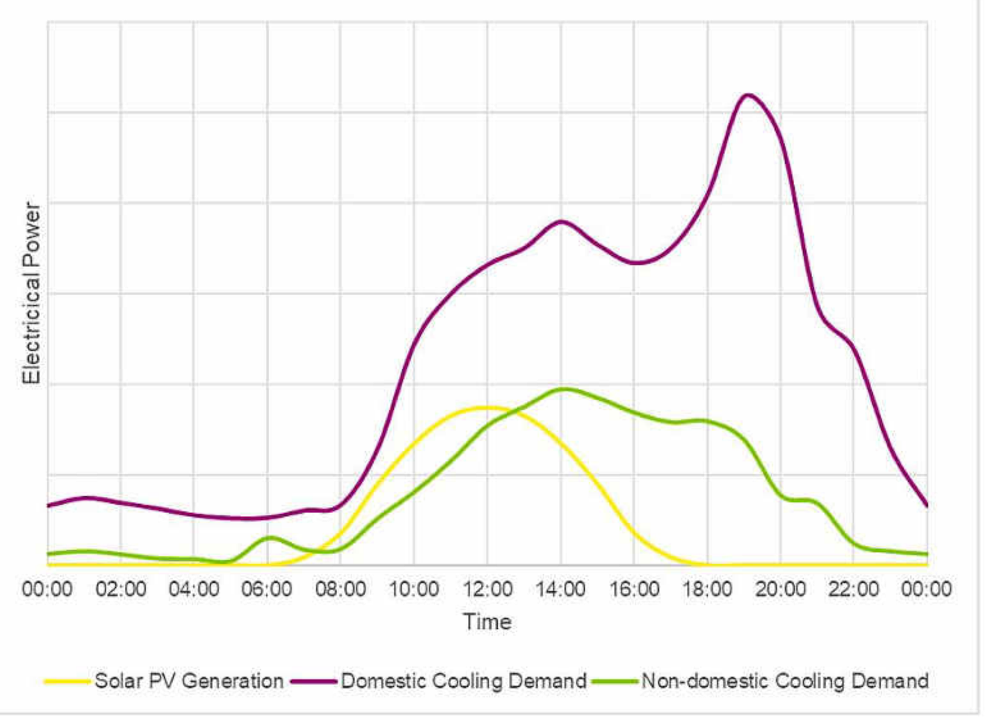


Figure 19 - comparison of modelled domestic and non-domestic cooling demand profiles with indicative output of solar PV. Source: 'Cooling in the UK', BEIS, the department for Business, Energy and Industrial Strategy, 2021.

Another challenge is that cooling equipment has to provide cooling output even when it is energy-inefficient to do so, for example, under conditions of partial cooling load or when rejection temperatures are high. Again, energy storage can potentially help out here, though this is not a simple electricity time-shift as in the on-site renewables case. What is needed here is a way of separating cooling generation (not electricity import) from cooling consumption. This way cooling can be supplied not just by running the equipment now but by providing previously stored cold thermal energy, either on its own or in combination with running the equipment now. **This is what CTES can do and electrical storage cannot.**

Uphill Battle

Earlier, we introduced some of the factors than influence cooling demand, both in terms of unit sales and energy use. Here we briefly revisit these factors in order to make an informed guess about how global cooling demand might evolve in the future. Looking first at the main factors influencing the unit sales of cooling equipment, with factors in red very likely to increase *unit sales* globally going forward:

Population size - the world population is currently ~8 billion and the UN estimates a population in 2050 of ~10 billion. This is 2 billion extra people, and the majority of these are expected to be born in climates with a high need for cooling, India being the prime example.

Affordable cooling access - looking at just one aspect of this, the size of the global middle class increased from 1.8 billion in 2009 to about 3.5 billion people in 2017, and is expected to grow to some 4 billion by 2021 and reach 5.3 billion by 2030. Richer people equals more access to cooling (assuming a reliable electricity supply).

Microclimate - the share of global population living in urban areas was 54% in 2015 and is forecast to rise to 68% in 2050, according to figures from the UN's World Urbanization Prospects database. This is an increase of 2.7 billion people. More and bigger cities implies greater cooling needs.

Climate - in 2100 global average temperatures are projected to be from 0.3 to 2.4°C hotter than today, according to Climate Action Tracker. At 1.0°C hotter, a common metric of cooling need is forecast to increase by 25% on average (CDD, see Figure 5), with the warmest month in some cities increasing by as much as 8°C.

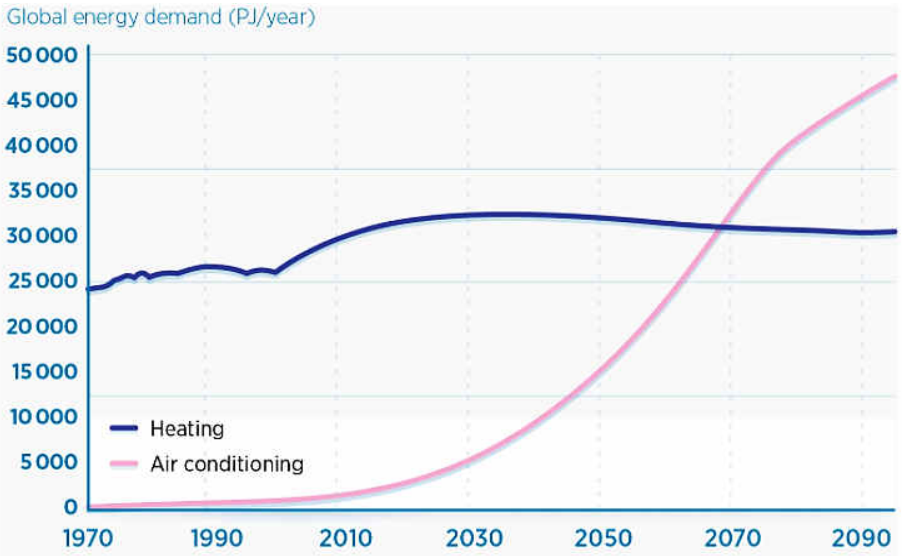


Figure 20 - projected global energy demand for heating and AC, 1970-2100. Source: IRENA webpage, accessed 01/22, see this for original source.

Turning now to the main factors influencing cooling *energy use*, with factors in red/green very likely increasing/decreasing energy use going forward:

Number of operational devices - this is currently about 4 billion devices and is expected to reach 10 billion by 2050, according to **Figure 7**.

Efficiency of operational equipment - the trend of year-over-year efficiency improvement for new equipment is strong and expected to continue, see **Figure 16**. However, there is a significant lag in the current state-of-the-art becoming commonplace in the operational stock.

Climate - as above, the climate is inevitably getting warmer, but temperature set points for refrigeration and AC are likely to stay the same, implying greater energy use.

In summary, unless energy reductions due to improved energy efficiency can offset the combined effect of all other factors - which is highly unlikely - then **global cooling energy use is going up**. One provocative if dated forecast for AC versus heating energy demand in shown in **Figure 20**. In summary, the path to net zero cooling will be an uphill battle, though the decarbonisation of the energy sector will provide a helping hand. Exactly how this battle might play out is beyond our scope.

Cold Thermal Energy Storage (CTES)

In this section, the last of four, we look at Cold Thermal Energy Storage (CTES) - what it is, what types there are, what properties it has, why you might pick one type over another, what benefits it can potentially provide, and a few stats about its market. The section concludes with a case study about a specific CTES implementation.

What is CTES?

Energy storage technologies come in a variety of forms, one of the most common of which, electrochemical batteries, typified by lithium-ion, we discussed in our 'Batteries' report. With electrochemical batteries the energy is input and output in electrical form, whilst the storage is achieved by an electrochemical process. By contrast, Thermal Energy Storage (TES) uses a thermal rather than an electrochemical process to provide a delay between the storage and retrieval of energy. Forms of TES exist that can store high temperature thermal energy, low temperature thermal energy - in this case we use the term Cold Thermal Energy Storage (CTES) - or both.

With CTES, the input energy can be electrical - using an electrical charging device which converts to thermal energy - or thermal directly, depending on the technology. The output is low temperature thermal energy for most types of CTES, though an electrical output is supplied in some cases. CTES can be used to supply delayed cooling on its own or in parallel with conventional cooling equipment, such as chillers.

At the highest level, CTES technologies are categorised by the thermal process used to store energy. There are 4 main types of process:

Sensible heat - stores thermal energy by cooling a liquid or solid storage medium without changing its phase. The storage medium needs at least a high heat capacity - ability to store a large amount of energy per unit temperature - for this to be effective. This is the most commonly deployed type of CTES. Examples include:

- Storing cold in a tank, typically using water as the storage medium. This is known as Water Tank Thermal Energy Storage (WTTES). Domestic water tanks are a small-scale example of this, though usually used to hold heat (at least in the UK), not cold. Larger examples come with volumes of up to ~100,000m^3.

Figure 21 - example of a latent heat CTES storage tank. This particular implementation uses water-ice as the phase change material; this is what is stored in this tank. See the later case study for further details. Source: Organic Heat Exchangers Ltd.

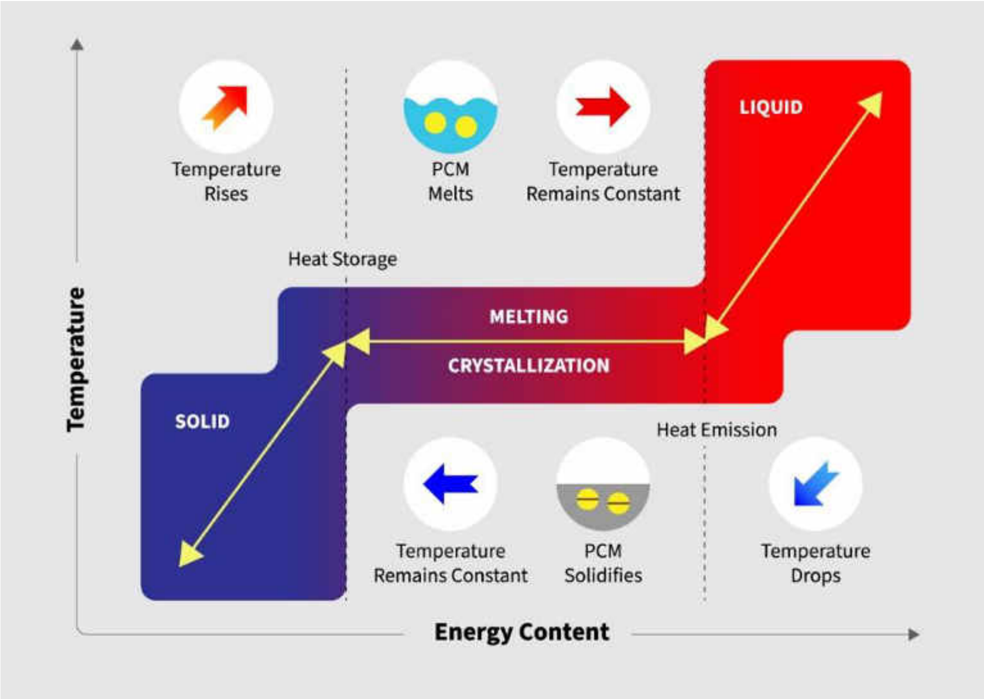


Figure 22 - basic principle of latent heat thermal energy storage. Source: Thermtest Instruments.

- Storing cold using particulate matter as the storage medium (e.g. ceramic bricks, rocks, concrete, packed beds). This is known as solid-state or packed-bed thermal storage. Heat is typically transferred to and from the storage medium using a fluid. Domestic electric storage heaters are a small-scale example of this.
- Storing cold underground using geological strata made up of soil, sand or solid bedrock, or water in artificial pits or aquifers as the storage medium. This is known as Underground Thermal Energy Storage (UTES).

Latent heat - stores thermal energy by changing the phase of a storage medium at a roughly constant temperature, most commonly solid to liquid and back. **Figure 21**, previous page, shows an example of this type, discussed in the later case study. **Figure 22** shows the basic principle. The storage medium needs at least a high latent heat and appropriate phase transition temperature for this to be useful and effective, as discussed in more detail later. Materials with a high latent heat are known as **Phase Change Materials (PCMs)**. As discussed earlier, latent heat is the basis of the vapour compression cycle used to generate cooling; here we are using a phase transition to generate delayed cooling. Examples of common low-temperature PCMs include ice, paraffin wax and salt-water mixtures.

Thermochemical heat - stores thermal energy using a reversible chemical process that releases/absorbs heat. An example is a system based on an absorption cycle, described earlier as a way of generating cold; it can also be used to store it.

Mechanical-thermal coupled systems - stores thermal energy in combination with mechanical energy storage. An example of this is Liquid Air Energy Storage (LAES), which stores electricity using both mechanical storage - compressing and expanding liquid air - and both hot and cold thermal storage to increase the overall efficiency. This is a new technology, not yet deployed at scale. See Highview Power's website for more.

Technical Properties

Before we get to the question of why you might choose one type of CTES over another, it is helpful to describe some of the technical properties CTES technologies possess. The values of these properties determine whether a particular type of CTES can be used at all, or is technically optimal, for a particular application. Typical values of these properties are shown in **Figure 23**, on this page, and **Figure 24**, on the next. These property definitions and values come from the 2020 report 'IRENA Innovation Outlook: Thermal Energy Storage'. IRENA is the International Renewable Energy Agency. Some of these are directly equivalent to those we described for electrochemical batteries in our 'Batteries' report, allowing for a degree of comparison.

Figure 23, right, shows the following properties:

Applicable scale - the ability to be used for 'small', 'district' or larger 'utility-scale' applications in a cost-effective manner. See the source for exact definitions of these terms.

Storage period - the possible duration energy can be stored for prior to effective use in cooling or producing electricity. Shorter durations can be used for daily demand shifting applications, whilst the longest durations can shift energy between seasons.

Potential vectors - the form of energy input and output (hot/cold/power).

And **Figure 24**, overpage, shows the additional properties:

Range of capacities - the range of the maximum quantity of energy available after completely charging. This is a function of the energy density and volume of the storage medium.

Range of power - the range of the rate at which energy can be charged and discharged; this depends on the thermal process involved, the storage medium and various design choices.

Operating temperature range - the range of temperatures over which operation is possible. This is dependent on the physiochemical properties of the storage medium.

Round-trip efficiency - the energy output divided by the energy

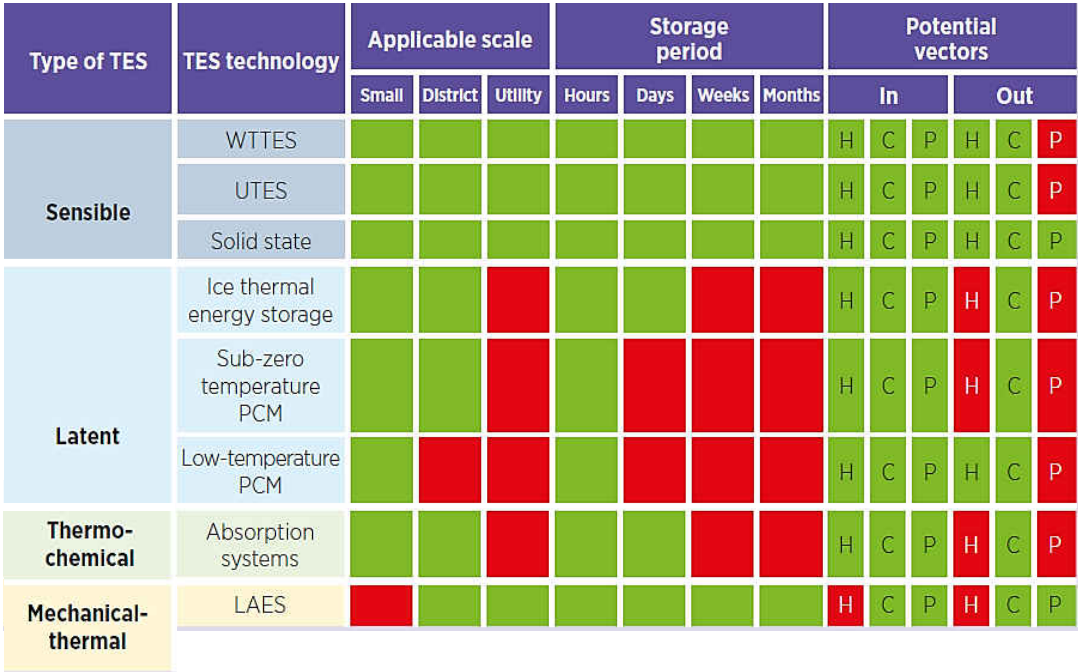


Figure 23 - applicable scales, operating durations and relevant energy vectors for selected CTES technologies. Notes: green denotes applicable; red denotes not applicable; C - cold; H - heat; P - power; WTTES - Water Tank Thermal Energy Storage; UTES - Underground Thermal Energy Storage; LAES - Liquid Air Energy Storage. Source: 'IRENA Innovation Outlook: Thermal Energy Storage', IRENA, 2020.

Type of TES	TES technology	Range of capacities	Range of power	Operating temperature	Round-trip efficiency	Storage period	Energy density	Lifetime (years or no. of cycles)
Sensible	WTTES	kWh to 1 GWh	kW to 10 MW	10 to 90°C	50 to 90%	Hours to months	15-80 kWh/m³ (1)	15-40 years
	UTES	MWh to GWh	MW to 100 MW	5 to 95°C	up to 90%	Weeks to months	25-85 kWh/m³	50 years
	Solid state	10 kWh to GWh	kW to 100 MW	-160 to 1 300°C	>90%	Hours to months	0.4-0.9 kWh/m³·K (heat capacity) (2)	> 5 000 cycles
Latent	Ice thermal energy storage	kWh to 100 MWh	kW to 10 MW	-3 to 3°C	>95%	Hours to days	92 kWh/m³	> 20 years
	Sub-zero temperature PCM	kWh to 100 kWh	kW to 10 kW	down to -114°C	>90%	Hours	30-85 kWh/m³	> 20 years
	Low-temperature PCM	kWh to 100 kWh	kW to 10 kW	up to 120°C	>90%	Hours	56-60 kWh/m³	300-3 000 cycles
Thermo-chemical	Absorption Systems	10 kWh to 100 kWh	10 kW to 1 MW	5 to 165°C	COP: 0.7-1.7	Hours to days	180-310 kWh/m³	50 years
Mechanical-thermal systems	LAES	MWh to GWh	10 to 300 MW	> 300°C (heat) -150°C (cold) -196°C (liquid air)	> 90% (thermal efficiency)	Hours to months	N/A	> 25 years

Notes: (1) The energy density of water TTES and UTES is based on a reference temperature at 20°C; sensible heat is not considered in the calculation of energy density of latent heat storage; (2) Energy density of solid state is determined by the operating temperature difference; energy density = heat capacity x temperature difference; (3) for "solar salt" (60% $NaNO_3$ and 40% KNO_3); (4) Only referring to calcium looping process (as opposed to other chemical looping examples); kW = kilowatt; MW = megawatt; MWh = megawatt hour; COP = coefficient of performance.

Note: N/A dennotes that no main needs were identified.

Figure 24 - key technical attributes of selected CTES technologies. Source: 'IRENA Innovation Outlook: Thermal Energy Storage', IRENA, 2020.

input after undergoing a full charge/discharge cycle. This tells you how effective the technology is at retaining and discharging thermal energy once stored. This parameter can be strongly dependent on the storage period.

Energy density - the maximum amount of energy that can be stored per unit volume of the storage medium.

Lifetime - either the number of years for which the CTES can be expected to operate as designed under certain operational conditions, or the number of charge/discharge cycles the CTES can be expected to perform. All storage systems experience fatigue and wear by usage, causing ageing and thermal degradation.

Cost

IRENA also estimates the 2018 price range for each CTES type in US$/kWh, the most common but not the only metric used for comparing storage prices, as follows:

Sensible	0.1-35
Latent	60-230
Thermochemical	15-150
Mechanical-thermal	N/A

No price was available for mechanical-thermal; this is a new technology, only deployed at pilot scale.

Selection

Our later case study employs a latent heat CTES system in which an ice slurry is used as the Phase Change Material (PCM). In order to explain the broad motivation behind this choice, in this section we highlight the main reasons why you might choose one CTES and PCM over another.

Choosing Between CTES Types

There is no such thing as an 'ideal' CTES so choosing a CTES for a particular application is always a trade-off between many technical, economic and other factors, some of which we presented over the last couple of pages. For any particular application some aspects will be much more important, others completely irrelevant. However, it is still useful to make some general remarks about the pro and cons of each CTES type. For brevity we will focus on the most useful and widely deployed types - sensible and latent heat.

Sensible Heat

As a group, sensible heat systems can: operate over a broad range of hot and cold temperatures; store very large amounts of energy; provide high rates of power; store energy from hours to months, meaning you can use them for any thermal shifting application, including seasonal. They are also cheap.

On the downside, sensible heat systems, by the definition of what sensible heat is, are variable temperature systems. This has a couple of consequences. On charging, to store more heat you have to go to a lower temperature. But at lower temperatures there is a larger temperature differential with the environment, meaning the harder you have to work in terms of insulation or expending extra energy to keep the temperature and hence amount of cold stored the same over time. On discharging, the cold will not be supplied at a single temperature, but across a range of temperatures, increasing all the time as the discharge process continues.

Another downside is that sensible heat systems have the lowest energy density of all the CTES types, meaning you will necessarily need a larger quantity of storage medium, and hence physical space, to store the same amount of energy. This is a consequence of the amount of energy involved with changing the temperature of a substance being orders of magnitude lower than, for example, the energy involved when the same substance changes phase (heat capacity<<latent heat capacity).

Latent Heat

Based on what we have already said it follows that latent heat systems have a higher energy density and smaller physical footprint than sensible heat ones. They also have a universally good round-trip efficiency and discharge at a nearly constant temperature, removing the downsides associated with a variable temperature system, and allowing the PCM to be chosen to provide a specific output temperature according to the application need. This is particularly useful for cold chain applications, where drugs or food have to be maintained within a narrow temperature range.

On the downside, latent heat systems are not suitable for the largest-scale applications in terms of energy capacity and power, according to **Figure 24**, and are more expensive than sensible heat.

Choosing a PCM

When selecting a latent heat CTES the choice of PCM is the most crucial aspect. The main requirements for the PCM include that it has:

- a phase transition at the required temperature;
- high latent heat (of fusion, assuming a solid-liquid transition, though other transitions are possible);
- high thermal conductivity;
- high round-trip efficiency;
- reasonable cost;
- high availability;
- low toxicity and flammability (this is important both for the container and, well, people).

Other than thermal conductivity we have already explained most of these, or the rationale is hopefully obvious. Thermal conductivity is crucial as it determines how readily the PCM can charge and discharge i.e. the maximum range of power. Unfortunately, many PCMs, including water-ice, have relatively low thermal conductivities, motivating the development of novel techniques to enhance the rate of thermal transfer. Despite low thermal conductivity, water-ice is one of the most widely-deployed PCMs. This is because it meets most of the other requirements well, including a useful solid-liquid phase transition temperature ($0^{o}C$), high heat of fusion (334 kJ/kg), good heat capacity (4.2 kJ/kg.K), high roundtrip efficiency (95% by **Figure 24**), high availability and low cost. To store cold energy using water-ice, electricity is typically used to generate ice using a standard chiller or a specially designed ice crystalliser. When cooling is required, cold is extracted from the ice using a heat transfer fluid. The heat transfer fluid can be simply be water - the liquid phase of the PCM - or an additional heat transfer fluid. The physical structure of the ice greatly influences the maximum achievable power output, as we see later in our case study.

Why Use CTES?

In the ‘Net Zero Cooling’ section we outlined how CTES could help in the transition to net zero cooling. In this section we recap and expand on the benefits of CTES, this time from two perspectives - the electricity system, and the site where the CTES operates. We assume that the CTES is charged using electricity, either from the grid or on-site renewables, outputs cold, and is used in partnership with a more conventional, electrically-powered source of cooling, such as a chiller (to repeat, CTES can also be used on its own). This is the main setup in our later case study. With this setup, cooling can be stored in the CTES for later use - we assume hours to days later, not seasons (this is a somewhat different use case) - and when end-users need cooling this can be provided by the CTES, the chiller, or both acting together.

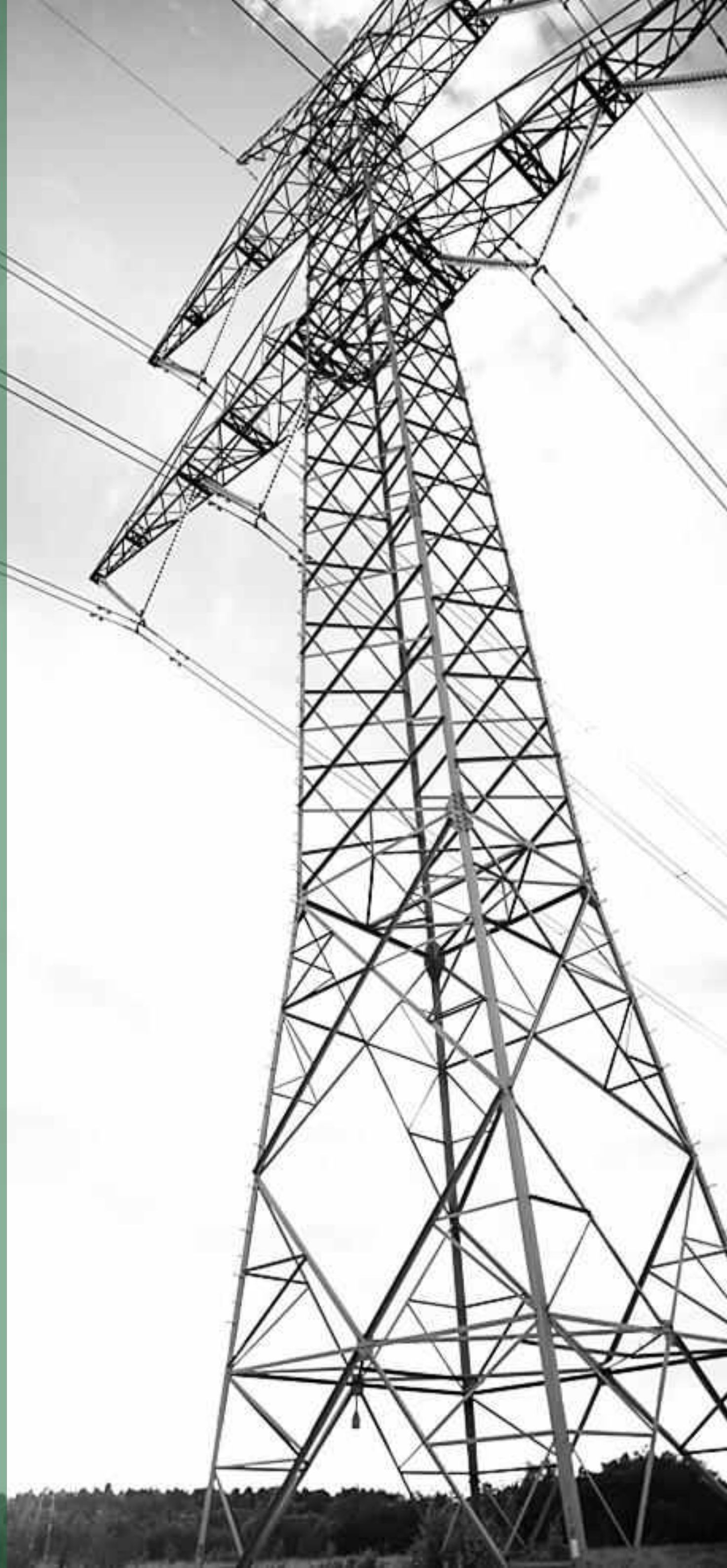
Electricity System Benefits

Our combined chiller-CTES system is potentially very beneficial for the electricity system as it can make a site’s grid-facing, cooling-related electrical load smaller and more flexible:

More flexible load. Without the CTES the chiller is pretty inflexible in terms of its electricity consumption. By adding the CTES, the site can now potentially ramp up or down its electricity consumption as needed by the system, while still meeting local cooling needs. In other words, the site may be able to provide enhanced **demand-side response and other grid services** to the System or Distribution Network Operator that it previously could not.

Smaller load. A reduced load comes about through the chiller efficiency improvements CTES can provide and, if the site has on-site generation, through its ability to maximise self-consumption of on-site generation, both things discussed in the previous section (heat provision may also be relevant, see overpage).

A grid with cooling loads that are smaller and more flexible should be able to **decarbonise more quickly, at a lower system cost**. This is because the combined peak cooling load - a significant problem for the grids of some of the hotter countries, as highlighted earlier - is lower, and can be dynamically flattened further if necessary. This reduces the need to build new generation capacity and other grid infrastructure simply to address this peak. The cooling loads can also be better matched with the output of variable renewables, allowing, for example, wind turbines to export to the grid when they might previously have been refused grid access.



CTES Site Benefits

Turning now to the benefits of the same setup for the site, some mentioned earlier, these potentially include:

Grid service provision - the site may be able to provide select grid services to the System or Distribution Network Operator, either directly or through an aggregator, earning money in the process. Examples of relevant services in the UK include the Balancing Mechanism, a last resort mechanism for matching supply and demand of electricity, and frequency response, used to keep the grid operating close to its nominal frequency of 50Hz.

Time-of-use optimisation - the site can import electricity from the grid when it is most economical to do so, not when the site happens to need cooling output. Electricity tariffs, which charge per unit of electricity, and the additional charges levied for use of the electricity network (Distribution Use of System (DUoS) and Transmission Network Use of System (TNUoS) charges in the UK) may have, or can be selected to have in the case of tariffs, a time-of-use element to their pricing formula.

Increased self-consumption of on-site generation. We looked at the on-site renewables case earlier.

Added cooling capacity - the site gets extra cooling capacity, which can help out an under-sized chiller already in use, or allow a new chiller to be sized for average - not peak - cooling demand, with the peak now covered by the CTES. In either case, the site also gets **backup cooling capacity** in the event of a problem with the main chiller.

Improved chiller efficiency - related to this added cooling capacity, a site gets the ability to reduce the time its chiller has to run under inefficient conditions (to recap, wrong combination of operating temperature and load, high rejection temperatures). This should also reduce maintenance needs.

Heat provision - the site gets a new source of heat. The CTES charging process uses electricity to generate cold, so like any refrigeration process has to eject heat. If this heat is recovered, this can reduce the need to create heat in some other way, improving the efficiency of the combined heating and cooling system.

Each of these points has the potential to make or save a site money. Due to very high electricity prices, this is particularly the case now (Jan 2022) in the UK. We provide an example of the quantification of these savings in our later case study. Some of these points can also reduce local or grid-imported carbon emissions.

Market

Much is said about how large and fast-growing the market for electrical storage is, in particular electrochemical storage in the form of lithium-ion batteries. While this is undeniable - Bloomberg New Energy Finance (BNEF) estimate that global capacity for stationary battery storage in 2020 stood at 29GWh, while the IEA estimate that 5GW of additions were made in 2020 alone - the installed capacity of TES (both hot and cold) is massively larger - at **234GWh** in 2019, according to IRENA - if not, admittedly, as fast growing. Notably, this figure of 234GWh *excludes* domestic hot water tanks.

Drilling down into this 234GWh figure reveals that TES for heat storage is currently the main application, though **CTES does account for 14GWh** - about half the size of stationary battery deployments - and 160 out of the 430 TES projects tracked by IRENA. This 14GWh includes uses for cooling in buildings and district cooling systems…

In buildings, water tank CTES is widely used across the globe. Solid-state and PCM including ice storage are proven technologies, but have only been deployed on a relatively minor scale. Underground CTES has been used in various cases, with the utility of smaller (individual building) scale installations being studied.

For district cooling, water tank CTES is deployed widely throughout the world. Underground CTES is in use in some countries, but is subject to the suitability of the subsurface environment. Ice produced using renewable electricity is currently used in some district cooling schemes, where its high energy density is particularly advantageous in urban areas.

CTES is also used in other applications, not included in the above tally. For example, ice and other PCMs are used in refrigerated transport, replacing diesel and other fossil fuel generators, and in stationary vaccine storage systems.

Forecast

IRENA forecasts that the global market for TES could triple in size from 2019-2030, to 800GWh, with CTES capacity roughly doubling in the same period, to 26GWh. This implies investments of about **US$560 million** in CTES over the next ten years, to reach **US$2.82 billion worldwide**. Most rapid growth is expected in 'some emerging economies where temperatures are reaching extreme levels and further advanced and large-scale cooling technologies are being adopted'.

Companies

Companies involved with CTES tend to be of two types. The first type is well-established companies involved with building, industrial or district cooling who sell the more-established CTES technologies as an extra product line. Examples include:

Araner - district heating and cooling, turbine cooling and water and ice CTES.

Balitmore Aircoil Company - evaporative and hybrid cooling and ice CTES.

The second type of companies is start-ups looking to commercialise novel forms of CTES. Examples, all of which are really quite different from one another, include:

Malta Inc - mechanical-thermal coupled, electricity->heat pump->thermal hot and cold storage->heat engine->electricity.

SunAmp - latent heat, unspecified novel PCM for both hot and cold applications.

Mixergy - sensible heat, stratified water tank, focus on residential applications.

Highview Power - mechanical-thermal coupled, LAES.

Organic Heat Exchangers - latent heat, ice slurry PCM. See the case study overpage.

Recent investment into these start-ups alone has been at least into the **hundreds of millions of US dollars**, perhaps suggesting IRENA's investment inflow forecast for the period to 2030 is extremely low.

Case Study: Organic Heat Exchangers Ltd

We conclude this section and report by focussing in on a single latent heat CTES technology. EnergiVault, the commercial name of this product, has been developed and patented by Organic Heat Exchangers Ltd, or O-Hx for short, a UK start-up. EnergiVault employs an ice slurry as the PCM. It can be deployed either on its own or in combination with new or existing chillers. The relevant market is therefore significant, covering the broad range of applications that employ chillers (we introduced chillers in earlier sections, starting here), as well as additional applications when used on its own, the prime example of this being refrigerated transport, mentioned on the previous page. The company's initial focus will be on stationary cold store applications, which, as we saw earlier in a UK context, are the businesses where cooling's share of total electricity and energy use is the highest. Such companies stand to gain the most from EnergiVault so are an obvious first target for O-Hx. Following successful innovation and proof-of-concept trials, full-scale commercial trials of EnergiVault are due to commence shortly.

EnergiVault Plus Chiller

When used in combination with a chiller, EnergiVault is connected directly to the chiller's secondary cooling circuit, with the same heat transfer fluid - commonly a water-glycol mix - used throughout the combined system. By using the same heat transfer fluid there is no need for a conventional heat exchanger to allow heat to flow to and from EnergiVault. This is one of the key advantages of this setup, shown in simplified form in **Figure 25**. We expand on this shortly.

On the right side of **Figure 25** is the conventional chiller circuit, consisting of a chiller connected to its cooling load. This circuit can still function independently as it traditionally would but, in addition, heat transfer fluid can be diverted to and received from the EnergiVault system, shown on the left side of **Figure 25**. In this way, EnergiVault can provide cooling capacity to cover some or all of the chiller's usual cooling load, or to offer surge cooling capacity above and beyond the capabilities of the chiller when operated alone.

EnergiVault consists of two main physical components - a thermal battery, which is essentially an insulated container, see the representation in **Figure 25**, and an electrically-powered device for 'charging' the thermal battery. Both come in a range of different sizes to 'allow a modular build-up depending on requirements'. The battery comes in sizes up to 100MWh - larger than other types of PCM and all non-sensible heat CTES can handle, according to **Figure 24**. The charger is sized according to the energy capacity of the battery and the desired recharge time, the

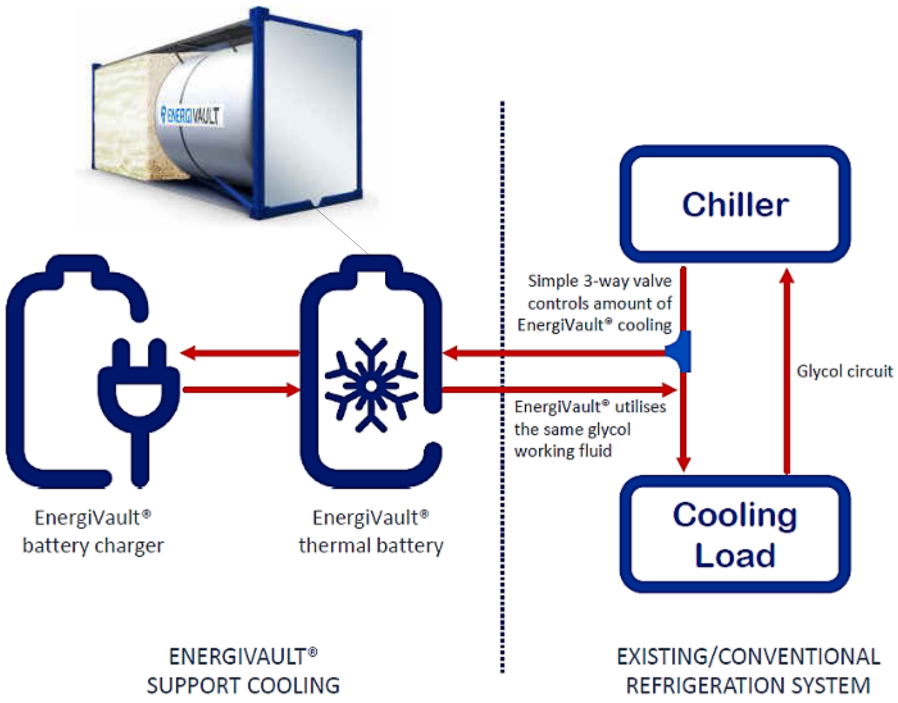


Figure 25 - setup in which EnergiVault provides support cooling for a chiller. Source: Organic Heat Exchangers Ltd.

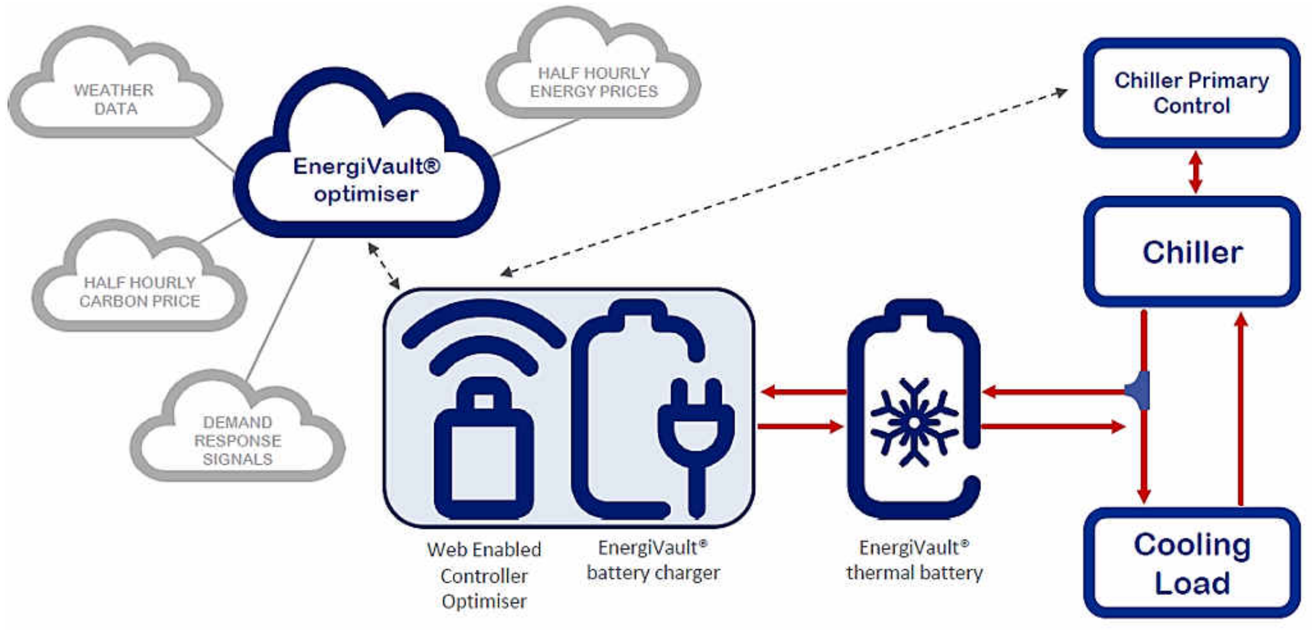


Figure 26 - version of **Figure 25** with added control and optimisation elements.

optimal value of which depends on the nature of the charger's electricity supply (for example, its time-of-use cost profile).

The core component of the 'highly efficient' charger is an ice crystalliser. This charges the battery by converting up to 60% of the heat transfer fluid within the battery into spherical ice particles a fraction of a millimetre across. This mixture of a liquid and ice particles is known as an ice slurry. It is an ice slurry that acts as the PCM in this particular CTES implementation. We explain why this unique PCM is used overpage.

The charger has its own refrigerant and refrigeration cycle and therefore generates waste heat. This heat is recoverable and can be made available at two temperatures - 40ºC (low grade heat) and 100ºC (high grade heat), even simultaneously. This heat output is therefore suitable for 'domestic hot water, space heating and many process heat needs'. **Figure 27**, overpage, illustrates one case in which you could imagine using both heat streams simultaneously - an EnergiVault implementation at an ice rink. In this example, EnergiVault is servicing multiple thermal needs - cold to maintain the ice pad, hot water for the changing rooms and background heating for the seating area.

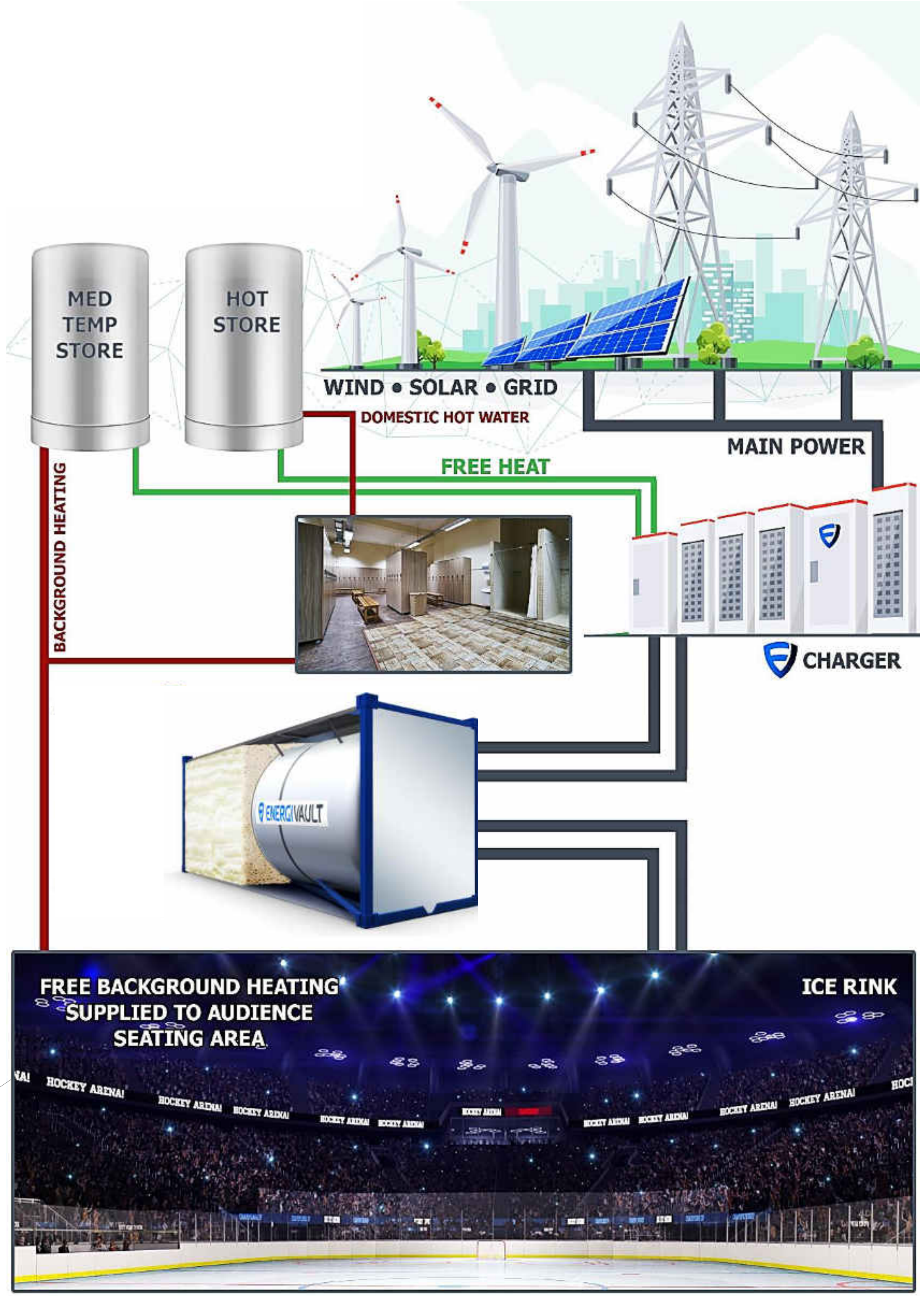
In its most basic mode, the battery maintains its charge level based on a set daily timing schedule, and the level of cooling support provided by the battery is determined by the temperature of the heat transfer fluid coming from the chiller. **Figure 26**, above, is a repeat of **Figure 25**, adding in several control and optimisation elements. These extra elements allow for more sophisticated modes of operation, including dynamic charging of the battery based on optimisation decisions made in the cloud by the 'EnergiVault optimiser', an AI (Artificial Intelligence) system. This reaches its decisions by assessing a range of relevant data, for example: availability of on-site power, grid electricity prices, carbon prices, weather data, grid service dispatch signals from the System Operator, etc. Another mode of operation involves EnergiVault turning the chiller down or off altogether, for example when it is operating inefficiently, or when requested by the System Operator - any cooling deficit is then made up by the battery. Further levels of sophistication are possible by integrating with building or process controls and other smart electrical assets, such as heat pumps and Electric Vehicle chargers. This is a good example of a smart, flexible cooling system, highlighted earlier as important properties for optimising energy efficiency. See the UK patent GB2560874B for the nitty gritty of how EnergiVault works.

Key Innovation

We explained previously why a latent heat CTES that uses water-ice as the PCM is fundamentally attractive versus alternatives. However, we also pointed out that many PCMs, including water, have relatively low thermal conductivities, which limits the maximum thermal transfer rate to and from the PCM.

The O-Hx solution to this problem is to massively increase the surface area over which the thermal transfer takes place between the PCM and the heat transfer fluid (which is simply the liquid phase of the PCM in this case). This is not done using a conventional heat exchanger as, according to O-Hx, whichever type is used will ultimately be limited by its surface area. Instead, O-Hx employs an ice slurry with carefully dimensioned ice crystals. This remains pumpable at low enough ice crystal concentrations but has a surface area to volume ratio ~500 times that of a block of ice. O-Hx calls this type of ice slurry an ‘organic’ heat exchanger because it ‘uses the slight film of organic material surrounding each particle as the only barrier to heat transfer’. This term appears to be unique to O-Hx, rather than one used more broadly in the industry. The heat transfer surface of the organic heat exchanger increases proportionately with the volume of energy in storage. The upshot is that EnergiVault has a **high discharge rate**, with the **maximum possible discharge rate ‘many times the charge rate’**. For example, a 1MWht battery could be charged over 16 hours using a small charger of ~65kWt. This same battery could support a cooling load of 6MW for 10 minutes, or, alternatively, a cooling load of 100kW for 10 hours. This level of flexibility is unavailable from any other heat exchanger type, according to O-Hx.

Figure 27 - example implementation of EnergiVault at an ice rink. As well as providing the cooling necessary to maintain the ice pad, waste heat from the charger is put to good use by providing hot water and background heating for the facility. Each temperature of heat uses a thermal store to improve the match between when heat is generated and consumed.



Benefits

We listed the beneficial services a chiller-CTES combination could provide to the site owner (and electricity system) in a previous section. These services can be supplied by EnergiVault, as well as by similar CTES implementations (though not necessarily as effectively). To recap in short form these were:

- Added cooling capacity, including peak demand and backup cooling capacity.
- Chiller efficiency optimisation.
- Heat provision.
- Time-of-use optimisation.
- Increased self-consumption of on-site generation.
- Grid service provision.

These are all things that can potentially save or make a site money and some can also reduce local or grid-imported carbon emissions.

O-Hx points out many technical reasons why it might be advantageous to chose an EnergiVault CTES, rather than any other kind. These include the following, some of which we have already mentioned:

- High maximum cooling rate, many times the charge rate. This means EnergiVault is able to support ‘massive’ cooling loads.
- Cooling rate is precisely controllable.
- Highly efficient charger. The charger can run on most refrigerants, including low-GWP ones. The state of charge in the thermal battery can be monitored in real-time.
- Available in a range of energy (up to a large 100MWh) and charging capacities. Capacity is expandable at any time.
- High energy and power densities, meaning a low physical footprint. Energy density is multiple times greater than water sensible heat CTES and lithium-ion batteries.
- Efficient, dual-temperature heat recovery.
- Minimal maintenance and decommissioning.
- No degradation of storage performance over time and therefore no charge/discharge cycle limit. The charger has an anticipated lifespan of 20 years+, the battery longer. This all compares well with lithium-ion, as we explore shortly.

Economics

O-Hx provides estimates for the operational savings an EnergiVault-chiller combination could potentially provide. For a typical food manufacturing company with high refrigeration and heating demand the 'typical maximum savings' are shown in **Figure 28**. The headline is a **maximum saving of 62%**, with the majority of these savings coming from the heat recovery process. O-Hx also provides ranges for each of the money-saving aspects shown in **Figure 28**, as follows: time-of-use optimisation,16-25%+; heat recovery, 23-35%; chiller efficiency optimisation, 4-10%; integrated energy insights, 5-10%. 'Integrated energy insights' means saving money by monitoring a facility's electrical, heat and cooling loads and identifying and responding to inefficient system operation. The time-of-use optimisation range extends to 25% or above by including revenue from grid service provision (something not included in **Figure 28**). Additional savings are possible by increasing the self-consumption of on-site generation. O-Hx puts the displacement saving of using locally-generated rather than grid-imported electricity at 5-10p/kWh. Electricity prices are currently (Jan 2022) skyrocketing in the UK so this may undersell the current saving.

Turning now to capital costs, retrofitting an EnergiVault system to an existing chiller has an expected **typical payback period of 2-4.5 years** for the same example company of **Figure 28**. Given that chillers last from 15-30 years, [according to Consulting-Specifying Engineer Magazine](), this means that it would be economical to retrofit during most of a chiller's lifetime. For new systems, it may be possible to save money on chiller CapEx by downsizing the chiller to cover the average rather than the peak demand (with EnergiVault covering the peak). However, for our example company the combined chiller-EnergiVault system is still expected to be more expensive than the chiller on its own, though the payback period is estimated at just **1.5-2.5 years**.

In summary, the economic case for EnergiVault is compelling in this, the most flattering of cases.

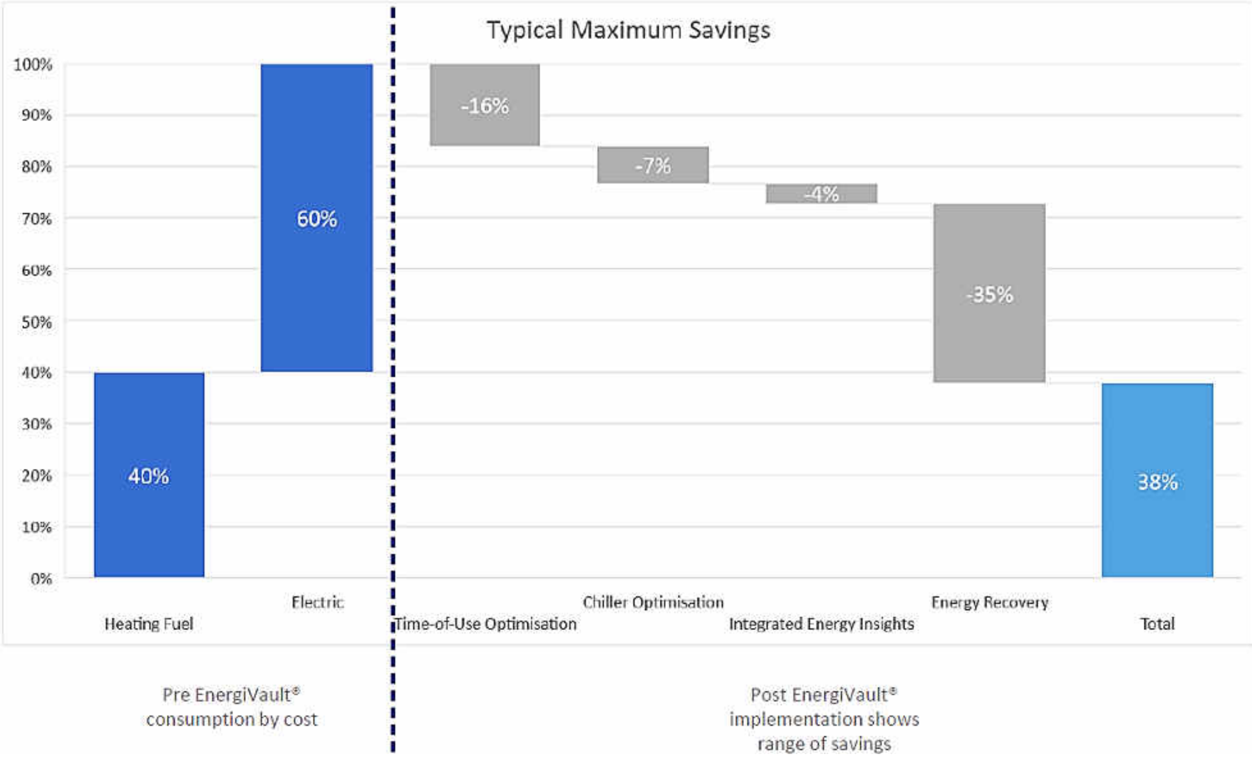


Figure 28 - estimate for typical maximum savings when using an EnergiVault-chiller combination for a food manufacturing company with high refrigeration and heating demand.

EnergiVault Versus Lithium-Ion

Earlier we pointed out that, although electrochemical batteries, typified by lithium-ion, can perform some of the same functions as CTES, the two are not directly equivalent. To recap in the EnergiVault case:

Lithium-ion decouples when electricity is imported from when electricity is exported to run cooling equipment to provide cold to an end-user, or for some other purpose (to run non-cooling equipment, or to provide grid services that require electricity export).

EnergiVault decouples when electricity is imported to generate cold from when cold is supplied to an end-user (from EnergiVault alone, or from EnergiVault in parallel with importing additional electricity to run cooling equipment).

This difference means EnergiVault can provide cooling functions that lithium-ion cannot (cooling capacity, chiller optimisation), and that lithium-ion can provide non-cooling functions that EnergiVault cannot. Heat is one interesting aspect of this comparison. Although both create considerable heat, EnergiVault has a built-in dual-temperature heat recovery function, whereas with electrochemical batteries, although the heat can in theory be recovered, the focus is usually just on getting rid of it as it impairs battery operation and can even lead to thermal runaway and, ultimately, fire.

In any case, the issue of EnergiVault versus lithium-ion is clearly a key question for O-Hx to address, given that lithium-ion is a very much more mainstream product, rapidly falling in price and improving in performance all the time (see our 'Batteries' report for more).

To this end, O-Hx has performed a comparison between EnergiVault and two lithium-ion Battery Electricity Storage Systems (BESSs), one that can discharge in 1 hour and another in 15 minutes, the latter of which would be capable of covering larger, shorter-duration peak loads, something EnergiVault is also capable of handling. The comparison is based on 2.4MWh of cooling per day, provided over a 20-year lifespan. The results are shown in **Figure 29**. The main finding is that the total lifetime cost for EnergiVault is roughly half that of the 1-hour discharge BESS. This is largely due to the significantly lower upfront costs, though the lifetime electricity cost is about 25% lower too. The 15-minute discharge BESS compares even less favourably due to its higher CapEx, a side effect of needing a battery with a higher maximum power to fully discharge in the requisite time. While it might be possible to pick holes in this comparison,

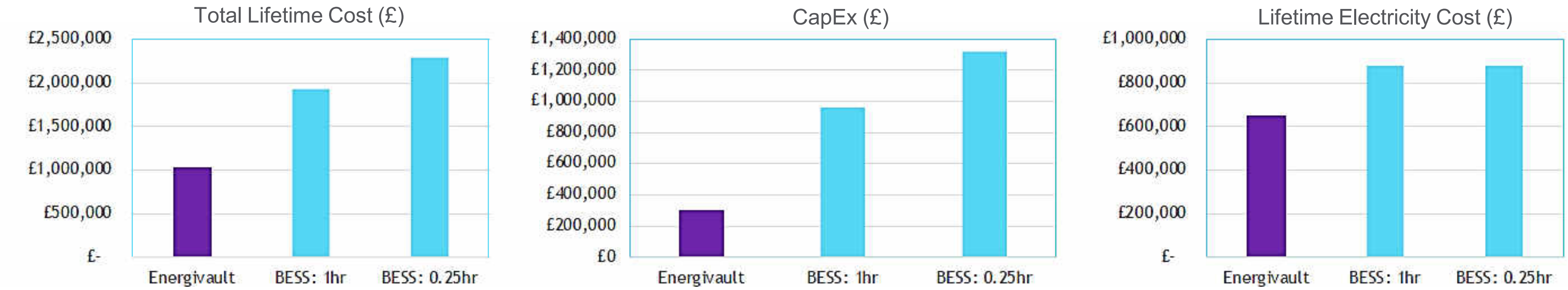


Figure 29 - comparison between EnergiVault and a 1-hour and ¼-hour discharge time Battery Energy Storage System (BESS). The comparison is based on 2.4MWh of cooling per day provided over a 20-year lifespan.

some fundamental points remain, regardless. These include:

Degradation, lifespan and **capital cost**. Lithium-ion batteries degrade over time, losing energy capacity. This means there is a limit to the number of times they can be cycled before replacement becomes necessary. Lithium-ion batteries used in large-scale BESS applications need to be replaced after roughly 8-10 years of use, according to our 'Batteries' report. By contrast, and as mentioned earlier, EnergiVault does not degrade in the same way over time and is therefore not cycle limited. Plus, the charger has an anticipated lifespan of 20 years+, the thermal battery longer. This means that an EnergiVault installation could potentially last the full lifetime of the chiller, while a lithium-ion battery could need to be replaced one or more times, significantly increasing the capital cost. In any case, EnergiVault's capital cost appears to be considerably lower even after factoring out the need to replace lithium-ion.

Round-trip efficiency. Comparing **Figure 24** with the appendix of our 'Batteries' report suggests that, as a group, CTES systems have a notably higher round-trip efficiency - output energy divided by input energy after a full charge/discharge cycle - compared to electrochemical batteries (as an aside, note that ice latent heat CTES has the highest round-trip efficiency out of all types of CTES, latent heat or otherwise). Part of this is that electrochemical batteries have to convert from alternating to direct current and back in a round-trip, using a device known as an inverter. The upshot is that - all other things being equal - it is **preferable to store energy in thermal rather than electrical form for cooling applications** (though you would also have to factor in potential changes to the round-trip efficiency due to the storage period involved, and some broader measure of round-trip efficiency would also include at least the efficiencies of the CTES's charger and the chiller). Independent sources support this idea; see the US Department of Energy's thermal energy storage webinar series and accompanying notes, for example. This source also supports our discussion about capital cost and lifetime.

Power output. With lithium-ion batteries you cannot scale the power and energy capacity independently (though with flow batteries you can). This means that in the case of high-power cooling applications it may be necessary to select a higher energy capacity battery (and a more powerful inverter) than you might otherwise, at extra expense. Due to its high maximum power output, EnergiVault is more naturally suited to high-power cooling applications.

Energy density. The energy density of EnergiVault is 'over three times' that of lithium-ion, according to O-Hx, meaning it potentially takes up this much less physical space.

Rare metals. Metals such as lithium, nickel and cobalt are required to make the most common forms of lithium-ion batteries. Lithium and cobalt in particular have a limited and geographically concentrated supply, impacting availability and cost, and cobalt also notably has social and human rights issues associated with its mining. We covered this in our 'Batteries' report. For EnergiVault, the main raw material by volume is presumably water, which is obviously cheap and has no supply chain issues. EnergiVault likely uses little to no rare metal.

This list, which does not claim to be the full story in what can be a complicated comparison, suggests that where the two overlap in function, such as in increasing self-consumption of on-site generation for cooling purposes, then EnergiVault is arguably the preferred option. And we have already stated several times that some cooling functionality is exclusive to EnergiVault - it's a cooling specialist, not a generalist like lithium-ion.

To summarise this case study: O-Hx has developed a useful and economic form of energy storage, which, as it is different enough from and superior in some ways in cooling applications to lithium-ion, could well find a significant market once the final steps towards full commercialisation have been undertaken. The energy storage market is certainly large enough for many forms of energy storage to thrive.

The Super-Short Report Summary

Cooling - the demand for which is inevitably going up - is critical to humans but power-hungry and harmful to the environment. This harm can be reduced by transitioning to net zero cooling, speeding up and reducing the cost of the overall net zero transition in the process. As part of this, CTES can help reduce indirect cooling emissions by decoupling cooling generation from consumption (electrochemical batteries cannot do precisely this). Ice slurry CTES, such as that being developed by O-Hx, is a technically proficient and economic CTES implementation.

Thanks for reading.

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