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The Future of Cooling

Opportunities for energy-efficient air conditioning

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Foreword

The world faces a looming "cold crunch." Using air conditioners and electric fans to stay cool accounts for nearly 20% of the total electricity used in buildings around the world today. And this trend is set to grow as the world's economic and demographic growth becomes more focused in hotter countries. As incomes and standards of living increase, more people will naturally want to buy and use air conditioners to keep cool. Wider access to cooling is necessary, bringing benefits to human development, health, well-being and economic productivity. But it will have a significant impact on countries' overall energy demand, putting pressure on electricity grids and driving up local and global emissions.

The International Energy Agency (IEA) is shining a spotlight on some of the blind spots of energy policy – issues that get little attention but are of crucial importance. The growth in global demand for space cooling is such a blind spot: it is one of the most critical yet often overlooked energy issues of our time. If left unchecked, energy demand from air conditioners will more than triple by 2050, equal to China's electricity demand today. This report highlights the threats associated with rising, unchecked cooling demand. It provides key insights into current and future trends in cooling, and it proposes policy responses to achieve a more sustainable pathway.

The answer lies first and foremost in improving the efficiency of air conditioners, which can quickly slow down the growth in cooling-related electricity demand. Indeed, the opportunity for efficient cooling lies in the market's current inefficiencies: there are huge disparities in the efficiencies of air conditioners sold today across the globe. Policy interventions can address this and will have a significant and rapid global impact.

Measures such as strong minimum energy performance standards are well known and well proven to drive up equipment efficiencies quickly and cost-effectively. In the longer term, the underlying need for cooling can also be greatly reduced by better building design and tougher building codes, as well as by increased rates of energy efficiency improvements in existing buildings.

This is particularly important today, given the slowdown we've seen in global energy efficiency improvements. Simply put, governments need to do more on efficiency, which is one of the key tools to reach long-term climate goals and also reduce energy-related air pollution. As part of the modernisation of the IEA, we have greatly expanded our work on energy efficiency, helping governments all over the world to understand efficiency issues and to identify and implement the right policy solutions.

Determined policy action is critical to ensure a sustainable path to the future of cooling and allow people to reap the benefits of cooling without straining energy systems or the environment. This is why the IEA is choosing this moment to present this report.

I hope that this report will help to raise awareness globally about one of the most critical energy issues of our time and that it will provide an important source of guidance for policy makers in particular who are working towards a more sustainable global energy system.

Dr. Fatih Birol

Executive Director

International Energy Agency

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Executive summary

The world is facing a looming "cold crunch"

The use of energy for space cooling is growing faster than for any other end use in buildings, more than tripling between 1990 and 2016. Space cooling – typically by means of an electric-powered fan or air conditioning (AC) system – is contributing increasingly to global energy demand. Global sales of ACs have been growing steadily and significantly: since 1990, annual sales of ACs nearly quadrupled to 135 million units. There are now about 1.6 billion in use, with over half in just two countries – the People's Republic of China (hereafter "China") and the United States. Those ACs vary enormously in energy efficiency, and keeping them running consumes over 2 000 terawatt hours (TWh) of electricity every year, which is two and a half times the total electricity use of Africa. Almost a fifth of all the electricity used in buildings is for cooling.

Rising demand for space cooling is already putting enormous strain on electricity systems in many countries, as well as driving up emissions. Increased AC loads push up not only overall power needs, but also the need for generation and distribution capacity to meet demand at peak times, placing further stress on the power system. In some countries, such as in the Middle East and also parts of the United States, space cooling can represent more than 70% of peak residential electrical demand on extremely hot days. Averaged across all countries, space cooling accounted for around 14% of peak demand in 2016. Building, maintaining and operating electricity capacity to meet that peak demand is very expensive because it is used only for limited periods, and this drives up overall costs. Meanwhile, carbon dioxide (CO_2) emissions from cooling have tripled since 1990 to 1 130 million tonnes (Mt), equivalent to the total emissions of Japan. Local air pollutants caused by cooling energy demand have similarly grown.

Growing demand for cooling is driven by economic and population growth in the hottest parts of the world. Global growth is shifting south, to countries that experience high temperatures that drive the demand for cooling, which is becoming affordable for more people as income levels rise. The lion's share of the projected growth in energy use for space cooling by 2050 comes from the emerging economies, with just three countries – India, China and Indonesia – contributing half of global cooling energy demand growth. And the efficiency of ACs varies widely - in all major markets today, people are typically buying air conditioners whose average efficiencies are less than half of what is available.

Absent firm policy interventions, cooling-related energy demand will soar

There is no doubt that global demand for space cooling and the energy needed to provide it will continue to grow for decades to come. Access to cooling is a major social issue. Of the 2.8 billion people living in the hottest parts of the world, only 8% currently possess ACs, compared to 90% ownership in the United States and Japan. But just how fast cooling-related energy demand grows hinges critically on government policy action. The analysis presented in this report shows that policies currently in place or planned would have only a very limited effect in slowing that growth.

In our Baseline Scenario, which takes account of the likely effect of current policies and targets, energy needs for space cooling will triple by 2050. Soaring AC ownership drives overall electricity demand to unprecedented levels. Global energy use for space cooling in 2050 reaches 6 200 TWh, with nearly 70% of the increase coming from the residential sector, and much of it taking place in a handful of emerging economies. The share of space cooling in total electricity use in buildings grows to 30%. Cooling becomes the strongest driver of growth in buildings electricity demand, responsible for 40% of the total growth, and the second strongest driver of all electricity growth, after industrial motors. In absolute terms, this means cooling growth would require adding the equivalent of all electricity demand today in the United States and Germany.

Meeting peak electricity demand becomes a major challenge in the Baseline Scenario. The challenge of meeting cooling demand growth in an affordable and sustainable manner is exacerbated by its particular effect on peak demand. The share of space cooling in peak electricity load is projected to rise sharply in many countries, with the biggest increases occurring in hot countries such as India, where the share jumps from just 10% today to 45% in 2050. Of course, increased supply of renewable power will be essential for meeting this demand, with one-third of the cooling-related generating capacity additions in the Baseline Scenario coming from solar power alone. But this is not sufficient, as the daily pattern of solar power supply does not always match that of cooling demand, with high cooling demand in many countries lasting well after the sun has gone down. As a result, electricity systems in the Baseline Scenario will have to install and maintain large amounts of expensive peak power generation capacity.

Policies to improve the efficiency of air conditioners could quickly curb demand

There is an opportunity to quickly influence the growth of cooling related energy demand through policies to improve efficiency. This report presents an *Efficient Cooling Scenario* that describes an energy pathway based on much stronger policy action to limit energy needs for space cooling, and is compatible with the ambitious goals to limit climate change that were agreed in the Paris Agreement in 2015. There are many actions that can be taken, but this report focuses on one area where policy action can deliver substantial energy savings quickly – making AC equipment much more efficient. Through more stringent minimum energy performance standards (MEPS) and other measures such as labelling, the average energy efficiency of the stock of ACs worldwide could more than double between now and 2050.

Globally, the use of energy for space cooling in the Efficient Cooling Scenario grows by less than half as much as in the Baseline Scenario. Cooling-related energy demand climbs to 3 400 TWh in 2050 – 45% lower than the level in the Baseline Scenario. The savings are equivalent to all the electricity consumed by the European Union in 2016. This global AC energy efficiency drive could take effect immediately, given the relatively short lifetimes of ACs compared with buildings or power sector infrastructure. By contrast, less stringent MEPS in the Baseline Scenario effectively lock in inefficient products.

More efficient air conditioners would bring major benefits

The Efficient Cooling Scenario greatly reduces the need to build new generation capacity to meet peak demand. Worldwide, the need for additional capacity up to 2050 just to meet the demand from ACs is 1 300 gigawatts (GW) lower in the Efficient Cooling Scenario, the equivalent of all the coal-fired power generation capacity in China and India today. In most countries and regions, the avoided capacity needs are in the form of coal and natural gas.

Less need for capacity also translates into lower investment, fuel and operating costs. Worldwide, the cumulative savings in the Efficient Cooling Scenario amount to USD 2.9 trillion (United States dollar) over 2017-50 compared with the Baseline Scenario. This translates into lower electricity costs for all. Globally, the average cost per person of supplying electricity to end users for air conditioning is around 45% lower than in the Baseline Scenario.

Measures to make ACs more energy efficient, coupled with decarbonisation of power generation, lead to a huge reduction in cooling-related CO_2 emissions. By 2050, those emissions drop to just 150 million tonnes in the Efficient Cooling Scenario – a mere 7% of those in the Baseline Scenario and 13% of their 2016 level. Half of the savings come directly from the improved efficiency of ACs. Similarly, emissions of key air pollutants drop by up to 85%, with again more than half the effect directly due to the more efficient ACs.

Policies to improve the energy performance of buildings would bring additional long-term energy savings

Measures to improve the energy performance of building envelopes would contribute to even bigger energy savings in the longer term. The way buildings are designed and built, including the choice of materials used in their construction, can have a huge impact on the need for ACs and the subsequent energy needed to provide cooling services. Policies for more efficient ACs, combined with policies for more efficient buildings, could actually keep energy demand for cooling flat, while allowing strong growth in access to cooling for populations around the world. This would require much tougher building energy codes, which need to be well-thought-out, coordinated with renewable energy policies, and properly enforced.

A concerted policy push to rein in cooling energy demand is needed urgently

Rigorous action by governments is needed urgently to curb the rapid growth in demand for air conditioning and achieve the outcomes described in the Efficient Cooling Scenario. In order to bring about a lasting reduction in the energy demand for cooling, Governments need to enable and encourage investments and – where necessary – mandate the required improvements in ACs, as well as buildings. Such action works: efficiency standards for ACs and building energy codes have been in place in many countries for many years, and have delivered large, cost-effective energy savings. Experience shows that such policies also work quickly to reduce the higher prices of more efficient solutions, very often with no observable increase in costs to consumers.

Priority must be given to mandatory standards and labelling for ACs. They are relatively straightforward to introduce and enforce, and hold the potential to make the biggest and quickest dent in rising cooling demand in the coming decades. A strong policy response can ensure growing access to space cooling does not come at the potentially huge costs – economic, social and environmental – described in this report. There is much experience and knowledge governments can draw upon in this regard, and the International Energy Agency (IEA) is ready to support global action to ensure a sustainable cooling outcome for the planet.

1. The role of cooling in the energy system

Keeping cool

There are several ways of keeping buildings cool. The most basic, which has existed since the dawn of mankind, is the use of shading, solar orientation and other building designs to keep the interior cool. Another basic means of cooling is an electric fan. The most advanced is air conditioning, which is much more effective in reducing temperatures to provide thermal comfort.[1] Heating, ventilation and air conditioning (HVAC) is the generic term given to systems that provide indoor thermal comfort and improved air quality.

Active air conditioning, as opposed to building designs that keep indoor temperatures down, is a relatively recent phenomenon. Although mechanical techniques for cooling indoor air were developed as early as the 19th century and the first modern electrical air-conditioning unit was invented at the beginning of the 20th century, the widespread use of ACs only started to take off, initially in the United States, in the 1950s with improvements in the performance of commercial devices, lower prices, and growing prosperity.

ACs available today vary enormously in scale and cost, from small (sometimes portable) devices designed to cool a single room to large-scale systems for entire buildings and district energy networks for cooling groups of buildings or big commercial premises, such as office complexes, shopping malls, hotels and hospitals. All those types of air conditioning (AC) systems are usually powered by electricity, though large systems can also be fuelled by natural gas, excess heat and direct solar energy. The vast majority of cooling takes place in buildings located in urban areas, both in the advanced industrialised countries and emerging economies.

Air-conditioning technologies

ACs come in different shapes and sizes

The overwhelming bulk of ACs in use throughout the world are based on vapour compression refrigeration cycle technology, which is also used in most refrigerators. This technology exploits a basic law of physics: when a liquid converts to a gas (in a process called phase conversion), it absorbs heat; and when it condenses again (to a liquid), it releases heat. ACs exploit this feature of phase conversion by forcing either natural or special chemical compounds, known as refrigerants, to evaporate and condense repeatedly in a closed loop of coils. The vast majority of those refrigerants in use today are human-made gases, with significant global warming potential (see Chapter 2).

Refrigerants have properties enabling them to change state at relatively low temperatures. A fan moves warm interior air over the cold, low-pressure evaporator coils. The refrigerant inside the coils absorbs heat as it changes from a liquid to a gaseous state, and thus cools the air. To keep cooling, the AC converts the refrigerant gas back to a liquid again. To do that, a compressor puts the gas under high pressure – a process that releases heat. The heat created by compressing the gas is then evacuated to the outdoors with the help of a second set of coils called condenser coils, and a second fan. This cools down the gas in the coils and turns it back into a liquid, and the

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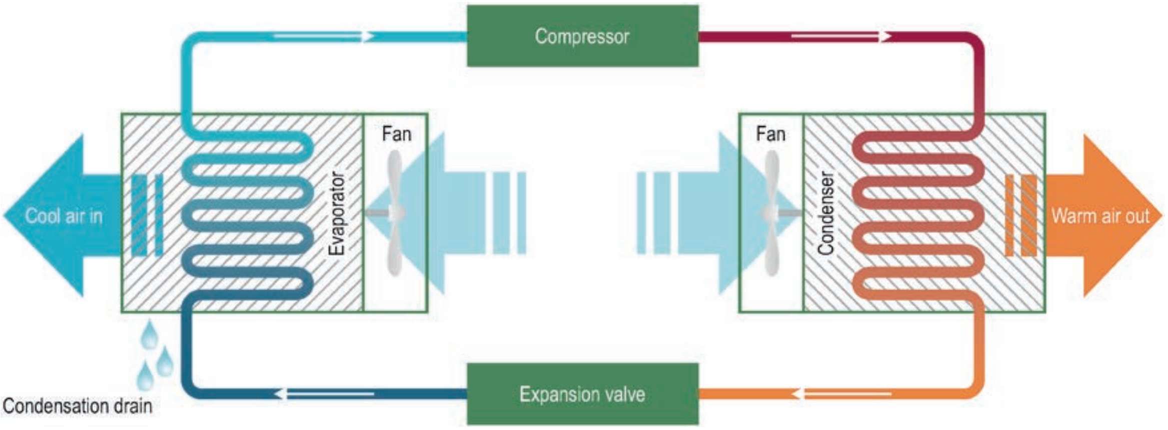
[1] Space cooling in this report includes air conditioning, electric fans and dehumidification in the residential and commercial (service) sectors. Cooling is also used in cars and trucks, as well as in industrial processes; these sectors are not included in the scope of this report.

process starts all over again in a constant cycle: liquid refrigerant, phase conversion to a gas and heat absorption, compression and phase transition back to a liquid again (Figure 1.1).

Figure 1.1 • How a standard vapour compression refrigeration cycle AC works



Key message • ACs use a refrigerant and a vapour compression cycle to move heat from one space to another, providing comfort and the sensation of fresh, cool air.

A less common and simpler form of air conditioning is evaporative cooling, which does not require a compressor or condenser, but does require a climate that is hot and dry. Water is evaporated on cooling fins and ventilated into the building by fans. Evaporating water absorbs a significant amount of heat (known as the latent heat of vaporisation), cooling the air in the same way that perspiration enables humans and animals to cool themselves.

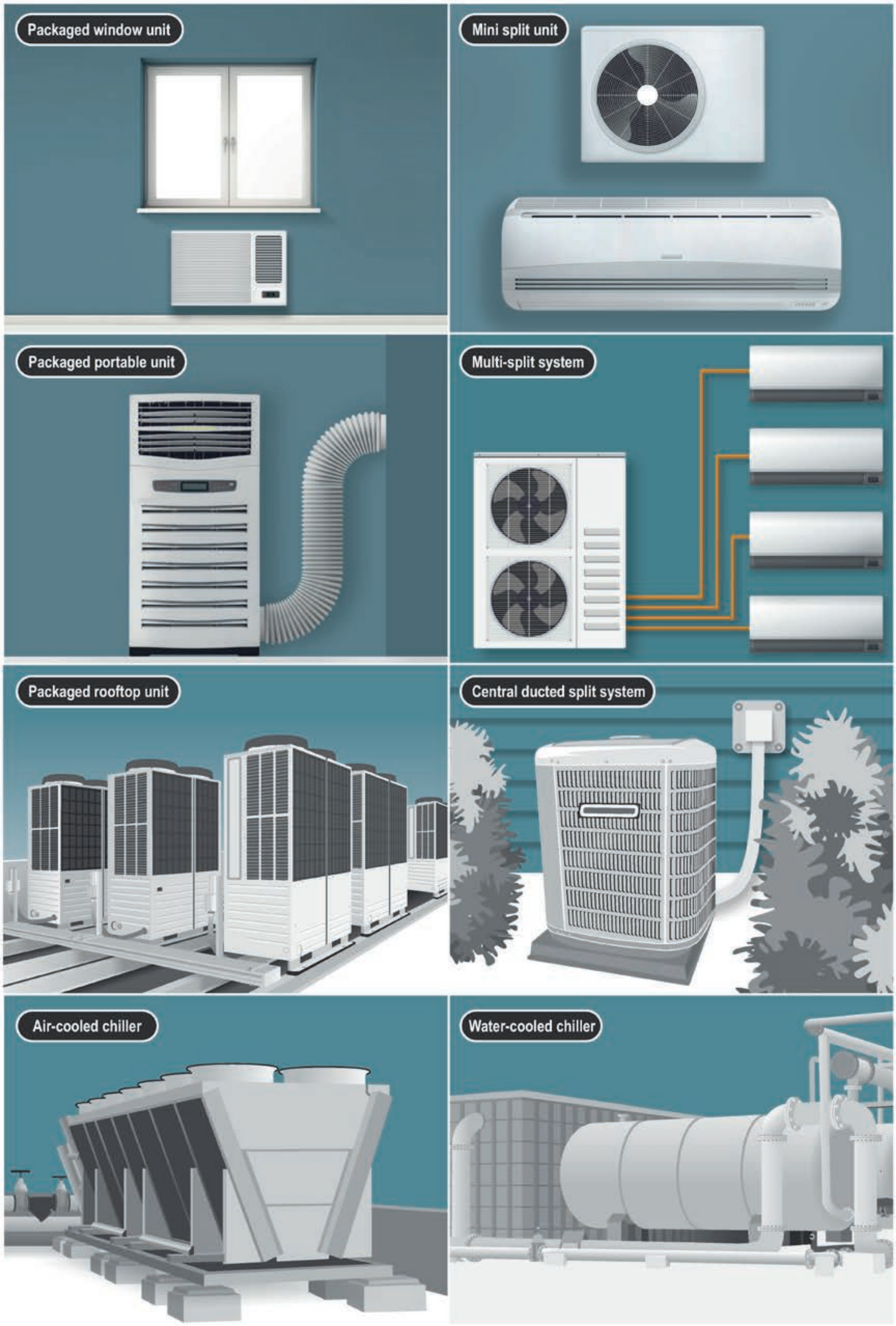
Another type of AC, typically used in the commercial (i.e. non-residential) sector, is a "thermally driven" adsorption or absorption chiller. Such chillers can be fuelled by gas or other sources of heat, such as industrial excess heat or solar thermal energy, which replaces the electricity used by a mechanical compressor. Absorption chillers are the most common type of thermally driven equipment worldwide, typically using a lithium bromide and water solution as the refrigerant. 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 degrees Celsius (°C).

In practice, standard ACs are available in different configurations: they can be packaged or split; ducted or ductless; portable or stationary; small or large (Figure 1.2).

ACs can make use of a variable- or fixed-speed fan; an inverter or fixed-speed compressor motor; variable- or fixed-flow refrigerant; and an evaporative or condensing heat transfer method (Box 1.1). The choice of system is determined by several factors, including the ease and cost of installation and operation, the amount of space to be cooled, the need for flexibility in adjusting temperatures, restrictions on indoor space and aesthetic considerations. The choice of system can have a major impact on the cost and energy efficiency of providing cooling. Refrigerant choice can also affect efficiency.

ACs can also be used for heating purposes through reversible heat pumps, which enable the refrigeration cycle to be reversed and provide heating instead of cooling (and vice versa). When the heat pump is in heating mode, the evaporator coil simply switches roles and becomes the condenser coil, producing heat, while the condenser unit becomes the evaporator, discharging cold air to the exterior. Depending on climatic conditions, this choice of equipment can meet both heating and cooling needs, and heat pumps are typically much more energy efficient than standard electric resistance heaters or fossil fuel combustion boilers.

Figure 1.2 • Common types of standard ACs



Key message • ACs come in different sizes and configurations, and choice depends on a variety of factors such as the space to be cooled, application type and aesthetic preferences.

Box 1.1 • Main types of ACs in use today

Packaged ACs range from small window units that cool a single room to large rooftop units that are capable of cooling an entire building (often as part of an overall HVAC system). All packaged ACs, also known as unitary systems, contain both the condenser and evaporator in a single box that moves hot air out of the building and cool air inside. The main types of packaged ACs are as follows:

- *Window units* that are small enough to fit into a standard window frame. They are sometimes referred to as "through-the-wall" units when sold to fit through a hole in a wall.
- *Packaged terminal ACs*, common in hotels, are characterised by a large unit under a window with a grilled opening passing through the wall connecting the condensing unit on the outside to the evaporative unit on the inside.
- *Packaged portable units* are designed to be easily transported inside a building from room to room, with a hose to evacuate the hot air from the unit to the exterior.
- *Packaged rooftop units*, also known as outdoor packaged units, are larger packaged chiller systems that deliver cooled air into the building through ducts.

Split-system ACs range from small room units to large systems that can cool a large complex of buildings. In all cases, the condenser is located outside the building and is separated through piping that carries the refrigerant to the evaporator, or air handling unit, on the inside of the building.

- *Ductless mini-split systems* deliver cooling to a building through refrigerant that is piped from the outdoor condensing unit to the indoor evaporator mounted on a wall or ceiling. Ductless systems have advantages over ducted systems, including lower distribution losses, increased energy efficiency and increased control of temperature in each room.
- *Ductless multi-split systems* allow multiple rooms to be cooled from a single outdoor unit, with a separate indoor evaporator unit(s). The main advantage of this system is the reduced number of outdoor units while retaining the flexibility for cooling individual rooms. Variable refrigerant flow systems are a variant of multi-split systems, which have been developed to deliver variable refrigerant quantity depending on the cooling needs of each evaporator.
- *Central ducted split-systems* deliver cooling through ducted air, whereby the evaporator is placed in a single central location, providing cooling for an entire residential or commercial building through a system of ducts. The temperature in each zone can be controlled separately.

Chillers are large ACs that produce chilled water and distribute it throughout a building or cooling network through pipes to an indoor system that cools the air. Compression cycle chillers can be centrifugal, reciprocating or screw driven. Absorption cycle chillers can be fuelled by electricity, natural gas or even solar heat. There are three main types of chillers:

- *Water-cooled chillers* use a condenser and refrigerant to reject heat to water, which is pumped to a cooling tower and circulated using fins to expel heat to the atmosphere (typically through evaporation). In certain cases, cooling towers can be replaced by ground heat exchangers, which can reduce the amount of water to be evaporated.
- *Air-cooled chillers* have condensers in which the refrigerant rejects heat directly to the outside air using one or more fans to cool the heat exchange coils.
- *Evaporative-cooled chillers* involve the use of a water spray to reject heat use more efficiently. Such chillers can make use of natural gas or co-generated sources of heat to drive the refrigeration cycle. This can be particularly useful in buildings with large cooling needs or with a concurrent need for both air conditioning and heating. They also alleviate overall electricity load.

Air conditioning is booming

Sales of ACs worldwide have been growing steadily in recent years, with only a brief dip in the aftermath of the 2008 financial crisis. Between 1990 and 2016, annual sales of ACs nearly quadrupled to 135 million units. The bulk of the units sold are packaged and split-system ACs for residential and smaller commercial buildings, though the typical size of commercial ACs, including chillers, and their associated energy use are generally much larger. By the end of 2016, an estimated 1.6 billion ACs were in use (Table 1.1). Measured in terms of cooling output,[2] roughly 11 675 gigawatts (GW) of capacity was in use at the end of 2016, up from 4 000 GW in 1990 (Figure 1.3). Of total capacity, just over half was in the residential sector.

Table 1.1 • Air-conditioning units and cooling capacity by country/region, 2016

	Installed stock						Annual sales					
	Million units			GW output capacity			Million units			GW output capacity		
	Res	Com	Total	Res	Com	Total	Res	Com	Total	Res	Com	Total
United States	241	132	374	2 295	2 430	4 726	16	8	24	314	129	443
European Union	43	53	97	192	654	847	9	3	12	34	41	75
Japan	116	33	148	407	352	759	9	2	11	47	14	61
Korea	30	29	59	129	220	348	2	2	4	19	15	34
Mexico	7	9	16	40	65	105	1	1	2	5	6	10
China	432	138	569	2 092	807	2 899	41	12	53	305	81	386
India	14	13	27	77	72	149	3	2	4	14	12	25
Indonesia	7	5	12	32	27	59	1	1	2	5	4	9
Brazil	14	14	27	59	68	127	1	0.3	1	5	1.4	6
South Africa	1	1	3	6	15	22	0.1	0.1	0.3	0.9	1.1	2.1
Middle East	30	18	47	147	153	299	4	2	6	29	16	45
World	1 093	529	1 622	6 181	5 491	11 673	94	40	135	848	359	1 207

Notes: Res = residential; Com = commercial; the data on air-conditioning capacity and units shown in this report, unless otherwise noted, include residential and commercial systems, including packaged and split units, chillers and other large space-cooling systems; district cooling and solar cooling applications are not included in these estimates; "China" = the People's Republic of China.

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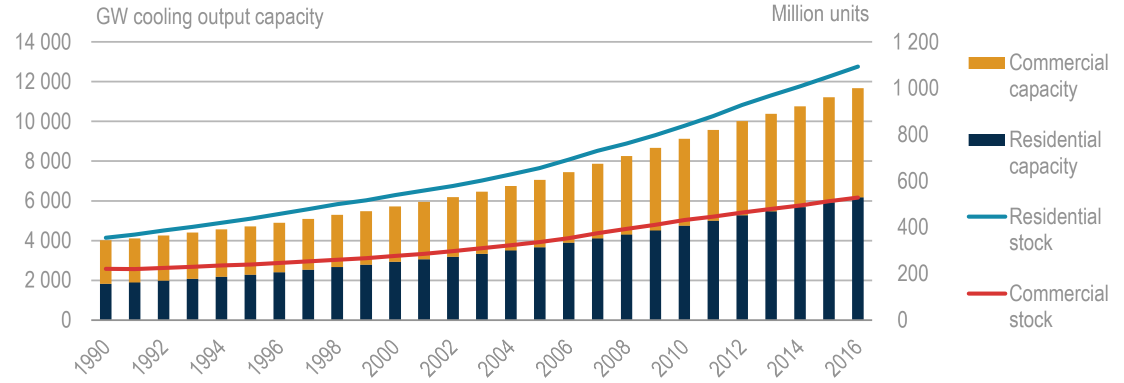
[2] In this report, cooling output capacity refers to the thermal output of air conditioning systems.

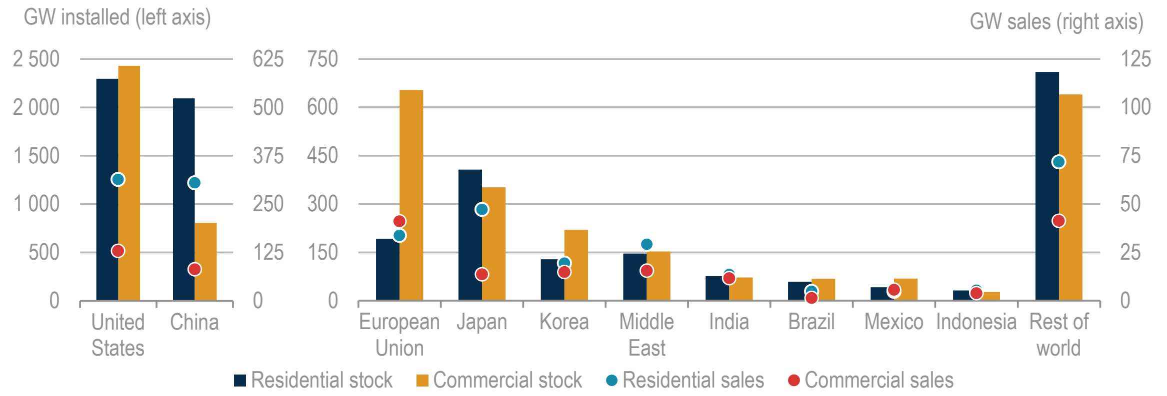
Figure 1.3 • Worldwide stock and capacity of ACs by sector



Key message • Sales of ACs, particularly to households, continue to grow briskly, pushing up the total stock of units and global cooling capacity.

Unsurprisingly, there are big differences in the size of the stock and sales of ACs across countries and regions, mainly reflecting differences in climate, population and prosperity. The United States has the largest amount of installed AC capacity, around 50% of it in the residential sector (Figure 1.4). In fact, 40% of all the installed cooling capacity in the world is in the United States. But that share is declining as air conditioning takes off in other parts of the world, notably in Asian countries. In 2016, sales of ACs in capacity terms were highest in the People's Republic of China (hereafter, "China"), where they totalled nearly 390 GW (53 million units). Sales continue to grow rapidly in the other main markets – especially India, Indonesia and the Middle East. In the United States, sales remain buoyant despite the already high level of market penetration thanks to an upturn in construction in the hottest southern regions, growth in colder climate zones (which can often have very hot summers) and replacements of older ACs.

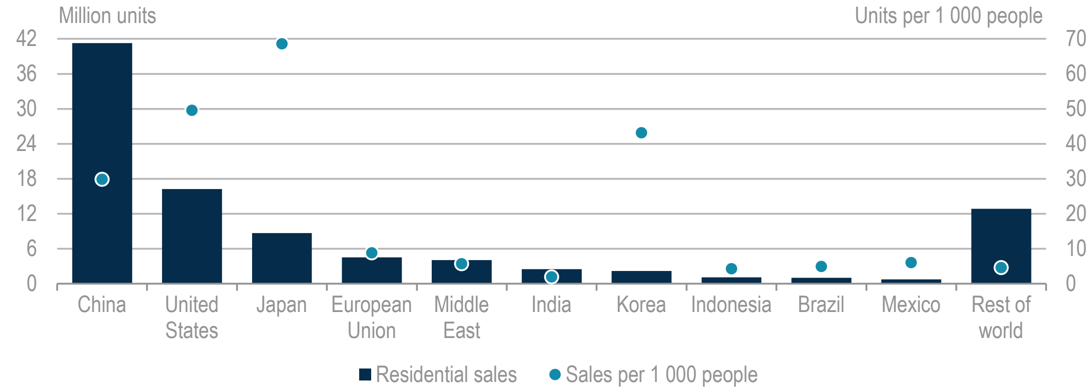
Figure 1.4 • Aggregate AC cooling output capacity and sales by country/region, 2016



Key message • The United States has the largest installed AC cooling output capacity in the world, but sales are now higher in China.

Specifically for residential ACs, China is currently the leading market in total unit sales (41 million units), although cooling output capacity of new sales in the United States is slightly higher (about 315 GW), given larger equipment sizing (e.g. for central HVAC systems). The next largest markets for residential AC sales are Japan and the European Union (Figure 1.5). Per capita AC sales vary enormously: they remain highest in Japan, the United States, Korea and China, but rates are rising quickly in most other countries, especially those in Asia.

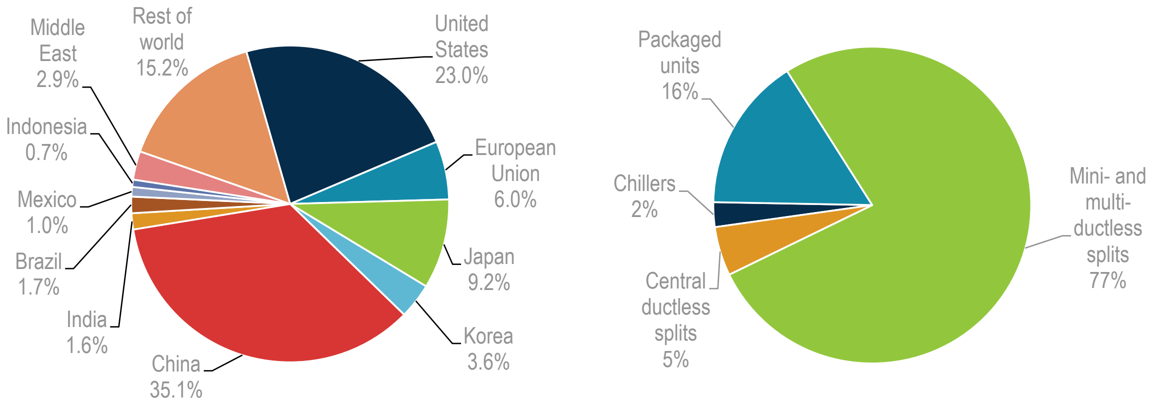
Figure 1.5 • Sales of residential ACs by country/region, 2016



Key message • The market for residential ACs is dominated by China, the United States, Japan and the European Union, but sales are rising strongly in other emerging economies, especially in Asia.

Of the 1.6 billion ACs in use throughout the world at the end of 2016, over half were in just two countries: China, which has 570 million units, and the United States, where there are 375 million (Figure 1.6). Other countries with more than 20 million units include Japan, with 150 million, Korea (60 million), Brazil and India (both nearly 30 million). The remaining ACs are mostly in the European Union, where there are nearly 100 million units, and the Middle East (around 50 million units). Nearly 70% of all the ACs globally is in residential buildings. Household ownership of ACs varies enormously across countries, from around 4% in India and less than 10% in Europe, to over 90% in the United States and Japan, and close to 100% in a few Middle Eastern countries. In China, nearly 60% of households now have at least one AC (see Chapter 2).

Figure 1.6 • Stock of ACs by country/region and type, end 2016



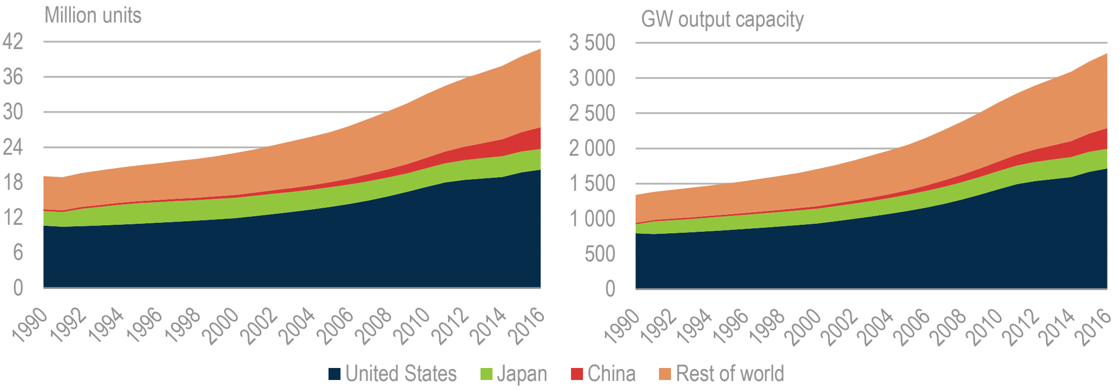
Total capacity = 11 675 GW (1.6 billion units)

Key message • Air conditioning is highly concentrated in a small number of countries, with two-thirds of all systems in use found in just three countries – China, the United States and Japan.

The overwhelming majority of ACs in use today around the world are split systems – either individual mini-split or multi-split ACs. Split systems have always been the preferred option in Asia and Europe. Central ductless split systems make up about 5% of the capacity of all the ACs in use worldwide, a share that has fallen marginally over recent years as the use of AC in smaller housing units, such as apartments, for which split systems are more amenable, has grown. There are also very big differences in the average efficiency of ACs across regions (see Chapter 2).

Chillers are used almost exclusively in commercial buildings, large central systems in large residential blocks and district cooling networks. There are an estimated 41 million chillers in use around the world (Figure 1.7), of which 35 million are electric powered and water or air cooled. Their capacity amounted to 3 350 GW, equal to 60% of total commercial air-conditioning needs. Thermally driven chillers, typically using natural gas, account for another 470 GW of cooling capacity, or nearly 5.5 million units. The United States remains the single largest market for chillers, with just under half of the global stock and 42% of sales in 2016, though these shares have been falling in recent years with market saturation. Demand for chillers has expanded the most in China since 2005, which now accounts for 10% of the total stock worldwide and 20% of the 2.4 million chillers sold across the world in 2016.

Figure 1.7 • Stock of chillers by country/region



Key message • The stock of chillers worldwide has been growing steadily, though less rapidly than standard package and split ACs, with most growth in the United States and China.

Household fans

Electric fans remain a common form of cooling. An estimated 2.3 billion residential electric fans were in use in 2016 around the world,[3] with an estimated 55% of all households globally owning at least one fan. Today, there are twice as many fans in use as ACs in households worldwide, but the ratio is falling quickly as AC ownership expands. Several types of fan are in use, ranging from portable table and pedestal fans to window, box and ceiling fans. In some countries, evaporative coolers or misting fans are also common, providing an additional feeling of comfort by converting liquid water to vapour – a process similar to human perspiration. These fans, which work in a similar way to ACs, reduce the temperature of the air, though their effectiveness depends on relative humidity (i.e. the level of water vapour already in the air).

Like ACs, household fans also come in a wide variety of shapes and sizes, which – along with their efficiency and how often they are used – affect their energy use (see below). They typically use less than 10% of the energy consumed by a packaged or split-system AC for an equivalent space.

Household fans will continue to play an important role in meeting growing cooling demand, especially in developing countries where fans are by and large much more affordable than a standard AC. In many countries, especially in Africa and South Asia, household fan ownership is expected to grow rapidly as more people gain access to electricity, providing greater comfort until households can afford to buy an AC. Depending on climate and building design, fans could continue to meet a significant share of residential space-cooling needs (see Chapter 4).

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[3] Data on the number of fans and their energy use are poor. The International Energy Agency (IEA) estimates that the energy use of residential fans globally was barely a tenth of that of ACs (see below). For these reasons, the focus of this report is on ACs.

Dedicated dehumidification systems

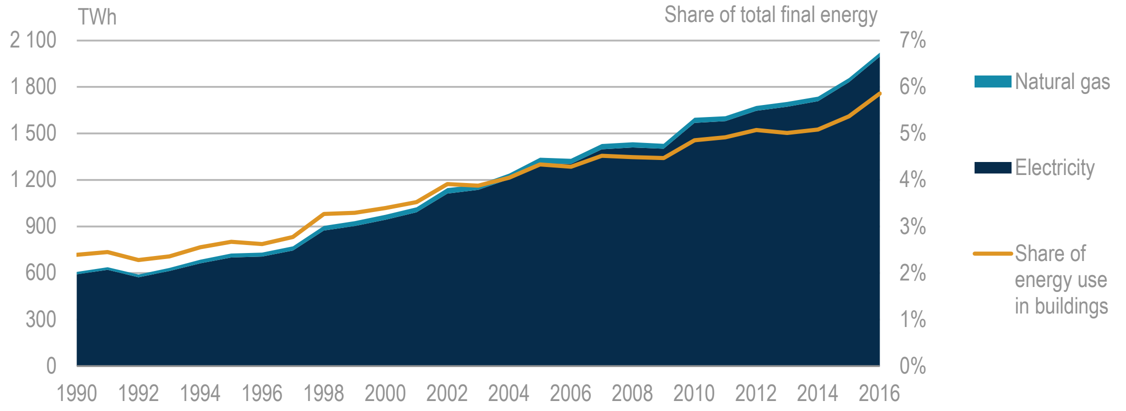
The use of dedicated dehumidification systems is growing, especially in developing countries with very humid climates and in the commercial sector where moisture removal can be very important. As building envelopes are improved with higher thermal resistance, humidity control may account for a larger portion of cooling loads. ACs effectively act as dehumidifiers, as reducing the temperature of a volume of humid air causes it to condense a portion of its moisture in the cooling system evaporator or air-handling unit.[4] Dehumidification on its own without lowering ambient indoor temperatures can often improve comfort in buildings at far lower cost than using ACs for dehumidification.

Energy use for space cooling

Historical trends

Space cooling is the fastest-growing use of energy in buildings, both in hot and humid emerging economies where incomes are rising, and in the advanced industrialised economies where consumer expectations of thermal comfort are still growing. Final energy use for space cooling in residential and commercial buildings[5] worldwide more than tripled between 1990 and 2016 to 2 020 terawatt hours (TWh) (Figure 1.8). The share of cooling in total energy use in buildings rose from about 2.5% to 6% over the same period. For commercial buildings, the share reached 11.5% in 2016, up from 6% in 1990. Cooling accounted for 18.5% of total electricity use in buildings, up from 13% in 1990.

Figure 1.8 • World energy consumption for space cooling in buildings



Key message • Energy use for space cooling, almost entirely in the form of electricity, is expanding rapidly in absolute terms and as a share of overall energy use in buildings.

Most of the energy used for space cooling is in the form of electricity; the share of natural gas – used almost entirely for thermally driven chillers or systems in commercial buildings – was just over 1% in 2016. Total electricity use for cooling worldwide amounted to 2 000 TWh in 2016, or

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[4] For this reason, there are typically drains and moisture-collecting pans near or attached to ACs. It is also why ACs discharge water when they operate on humid days.

[5] The data on energy use for space cooling presented in this report cover residential and commercial buildings. Globally, most energy is used for ACs, though dehumidifiers and fans can also represent significant shares in some countries. Unless otherwise noted, final energy for space cooling in this report includes final electricity consumption for ACs, fans and dehumidifiers as well as natural gas use (mostly for chillers) in the buildings sector.

nearly 10% of the 21 000 TWh of electricity consumed globally in all sectors that year. The electricity used for space cooling required around 400 million tonnes of oil equivalent of primary energy – or 3% of world total primary energy use – taking account of the large amounts of energy lost in transforming primary energy sources into electricity. This is equivalent to all the energy used for international aviation and shipping worldwide.

Regional trends

There are big differences in the level of and trends in energy use for space cooling across countries and regions, mainly according to the underlying need for cooling and the level and pace of economic development. In absolute terms, the United States remains by far the world's biggest market (Table 1.2). In fact, 328 million Americans consume more energy for cooling than the 4.4 billion people living in all of Africa, Latin America, the Middle East and Asia (excluding China), and just under all the electricity used for everything by the 1.2 billion people in Africa.

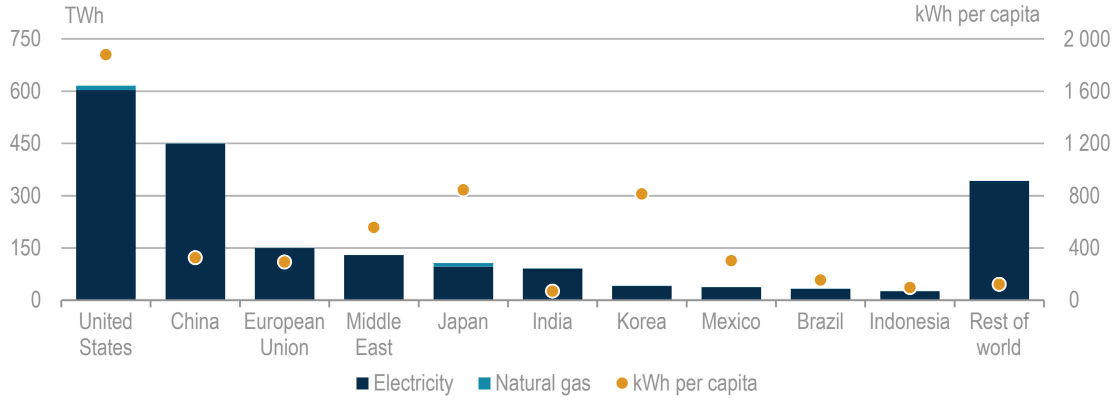
Table 1.2 • World final energy consumption for space cooling in buildings by country/region

	TWh				% of total building final energy use in 2016
	1990	**2000**	**2010**	**2016**	
United States	339	448	588	616	10.6%
European Union	63	100	149	152	1.2%
Japan	48	100	119	107	9.5%
Korea	4	17	34	41	8.5%
Mexico	7	16	23	37	9.8%
China	7	45	243	450	9.3%
India	6	22	49	91	3.4%
Indonesia	2	6	14	25	3.0%
Brazil	10	19	26	32	7.7%
South Africa	4	6	6	8	2.8%
Middle East	26	49	97	129	9.3%
World	608	976	1 602	2 021	5.9%

Demand for energy for space cooling in the United States appears to have levelled off in recent years, mainly due to market saturation with improvements in energy efficiency largely offsetting the impact of population growth, migration to hotter parts of the country and rising outdoor temperatures. Demand over 2011-16 averaged 560 TWh per year, only 2.5% higher than over 2001-10 (consumption fluctuates markedly with annual variations in the weather). In 2016, cooling made up about 10.5% of the total energy use in buildings in the United States, followed by Mexico (9.8%), Japan (9.5%), China (9.3%) and Korea (8.5%).

The enormous disparities in access to space cooling across the world are reflected in per-capita levels of energy consumption, which vary from as little as 70 kilowatt hours (kWh) in India to more than 800 kWh in Japan and Korea and as high as 1 880 kWh in the United States (Figure 1.9). Africa has some of the hottest places on the planet but AC ownership is still typically below 5%. Consumption of electricity for cooling there amounted to a mere 35 kWh per person on average in 2016. Even in Europe, which has a relatively mild climate, the average electricity consumed per person for space cooling is still more than all the electricity used per person in buildings in Africa, Brazil and Indonesia, which have much hotter climates and far greater cooling needs.

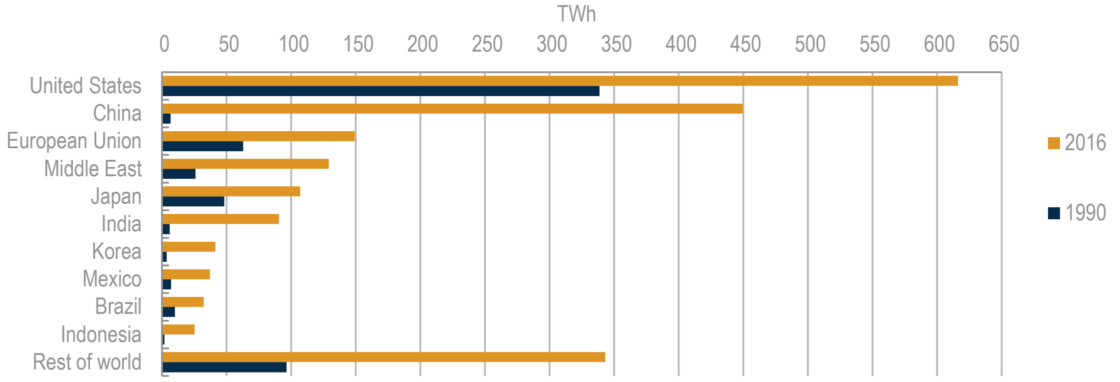
Figure 1.9 • Final energy use for space cooling in buildings by fuel and country/region, 2016



Key message • The United States and China account for close to half of all the energy used worldwide for space cooling, most of it in the form of electricity.

China has seen by far the biggest – and fastest – increase in energy use for space cooling since 1990, with a surge in sales of ACs (Figure 1.10). Cooling used a mere 6.6 TWh in 1990; by 2016, it consumed 450 TWh, a staggering 68-fold increase. And growth is showing no signs of slowing; it amounted to more than 10% in 2016, the fastest rate since 2009. China's total energy use for space cooling – and in particular ACs – is fast approaching that of the United States and is likely to surpass it soon given China's considerable population, though average energy use for cooling per person in China is still less than 20% of that in the United States. Demand in other emerging economies, notably India, is also growing very rapidly, having risen 15-fold since 1990.

Figure 1.10 • Final energy consumption for space cooling by fuel and country/region



Key message • Energy use for cooling has been surging in China and other emerging economies, though it remains highest in the United States.

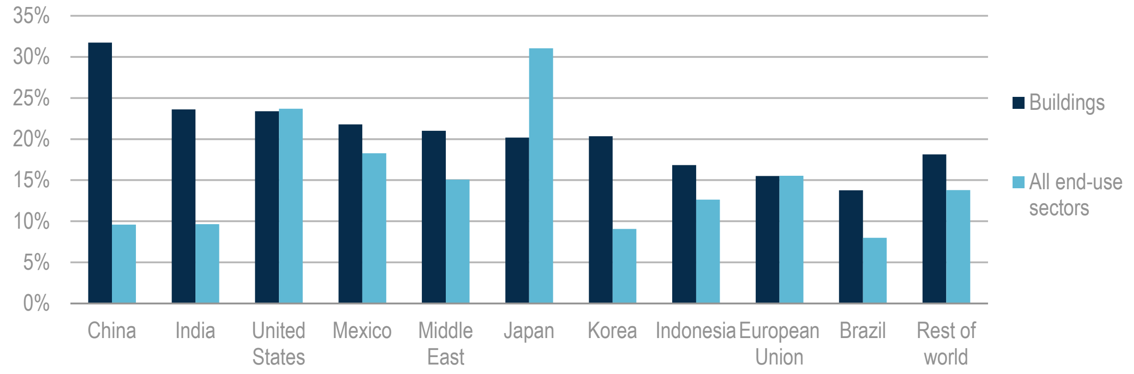
Data on fan ownership and energy use is patchy, though household surveys and country studies show that electric fan use in buildings can be a substantial portion of household energy use, especially in hot countries where AC ownership is still low. For instance, ceiling fans alone were estimated to account for approximately 6% of residential electricity use in India in 2000 (Shah et al., 2012). The International Energy Agency (IEA) estimates that household fan use globally consumed more than 80 TWh in 2016, or nearly 1.5% of residential electricity consumption. Household fan electricity consumption worldwide has increased 3.6 times since 2000 and far more in some hot and rapidly growing countries, such as India and Indonesia.

Implications for the electricity system

Rising demand for cooling is already having a major impact on power systems since most cooling needs are met by electricity-powered fans or ACs. Increased air-conditioning loads in particular raise not only overall electricity demand, but also peak electricity loads.

Electricity is the fastest-growing form of final energy worldwide: its share of total final energy use across all end-use sectors rose from 13% in 1990 to nearly 19% in 2016. The rapid pace of growth in demand for air conditioning is just one of the drivers of this growth: electricity is increasing in importance in all sectors. Space cooling accounted for around 13% of the overall growth in electricity demand between 1990 and 2016 and 22% of the increase in electricity use in buildings alone. The share for the latter was highest in China at one-third (Figure 1.11).

Figure 1.11 • Share of cooling in increased electricity demand by country/region, 1990-2016



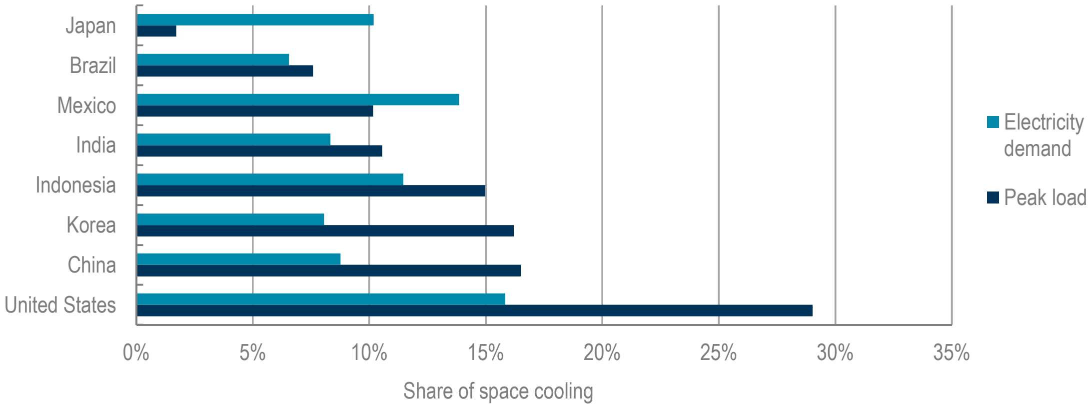
Key message • Space cooling has been a major contributor to the increase in electricity use in buildings since the 1990s.

Space cooling can account for a large share of peak demand, placing further stress on the power system, especially during periods of extreme heat. Cooling demand typically jumps during a heatwave, placing greater demands on the power system, the reliability of which can be further undermined by hot equipment increasing the risk of outages. For example, the output of solar panels and gas turbines can drop off at very high ambient temperatures. Electricity networks can also be affected, as high demand and high temperatures heat up power lines, impairing their performance.

In some places, such as the United States, space cooling can represent more than 70% of peak residential electricity demand during extremely hot days. For example, cooling represented 74% of peak electricity demand in Philadelphia on a particularly hot day in July 2011 (Cohen et al., 2017). Even in areas where air-conditioning demand today is less widespread, such as much of Western Europe, heatwaves can push up electricity demand dramatically. For instance, the heatwave in France in August 2003, when temperatures rose to around 40°C across most of the country, boosted power needs by about 4 000 megawatts (MW), or around 10%, compared with normal peak summer electricity demand (Létard, Flandre and Lepeltier, 2004). In China, demand for cooling pushed overall electricity demand to record highs during the summer heatwave in 2017 (SGCC, 2017). In some places, such as Beijing on the 13 July 2017, more than 50% of the daily peak load was related to cooling.

In 2016, the IEA estimates that space cooling accounted for around 10% of total electricity demand averaged across all countries (Figure 1.12). The highest shares were in the United States, where it reached 16%, the Middle East (15%), Mexico (14%) and Japan (10%). In most countries with significant seasonal cooling demand, air conditioning's contribution to peak electricity demand is markedly higher than to total demand throughout the year. For example, air-conditioning demand in Madrid in Spain accounted for one-third of total peak consumption in June 2008 (Izquierdo et al., 2011). Where there is demand for cooling throughout the entire year, such as Singapore or many countries in the Middle East, the share of air conditioning in peak load can be as high as 50% or more. In Saudi Arabia, air conditioning accounts for a staggering 51% of total electricity demand, with summertime demand twice as high as during the cooler "winter" months (Demirbas, Hashem and Bakhsh, 2017). Obviously, the efficiency of AC equipment has a huge impact on this effect, with one analysis suggesting that a 30% improvement in global AC performance by 2030 would reduce peak load by the equivalent of as much as 710 mid-sized coal power plants (Shah et al., 2015).

Figure 1.12 • Share of cooling in peak load and total electricity demand by country/region, 2016



Notes: The share of cooling in national peak load has been calculated for the moment in the year at which the overall peak in total electricity demand occurs; the contribution of cooling to local peak load in towns and cities can be much higher.

Key message • Space cooling is a significant contributor to electricity demand, especially at peak.

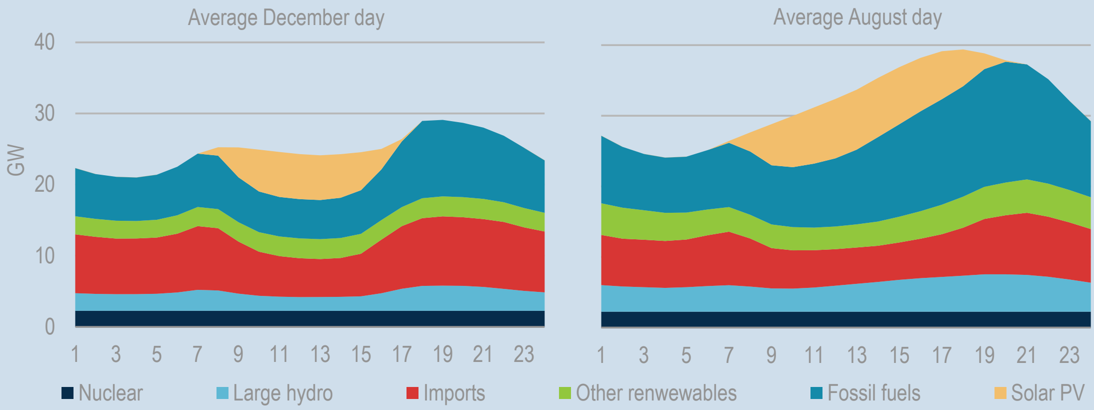
Building, maintaining and operating electricity capacity to meet peak demand is particularly costly – often between two and four times the cost per kWh of baseload electricity supply and sometimes higher – because the generation and network capacity dedicated to meeting peak load is used only for limited periods. The capital cost associated with this capacity normally represents a large portion of the total cost of supplying electricity at peak (Box 1.2). This is reflected in consumer electricity prices either directly through time-of-day or seasonal tariffs, or through average annual tariffs that are based on the cost of supply throughout the year.

Box 1.2 • Meeting electricity peak load

Peak load or demand is used in the electricity sector to describe the highest level of electricity demand measured over a period of half an hour or an hour that occurs within a given time period, such as a day, season or year. For most electricity systems, daily peak occurs early in the morning, when people wake up, and in the evening, when people return from work and make use of household appliances and lighting. In hot and humid countries with high levels of electricity demand for cooling, the daily peak may occur in the afternoon or evening, when ambient temperatures are highest. Countries with hot summers and cold winters may see peaks in both seasons depending on the extent to which electricity is used for heating purposes. California is an example of the former, with air conditioning being the main driver of peak load in the summer, while daily peak loads and electricity demand are much lower during the winter (Figure 1.13).

Power system operators are responsible for ensuring that generating, transmission and local distribution capacities are sufficient to meet expected peak load at all times – even if the peak period lasts for just one hour each year. Generally, a safety margin, known as reserve capacity, is built into the system in the event of an unexpected surge in peak load or loss of capacity due to an accident or unscheduled maintenance. If peak demand exceeds the maximum supply that the system can provide, unplanned power outages, deliberate shedding or brownouts (a deliberate or unplanned drop in voltage) will inevitably occur. This is more likely to happen in systems with limited reserve capacity, dilapidated infrastructure and rapidly rising demand, especially during heatwaves when the use of ACs surges. During such episodes, the authorities may request the public to curtail their energy use or shift it to an off-peak period.

Figure 1.13 • Average daily electricity load profiles for winter and summer in California, 2017



Notes: Fossil electricity generation in California is more than 99% based on natural gas; PV = photovoltaic.

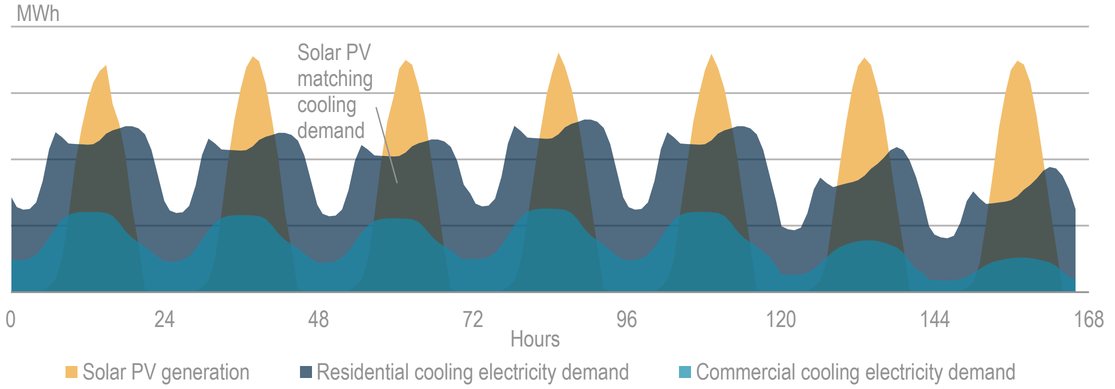
Source: CAISO (2018), *Daily Renewable Watch*.

Key message • Air-conditioning loads during the summer drive the need for additional power generation capacity, in particular gas-fired power plants, compared with the winter.

Meeting electricity peak load is expensive. It requires the electricity system to install and maintain large amounts of capacity than can be ramped up quickly at short notice, even though a significant portion might only be used for a few hours or days each year – if at all. Power generators normally build specific types of capacity for this purpose, and owners of this capacity must be remunerated, either through a capacity payment – a fee for simply making the capacity available if needed – and/or a very high tariff for the power supplied during peak periods. In general, economics dictate that peaking capacity typically has a relatively low cost of construction per kilowatt of capacity, but high costs of operation. In many countries, diesel generators or single-turbine gas-fired plants are the main types of peaking capacity. Other options, such as pumped storage hydroelectricity and batteries, can have lower operating costs, but they typically have much higher capital costs. Demand management and response, which can lower peak demand, can be a more economic option in many cases (see Chapter 2).

One characteristic of air-conditioning load that can help to lower the cost of adding new electricity capacity is the partial matching of the profile of cooling demand with solar output. On sunny days, output from solar PV panels peaks in the middle of the day and falls to zero as the sun goes down; outdoor temperatures generally follow this pattern, particularly in hot, dry locations, albeit with a lag, as heat accumulates in the air and in the structure of buildings (Figure 1.14).

Figure 1.14 • Illustrative daily profile of space cooling load and solar PV electricity generation



Key message • The profile of electricity demand for space cooling generally matches to some degree that of solar PV output, which can help to lower the cost of meeting peak load.

In climates with a strong seasonal variation in cooling demand and little heating demand, solar PV can be a good match with cooling load during the cooling season. In practice, the demand for air conditioning follows broadly the outdoor temperature throughout the day, in particular in office buildings, although there is often a surge in demand from residential households in the evening, especially as people return home from work and switch on their ACs. While there is considerable complementarity of solar capacity with cooling demand when the sun is shining, additional electricity generation capacity using other energy sources or storage (batteries or thermal energy storage such as chilled water or ice storage) is needed to cover cooling needs beyond the hours when solar energy is available. In addition, there may be a seasonal mismatch of air-conditioning demand and solar PV output, especially in countries with hot summers and mild but sunny winters, when the use of ACs is low but PV generation is high (the left-hand chart in Figure 1.13 illustrates this situation in California). Meeting net load, defined as total load minus solar PV and wind generation, requires a flexible electricity system with a significant amount of dispatchable generating capacity that can be called upon whenever needed (such as gas turbines), electricity storage or demand response (see Chapter 2).

Impact on the environment

ACs themselves only emit greenhouse gases (GHGs) when leakage or improper disposal of refrigerants occurs, though these refrigerants are extremely powerful GHGs that contribute to climate change (Box 1.3). But the generation of the electricity needed to power those ACs can give rise to sizeable emissions, except in the case of pure renewables-based cooling systems.

Emissions of GHGs related to the use of energy for space cooling hinge primarily on the fuel mix in power generation. For the world as a whole, fossil fuels accounted for 65% of total power generation in 2016 (coal for 37%, gas 24% and oil 4%), resulting in average emissions of around 505 grams of carbon dioxide (CO_2) per kWh (gCO_2/kWh) of generation (the carbon intensity). Space cooling required a total of 2 000 TWh of electricity in 2016, corresponding to emissions of 1 130 million tonnes (Mt) of CO_2 based on the carbon intensity of electricity generation at times of air-conditioning demand and taking account of losses in transmission and distribution.

Box 1.3 • Air-conditioning refrigerants and climate change

ACs use refrigerants that can impact climate change in two ways: through their influence on energy-related emissions and from refrigerant leakage. Refrigerants impact energy use as the effectiveness of the heat transfer is dependent on the type of refrigerant; in other words, some refrigerants can improve the operational efficiency of ACs. Refrigerants also contribute to global warming if leaked to the atmosphere, as they are usually comprised of hydrofluorocarbons (HFCs). HFCs are a family of gases that have become the predominant type of refrigerant in recent years with the phasing out of the manufacturing of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) under the 1987 Montreal Protocol in order to protect the stratospheric ozone layer. HFCs were not included in the Montreal Protocol as they are relatively harmless to the ozone layer.

In October 2016, 197 parties to the Montreal Protocol agreed on the Kigali Amendment to progressively phase down the production and use of HFCs around the world. The amendment takes effect in different countries between 2019 and 2028, depending on national levels of development. The start date is 1 January 2019 for the European Union and the United States, while China will have to start to cap their use by 2024. For a third group of developing countries with particularly hot climates – Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and the United Arab Emirates – the start date is 2028.

Implementation of the agreement is expected to prevent up to 80 billion tonnes CO_2 equivalent of emissions by 2050, making a significant contribution to global ambitions to limit the global temperature rise to below 2°C.

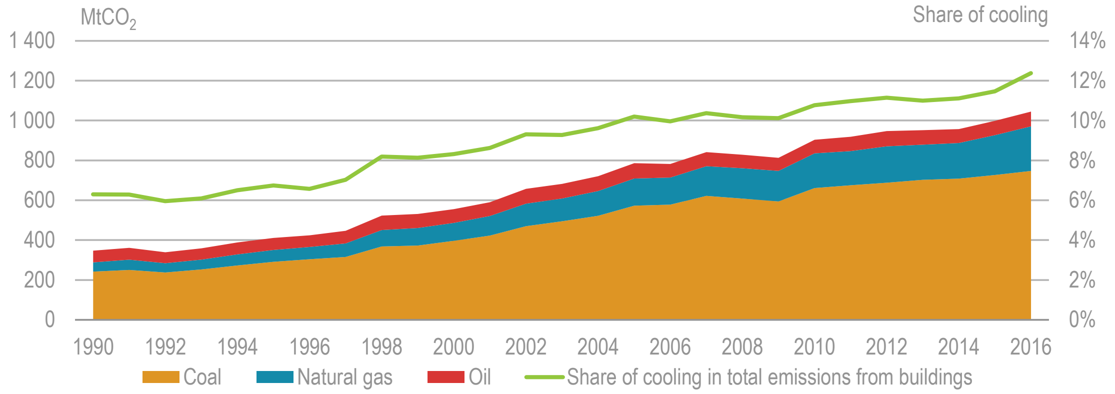
The Kigali Amendment is supported by other actions that seek to improve the efficiency of space-cooling and refrigeration equipment, reduce the need for refrigerants and minimise the impact of energy use for cooling and refrigeration on climate change. The Kigali Cooling Efficiency Program (K-CEP) is a programme funded by 18 philanthropist foundations to further increase the energy efficiency improvements achieved through the HFC phasedown (see the next section). A number of natural and synthetic alternatives to conventional refrigerants that are both harmless to the ozone layer and do not contribute significantly to climate change are available or being developed. Unfortunately, many of them have drawbacks, such as higher costs, flammability or toxicity. Research and development is progressing rapidly in this area.

K-CEP will work with partners and countries to provide guidance and support the transition to more efficient cooling equipment and the phasing down of HFCs. In support of this, the IEA is hosting the Kigali Progress Tracker, which will bring together all cooling-related information into a single platform. This new Global Exchange on Cooling is collecting information on cooling efficiency and enables users to generate charts, maps and download data on cooling energy, policy and technology data. Key data includes information on minimum energy performance standards (MEPS) and labels across 57 countries, alongside summaries of cooling equipment efficiencies and data mined for more than 2 million pieces of cooling equipment. The Exchange also includes information on cooling energy use by country and region.

Note: For additional information, visit: www.iea.org/exchange/cooling/; www.k-cep.org.

Adding in direct emissions from the use of fossil fuels (almost entirely natural gas) from direct use in chillers, global cooling-related CO_2 emissions amounted to 1 135 Mt – triple the level of 1990 (Figure 1.15). The share of cooling in total energy-related emissions from buildings doubled to 12% over the same period.

Figure 1.15 • World CO_2 emissions associated with space cooling energy use by source

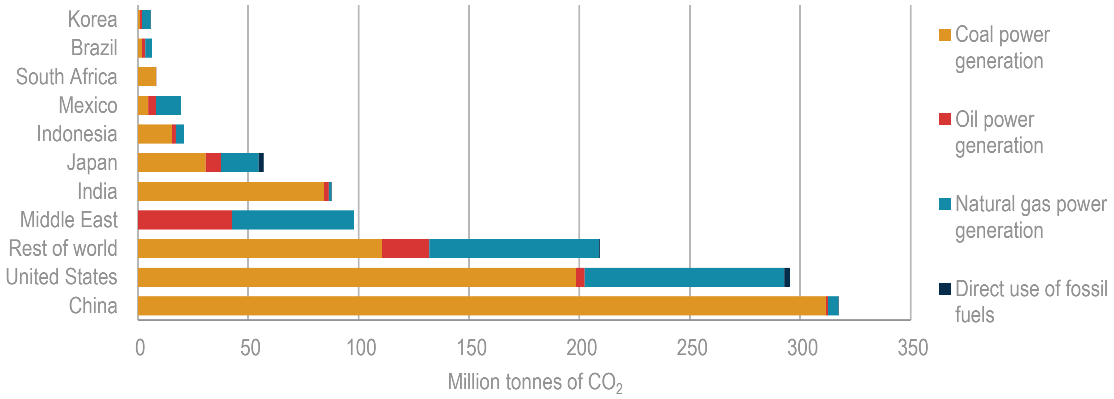


Notes: Emissions take account of losses in transmission and distribution; they include indirect emissions from power generation and direct emissions from the use of gas in chillers; up to 2015, annual average CO_2 intensities have been used, while for 2016 and in the scenario analysis for future years, the CO_2 intensities at times of air-conditioning demand have been used; for 2016, this results in a global average annual CO_2 intensity for cooling of 578 gCO_2/kWh, including transmission and distribution losses (derived from the modelling analysis in this report – see Chapter 3).

Key message • The share of space cooling in total energy-related CO_2 emissions in buildings, mainly caused by coal burning in power stations, doubled between 1990 and 2016.

China and the United States together contribute about 55% of global cooling-related CO_2 emissions – a slightly larger percentage than their share of global cooling-related demand because a large proportion of the electricity needed to meet that demand comes from coal-fired power plants in both countries. CO_2 emissions per kWh from coal plants are generally around twice as high as from gas plants and about a quarter higher than from oil plants (Figure 1.16).

Figure 1.16 • Energy-related CO_2 emissions from space cooling by source and country/region in 2016



Key message • Some 54% of global CO_2 emissions caused by cooling come from power stations in the United States and China, which rely heavily on coal.

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2. Drivers of energy use for cooling

Obviously, the basic driver of cooling demand is climate, i.e. the temperature of the air and the level of humidity. Air conditioning is commonplace today in countries that experience hot weather for at least several weeks or months of the year. In cool-climate countries, mainly in the northern hemisphere, air conditioning is quite simply unnecessary most of time, with electric fans generally sufficing during heatwaves. But an unpleasantly hot climate is not a sufficient condition for everyone to avail of air conditioning: households and the owners of commercial buildings have to be able afford to buy an air conditioning system (AC) in the first place and then to pay for the electricity to run it. It follows that, in hot countries, rising incomes and population are pushing up demand for cooling.

Climate aside, the amount of energy needed to meet demand for space cooling varies mainly according to the type and efficiency of the equipment used, how it is used and how often it is used, as well as the type and thermal efficiency of buildings. Decisions by occupants about the type of AC, which rooms get cooled and when, and temperature settings can have a considerable impact on cooling energy demand. For example, in many Chinese households today, small mini-split ACs are used in several rooms, but the occupants often turn the equipment on only when they are inside the room and feel hot. This “part-time, part-space” type of cooling demand can use as much as five times less energy compared with running ACs in every room all summer.

The energy consumption per unit of cooling output of ACs currently on sale around the world varies massively. Technological advances mean that new ACs already on the market or that will come to market imminently are a lot more efficient and could hold back the overall growth in energy demand for cooling. Prices can also be expected to come down. In general, more efficient equipment does not automatically cost more to buy than less efficient.

But demand for thermal comfort can be met in different ways, some of which involve no energy at all. For example, a well-designed building in a moderately hot climate may need little or no mechanical cooling. In other words, investments in improving the energy performance of residential and commercial buildings may be more economically attractive over the lifetime of those buildings than simply installing and running ACs.

There is also scope for electricity utilities to manage the cost of electricity by proactively changing the pattern of demand for electricity to power ACs and lowering peak electricity through a set of techniques known as demand-side management. Differentiated pricing involving higher prices of electricity during peak periods can also incentivise changes in behaviour and purchases of more efficient equipment.

In the longer term, emerging technologies, such as solar cooling (either thermal or photovoltaic), battery and thermal storage, and integrated solutions, such as district cooling networks, could also have a major impact on the needs for grid-based electricity capacity. Going one step further, the use of the heat ejected from ACs could also contribute to meeting hot water needs, either within a single building or a larger area through district cooling networks.

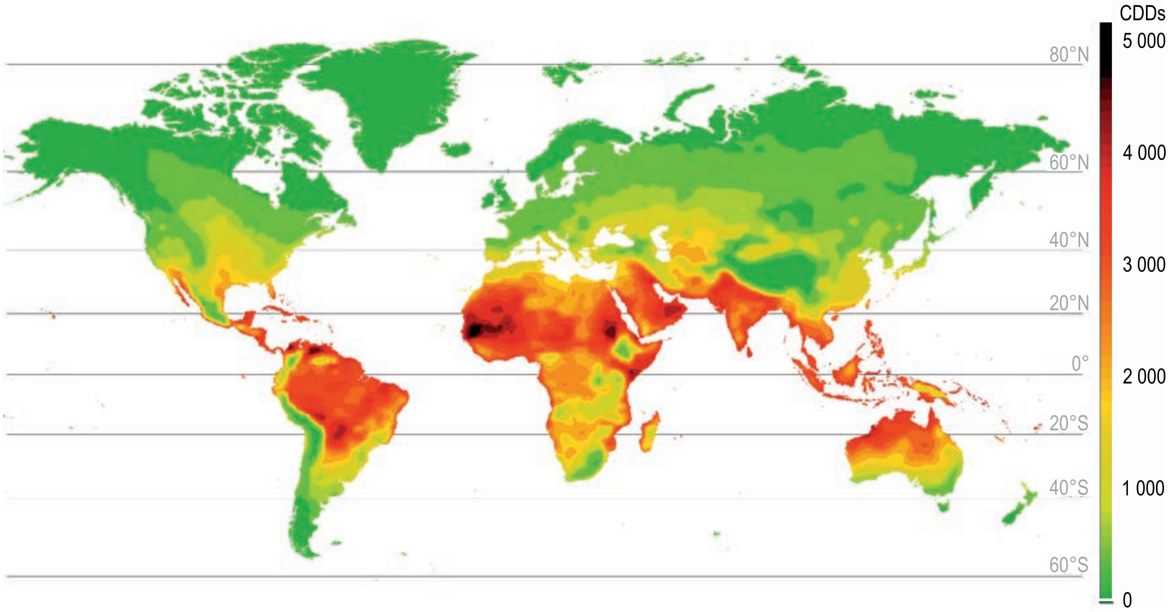
Climate

The principal climatic factor that determines demand for space cooling is air temperature, though humidity also matters. The two often go hand in hand, as the higher the temperature, the higher the capacity of the air to hold water, though some desert regions may experience very high temperatures and relatively low humidity. High levels of humidity tend to increase the need for cooling to achieve a given level of thermal comfort, and ACs automatically lower the level of humidity as well as the temperature of air.

Generally, cooling is considered necessary only in countries where the average daytime temperature exceeds a certain threshold for a certain number of days. Although some countries or regions may frequently experience moderately high temperatures during the summer, if the cooling period is short, most households and owners of some commercial building will not usually bother to invest in an AC, preferring to use electric fans. This is the case in most northern European countries, where daytime temperatures can exceed 30 degrees Celsius (°C) during the summer but rarely for more than a few hours on a few days each year. Consequently, very few households in those regions have an AC – just 3% in Germany and the United Kingdom, and 5% in France – though most large offices and many other types of commercial building have centralised heating, ventilation and air conditioning (HVAC) systems. Fans are the most common form of cooling used during heatwaves in those countries.

The need for space cooling worldwide is highly concentrated in areas lying within a narrow band running roughly parallel with the equator and covering the tropics and sub-tropics (Map 2.1). Based on cooling degree days (CDDs), which measure the positive deviation of temperatures from a reference point in a given location over a specified period, that potential is more than ten times higher in the hottest parts of the world, such as the Middle East, Africa, India and the Caribbean, than in the temperate zones, including much of North America, western Europe, southern Argentina and Chile. Relative humidity – and the increased sensation of heat that humidity can give, even at relatively comfortable dry temperatures – also explains significant demand for cooling in some temperate regions, such as the Northeast United States (Box 2.1).

Map 2.1 • CDDs across the world, mean annual average 2007-17



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Notes: See Box 2.1 for an explanation of how cooling degree days are calculated; the CDDs shown here are relative to a base temperature of 18°C.

Sources: Derived using NCAR (2004), Community Climate System Model, Version 3.0, www.cesm.ucar.edu/models/ccsm3.0/; NCAR (2012), GIS Program Climate Change Scenarios, Version 2.0, www.gisclimatechange.org; NOAA (2018), Global Summary of the Day (GSOD) 1990-2017, https://data.noaa.gov/dataset/dataset/global-surface-summary-of-the-day-gsod; CIESIN (2017), Gridded Population of the World, Version 4 (GPWv4): Population Count Adjusted to Match 2015 Revision of UN WPP Country Totals, Revision 10, https://doi.org/10.7927/H4JQ0XZW.

Key message • The influence of climate on cooling demand is much higher in tropical and sub-tropical regions, but other factors such as humidity and building performance also play a role.

Box 2.1 • CDDs and the heat index

There are several ways of measuring the impact of the weather on the overall need for cooling. The traditional approach is by calculating CDDs, which are widely used by electricity utilities to predict load for cooling in the near future based on weather forecasts.

A degree day measures how cold or warm a given location is, by comparing the mean of the high and low outdoor temperatures recorded each day to a standard temperature (for example, 65° Fahrenheit [°F] in the United States and 18°C in Europe). For the purposes of this report, CDDs are measured in °C, standardised to 18°C, in all countries. That standard temperature may differ across countries, depending on conventions, cultural norms and individual expectations of cooling comfort.

CDDs measure how much the mean temperature exceeds the standard temperature each day over a given period (e.g. a week in the summer or the entire year). For example, a day with a high temperature of 30°C and a low of 20°C, and thus a mean temperature of 25°C, has 7 CDDs (25-18). If the next day has a mean temperature of 28°C, it has 10 CDDs. The total for the two days is therefore 17 CDDs. Normally, CDDs are calculated according to the dry bulb temperature (the temperature of the air measured by a thermometer freely exposed to the air, but shielded from radiation and moisture).

CDDs tend to be correlated with latitude, as seen in Map 2.1, but there are exceptions. Some regions with cold or even very cold winter climates, such as Northeast and Midwest United States, as well as parts of Canada and the Russian Federation, can also have a very hot summer lasting several weeks, resulting in relatively high CDD levels and large cooling demands.

To account for the influence of humidity, a heat index*, which corrects CDDs by combining air temperature and relative humidity in order to determine the temperature as perceived by humans, can be used. Relative humidity – that is, how saturated with moisture the air is – can make it difficult for the body to perspire and therefore make it feel hot, even when dry temperatures are not that hot. For example, if the dry temperature is 30°C and the relative humidity is 50%, then it will feel like 31°C; but if the relative humidity reaches 100%, then it would feel like 44°C. In other words, the humidity makes it "sweltering hot".

The higher the relative humidity, the higher the temperature actually feels and the higher the corrected CDDs. For instance, the average annual number of CDDs in Indonesia is around 3 400, but when humidity is taken into account, that number is about 10% higher on average. The resulting number is weighted by population across a country or region and the entire year. This report uses the CDD heat index to model cooling demand (see Chapter 3).

* www.nws.noaa.gov/om/heat/heat_index.shtml.

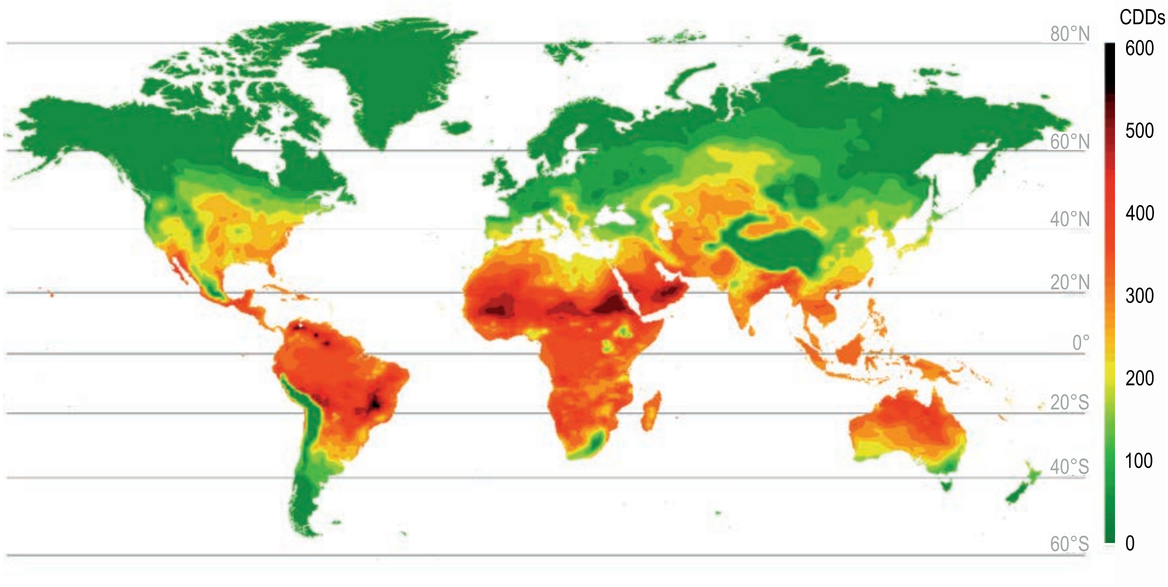
The distance between hot zones with more than 4 000 CDDs per year and cooler zones with less than 1 000 CDDs can be as little as 1 000 kilometres (km) north to south, even where there is little difference in altitude (CDDs are strongly correlated in an inverse manner with altitude as well as latitude). Some of the hottest places are also among the poorest, such that most of that latent demand for cooling is currently unmet; the potential for more cooling demand in these regions as incomes rise is enormous.

CDDs fluctuate over time with the weather – not just over the course of each cooling season, but from one year to the next. Surges in CDDs in a given location can lead to a permanent shift in actual cooling load to the extent that they result in additional purchases of ACs or fans. For example, a series of heatwaves in France have led to periodic surges in sales in ACs in certain regions (Eme-Ziri, 2015). This has led to a permanent increase in cooling load during normal summers, as many of the consumers that decided to buy an AC during a heatwave now make use of those units regularly during the summer months instead of the fans they used before.

Rising average temperatures as a result of climate change will unquestionably lead to a significant increase in CDDs around the world, though at differing rates across regions. We calculate that a 1°C increase in global average temperature by 2050 (compared with today) will lead to an average increase in CDDs of 25%, averaged across regions.[1]

The projected increase in global average temperature is far from even across the planet, with some regions set to experience significantly bigger hikes than the average. Correspondingly, the number of CDDs is also set to rise in an uneven fashion. The biggest increases in CDDs in absolute terms occur in Africa, Latin America, southern and eastern Asia, and the Middle East, ranging from 15% to 40% (Map 2.2). There are also significant increases in CDDs in the temperate climatic zones, including southern and northern Europe, and northeast United States, which will lead to more households acquiring ACs and probably a proportionately greater increase in air-conditioning load. For example, some parts of France see an increase of more than 2°C in average July temperatures by 2050, boosting CDDs by up to 50%.[2] In Italy, where ownership of ACs has grown considerably in recent years, the number of days during which average mean temperature rises to over 25°C doubles by 2050.

Map 2.2 • Increase in CDDs in the Baseline Scenario relative to historical CDDs, 2016-50



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Notes: The CDDs shown here are relative to a base temperature of 18°C; see Chapter 3 for an explanation of the Baseline Scenario.

Sources: Derived using NCAR (2004), Community Climate System Model, Version 3.0, www.cesm.ucar.edu/models/ccsm3.0/; NCAR (2012), GIS Program Climate Change Scenarios, Version 2.0, www.gisclimatechange.org; CIESIN (2017), Gridded Population of the World, Version 4 (GPWv4): Population Count Adjusted to Match 2015 Revision of UN WPP Country Totals, Revision 10, https://doi.org/10.7927/H4JQ0XZW.

Key message • CDDs are projected to increase by around 25% globally by 2050, with the biggest increases occurring in already hot places where income and population are rising fastest.

Population densities in the regions facing the biggest increases in CDDs are generally higher than in the rest of the world; adjusting for this, the International Energy Agency (IEA) estimates that the actual increase in CDDs by 2050 globally will be closer to one-quarter (Table 2.1). Also, as the increase in CDDs is generally highest in regions with the fastest rates of growth in both household income and population, the impact on overall air-conditioning load would undoubtedly be

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[1] Derived using NCAR (2012), GIS Program Climate Change Scenarios, Version 2.0, www.gisclimatechange.org.

[2] Based on IEA analysis using NCAR (2012), GIS Program Climate Change Scenarios, Version 2.0, www.gisclimatechange.org.

significantly greater than the projected increase in CDDs suggests, as a large proportion of current cooling needs are not being met. Urbanisation will also contribute to increased ambient temperatures and cooling needs.

Table 2.1 • Outlook for CDDs by country/region in the Baseline Scenario

	2016		2050		
	CDDs	**Million persons**	**CDDs**	**Million persons**	**Change in CDDs over 2016**
United States	764	328	973	392	27.4%
European Union	292	511	343	505	17.5%
Japan	909	127	1 040	108	14.4%
Korea	762	51	844	51	10.7%
Mexico	868	123	1 188	156	36.8%
China	1 051	1 384	1 169	1 351	11.3%
India	3 084	1 327	3 486	1 705	13.0%
Indonesia	3 390	261	4 051	322	19.5%
Brazil	1 846	210	2 314	238	25.4%
South Africa	714	55	746	66	4.6%
Middle East	2 337	232	2 516	354	7.6%
World	1 905	7 422	2 388	9 714	25.4%

Notes: CDDs shown here are calculated on the basis of a temperature of 18°C; historical population distributions were used to calculate the weighted CDDs in 2016 and expected population growth rates (without taking into account potential shifts in population distribution from migration patterns) were used to calculate future trends. "China" = the People's Republic of China.

Sources: CDDs from IEA analysis derived using NCAR (2004), Community Climate System Model, Version 3.0, www.cesm.ucar.edu/models/ccsm3.0/; population: UNDESA (2017), *World Population Prospects: the 2017 Revision*, https://esa.un.org/unpd/wpp.

Climate change and the use of energy for air conditioning are locked into a vicious circle. Climate change is raising atmospheric temperatures, directly increasing the need for cooling, which is resulting in more burning of fossil fuels in power stations to meet the increased electricity load, which is contributing, in turn, to more climate change. Breaking this circle ultimately hinges on arresting climate change; that will require curbing the amount of energy used for cooling and for other end uses, as well as decarbonising the energy mix.

Economic growth and affordability

While climate is the main underlying driver of demand or desire for cooling, income and wealth determine the degree to which that demand is met. In the richest countries, prosperity barely constrains how much households and businesses cool their homes and offices. For example, in Singapore, one of the hottest and most humid countries in the world, an estimated 99% of private apartments have an AC, which is switched on for most of the time that the apartment is occupied (Happel et al., 2017).[3]

Air conditioning is much less commonplace in lower-income countries, even where the climate is hot and humid, where it is still largely confined to the homes of the richest people, modern

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[3] Singapore's founding father, Lee Kuan Yew, once claimed that AC was a major contributor to Singapore's economic success: "Air conditioning was a most important invention for us, perhaps one of the single inventions of history. It changed the nature of civilization by making development possible in the tropics. Without air conditioning you can work only in the cool early-morning hours or at dusk" www.vox.com/2015/3/23/8278085/singapore-lee-kuan-yew-air-conditioning.

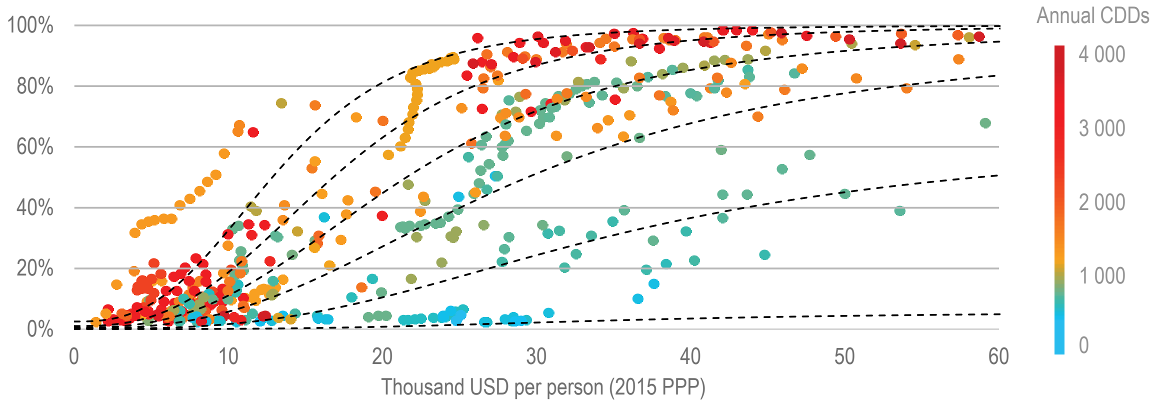
offices and some other commercial premises. Only 4% of households in India possess an AC, despite having extremely high cooling needs. That is because most people cannot currently afford an AC, and many people lack access to electricity in any case. But AC ownership and use is rising rapidly in India and other hot and humid countries as incomes rise, access to electricity improves and prosperity becomes more widespread. In short, air conditioning is becoming affordable for more and more people.

In practice, the precise relationship between economic growth and reliance on air conditioning varies substantially by country and depends mainly on climatic factors. Other things being equal, a rise in income will typically lead to an increase in air-conditioning demand, especially in the hottest countries. As household incomes pass a certain threshold, sales of ACs and their usage start to take off, replacing or supplementing the use of electric fans.

Rising prosperity also contributes to the *need* for space cooling. As household incomes rise and offices become better equipped, the sheer quantity of electronic devices and appliances –including televisions, computers, printers, refrigerators, washing machines and freezers – typically increases markedly. Those objects all consume energy, emitting heat while in operation and in standby mode and adding to the heat that comes directly from everyday activities like bathing, cooking and lighting, as well as from people themselves. Those heat gains add to air-conditioning demand. Improvements in the energy efficiency of appliances are helping to reduce this, but this factor is being more than offset by the rapid growth in their number.

The IEA has analysed the relationship between average per-capita income and AC ownership, categorising 68 countries across more than 500 country data points according to their climate, using CDDs adjusted for relative humidity (i.e. a heat index). The climate-wealth relationship is strong – especially for the countries with the hottest climates (Figure 2.1). In countries with average CDDs under 500, such as in Scandinavia, AC ownership is extremely low as it is rarely hot enough to warrant it, though ownership is slightly higher among the richest countries. At the other extreme, in countries with CDDs over 3 000, including Brazil, Egypt, India, Thailand, Indonesia and Venezuela, AC ownership rises very steeply with income as cooling is virtually essential for people to live and work in comfort.

Figure 2.1 • Per-capita income and rate of household ownership of air conditioners



Notes: The dotted lines shown here are illustrative pathways for a typical place or country according to CDDs adjusted for relative humidity (see Box 2.1 for an explanation of how the heat index is calculated); PPP = purchasing power parity.

Key message • For a given type of climate, the rate of household ownership of ACs rises with economic development and incomes – very quickly in the case of the hottest and most humid countries.

For the categories in between, the correlation is generally a little less strong, largely because of differences in humidity. For example, in Ukraine, and parts of Japan and the United States, AC ownership is high relative to the number of CDDs, perhaps because of sociocultural preferences and expectations of thermal comfort, but also because they tend to have higher relative humidity. The opposite is the case in countries with moderately hot, Mediterranean-type climates, such as Italy, Portugal, Spain and South Africa, with hot but relatively dry summers.

Other factors affect the relationship between income and space-cooling demand, including the structure of the economy, the price of ACs, the cost of electricity and cultural preferences. In many countries, air conditioning can also be viewed as a status symbol – much like owning a car – leading people to not just buy an AC but also use it intensively, by setting the cooling temperature at a low level or running it when no one is home.

Countries with a relatively large services (commercial) sector also tend to have higher space-cooling demand relative to income, as there is more building space to cool. Also, relatively high prices of ACs (due to sales taxes or import tariffs) and electricity can dampen sales of ACs as incomes rise, though this tends to delay rather than halt the rise in ownership of ACs as incomes rise. Cultural factors also seem to affect the attractiveness of ACs in some countries; for example, Europeans have generally been less inclined to install an AC compared with their American counterparts until recently, though this is now changing, with AC ownership in Italy, Spain, Greece and southern France rising rapidly in the last decade. Greater adoption of reversible heat pumps, which can provide both heating and cooling services, is another driver of growing cooling demand in some of those countries.[4]

In view of the strong relationship between income and cooling demand, the prospects for economic development in the hottest parts of the world will be crucial to the outlook for cooling and the energy needed to provide that service. For the purposes of this report, all projections of cooling demand (set out in Chapter 3) are underpinned by a single set of assumptions about economic growth across the world. Those assumptions are the same as those used for the most recent editions of the *World Energy Outlook (WEO 2017)* (IEA, 2017f). Growth in gross domestic product (GDP) worldwide is assumed to average 3.1% over 2016-50 (Table 2.2). Among the leading cooling markets, growth is highest in India, at 5.6%, and lowest in the United States (2%).

Table 2.2 • Assumed average annual rates of growth in real GDP by country/region

CAAGR (%)	2000-16	2016-30	2030-50	2016-50
United States	1.8%	2.0%	1.9%	2.0%
European Union	1.4%	1.7%	1.4%	1.5%
Japan	0.7%	0.7%	0.7%	0.7%
Korea	3.9%	2.7%	1.3%	1.9%
Mexico	2.1%	3.3%	2.5%	2.8%
China	9.2%	5.4%	2.5%	3.7%
India	7.3%	7.2%	4.5%	5.6%
Indonesia	5.4%	5.4%	3.3%	4.2%
Brazil	2.4%	2.5%	2.7%	2.6%
South Africa	2.9%	2.6%	2.7%	2.6%
Middle East	4.3%	3.7%	3.0%	3.3%
World	3.6%	3.7%	2.7%	3.1%

Notes: CAAGR = compound average annual growth rates; growth rates based on GDP in United States dollars (USD) in PPP in constant 2015 terms; assumptions apply to both the Baseline and Efficient Cooling Scenarios.

Source: IEA (2017f), *World Energy Outlook;* IMF (2017), *World Economic Outlook Database*, www.imf.org/external/pubs/ft/weo/2017/01/weodata/index.aspx.

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[4] http://stats.ehpa.org/hp_sales/story_sales/

Demographic factors

Population growth

Population growth is another important driver of cooling demand. This factor is strongly linked to economic growth: countries that are expected to enjoy the fastest rates of economic growth are generally those that have the fastest projected rates of population growth. Populations are set to grow most rapidly in regions with the hottest, and sometimes most humid climates, which will contribute to higher cooling demand. Energy access in many of those countries – for instance, in sub-Saharan Africa – is still often limited today, but is improving, which is increasing opportunities for households to use fans and ACs.

As with economic growth, our assumptions about population for both scenarios presented in this report are in line with those in the *WEO 2017* (IEA, 2017f), which uses the medium variant of the latest projections of the United Nations *World Population Prospects* (UNDESA, 2017). The world population rises by 0.9% per year on average, from 7.4 billion in 2016 to 9.7 billion in 2050 (Table 2.3). The fastest growth in population is in Africa, where the average number of CDDs is above 2 500. By 2050, three-quarters of all the people in the world will be living in either Africa or the Asia Pacific region.

Table 2.3 • Demographic assumptions by country/region

	Average annual growth rate			Population (million)		Urbanisation rate	
	2000-16	**2016-30**	**2030-50**	**2016**	**2050**	**2016**	**2050**
United States	0.8%	0.7%	0.4%	328	392	81.9%	87.5%
European Union	0.3%	0.1%	-0.1%	511	505	75.0%	83.0%
Japan	0.0%	-0.4%	-0.6%	127	108	93.9%	97.7%
Korea	0.5%	0.3%	-0.2%	51	51	82.6%	87.6%
Mexico	1.2%	1.0%	0.5%	123	156	79.5%	86.4%
China	0.5%	0.2%	-0.2%	1 384	1 351	56.9%	76.0%
India	1.5%	1.0%	0.6%	1 327	1 705	33.2%	50.3%
Indonesia	1.3%	0.9%	0.4%	261	322	54.4%	70.9%
Brazil	1.1%	0.6%	0.2%	210	238	85.9%	91.0%
South Africa	1.4%	0.6%	0.4%	55	66	65.3%	77.4%
Middle East	2.3%	1.6%	1.0%	232	354	70.3%	78.7%
World	1.2%	1.0%	0.7%	7 422	9 714	54.4%	66.1%

Notes: Assumptions apply to both the Baseline and Efficient Cooling Scenarios.

Sources: IEA (2017f), *World Energy Outlook;* UNDESA (2017), *World Population Prospects: the 2017 Revision*, https://esa.un.org/unpd/wpp.

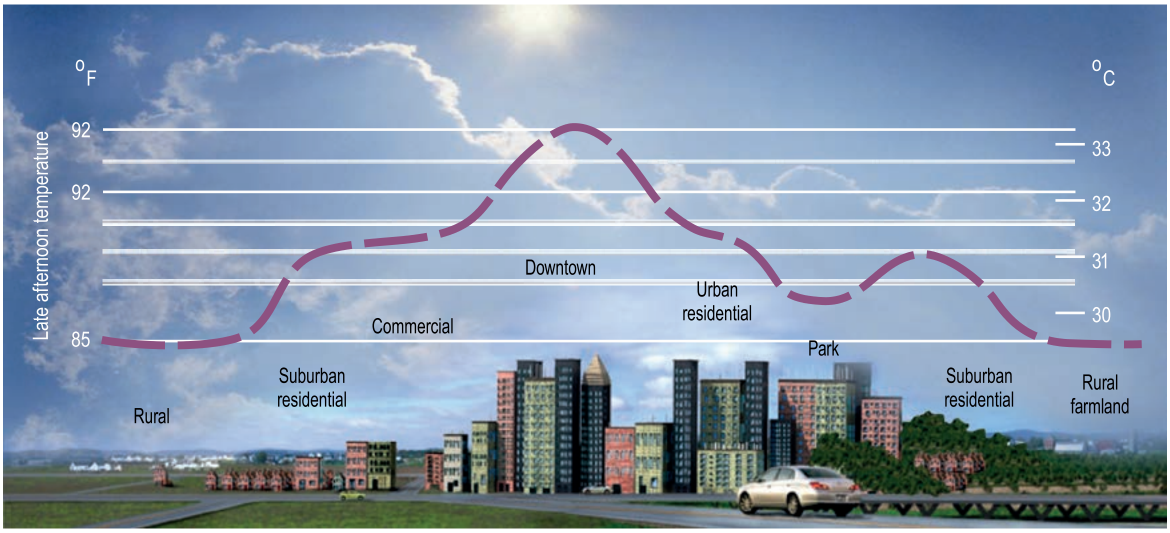
Urbanisation

Urbanisation – the gradual increase in the proportion of people living in urban areas resulting mainly from rural-urban migration – is also set to accentuate the increase in demand for cooling, by increasing the size of urban zones and the density of urban populations. Most cooling today occurs in towns and cities, partly because incomes tend to be higher and because rural lifestyles make cooling less important – e.g. farmers are generally less concerned about keeping cool than office workers. But it is also because temperatures are generally higher in urban areas than the surrounding countryside. Ironically, cooling is one reason for this difference.

Several reasons explain why cities are hotter. Buildings housing people, appliances and machinery – including equipment for cooling – generate heat when they use energy. Buildings and other hard physical structures can also absorb and store heat, slowly emitting some of that heat during the night and contributing to higher temperatures. Part of this is due to the fact that cities are less reflective than rural areas, i.e. they soak up more of the sun's heat (IEA, 2013a). Evaporation, which absorbs energy, is also lower in cities where vegetation is replaced by concrete. Local climate and the geography of surrounding areas also matters as they both affect the efficiency with which convection transfers heat from the city to rural areas (Zielinski, 2014). The relative importance of these different contributory factors varies, but there is no doubt that the more densely populated a city and the bigger the land area it covers, the bigger this "heat island effect" is (Figure 2.2).

Cooling can be major contributor to the heat island effect, as well as a consequence. Cooling by means of an AC, which simply moves heat around, requires the evacuation of hot air to the outside of buildings. It is estimated that air conditioning can raise temperatures by more than 1°C overnight in some cities (Salamanca et al., 2014). Higher outdoor temperatures in the summer increase the overall need for cooling, leading to more hot air, higher temperatures and increased use of cooling in a classic feedback loop. On top of that, higher outdoor temperatures will result in reduced efficiency of cooling equipment (see below). The net result of this urban heat factor is likely to play a major role in pushing up cooling use in India, for instance, where urban population density is high and rising, and where the use of ACs is set to surge as incomes grow and CDDs rise sharply with climate change (see above). Technical solutions, including storing heat from ACs in the ground or in water, exist but can be costly and are not always practical.

Figure 2.2 • Illustration of the heat island effect



Source: LBNL (2013), Heat Island Group, http://heatisland.lbl.gov/.

Key message • Cooling is one of several contributors to the heat island effect, which creates a need for more cooling in a classic feedback loop.

Urbanisation has been under way for a long time and is expected to continue apace over the coming decades. The share of global population living in towns and cities rose from 43% in 1990 to 54% in 2016 and, according to United Nations' projections, is set to reach 66% in 2050. That corresponds to an increase of 2.4 billion people, or 60%, in the urban population (UNDESA, 2014). How these people are housed and how they go about cooling their homes is uncertain, but more and bigger cities will surely contribute to the heat island effect and drive up overall cooling needs. Establishing parks and gardens and reducing heat from reflective surfaces are among the solutions being pursued in some cities to mitigate this problem, as well as to improve the overall quality of city life.

Ageing and illness

Another factor that may help drive up cooling demand is a rising proportion of older people in the population. In 2017, an estimated 962 million people, or 13% of the world's population, were aged 60 or over; by 2050, this share will reach over a quarter in all regions except Africa, with their number reaching 2.1 billion in 2050 (UNDESA, 2017). Generally, older people are less heat tolerant than the young. Heatwaves can greatly increase mortality rates in the short term. For example, almost 15 000 more people than usual are estimated to have died during the August heatwave of 2003 in France, 80% of them over 75 years old (INSERM, 2004). The French government subsequently adopted a requirement that all retirement homes have at least one room air conditioned to less than 25°C on each floor during extreme periods of heat.

Hospitalisation rates of older adults during heatwaves can also be significantly higher, particularly for those without access to air conditioning. Hot weather can contribute greatly to a number of health disorders, including fluid and electrolyte disorders, renal failure and heat stroke (Bobb et al., 2014). The need for air conditioning is also more important for those suffering from illness. Data on the impact of this affect is sparse, but some studies suggest that it may be significant in certain cases. For example, an Australian study found that people suffering from multiple sclerosis, which makes most sufferers more sensitive to heat, used their ACs 15 times more than the rest of the population (Summers and Simmons, 2009).

As with other factors, age and illness do not necessarily explain AC trends across markets. For instance, older populations in the People's Republic of China (hereafter, "China") today tend to use ACs less – if at all – perhaps because they never previously owned an AC or never worked in an air-conditioned environment, lowering their expectations of thermal comfort (Chen, Wang and Steemers, 2013; Liu et al., 2015). These trends may change in years to come, especially as air conditioning in China and elsewhere becomes commonplace.

Energy efficiency of cooling equipment

As with many other types of appliances and equipment installed in buildings, the energy efficiency of ACs currently in use and for sale around the world has been rising in recent years because of incremental improvements in air-conditioning technology and shifting demand, though enormous variations remain across countries and regions. The average seasonal energy efficiency ratio (SEER) – a commonly used measure of the efficiency of cooling equipment that takes into account changes in operating conditions throughout the cooling season (Box 2.2) – of ACs in the residential sector weighted by sales reached 4.2 in 2016, about 50% higher than in 1990. The average SEER of commercial AC sales improved slightly more – by 57% since 1990 – to the same global average of around 4.2 in 2016. Because most packaged and split ACs – around 50% of installed cooling output capacity globally – last on average around 10 to 12 years, the average SEER of the stock of ACs in operation has risen at a similar pace but with a slight lag; ACs in use in 2016 averaged a SEER of around 3.9 in the residential sector and slightly lower at 3.7 in the commercial sector.

Box 2.2 • Measuring the energy efficiency of ACs

The energy efficiency of ACs can be measured is several different ways, though all involve some comparison of the amount of energy input required to produce a unit of cooling output (or vice versa). ACs move heat rather than convert it from one form to another, so standard measures of thermal efficiency are not appropriate for describing the performance of these devices. Conventions vary by country. Commonly used metrics differ according to units (metric or imperial), the purpose of measurement (efficiency at full load, at the time of peak demand or across a season) and test conditions (notably indoor and outdoor temperatures). They are sometimes adapted to the conditions in a specific country. The most widely used metrics around the world are as follows:

- *Coefficient of performance (CoP):* The ratio used for either heating or cooling equipment to describe the amount of useful energy (i.e. heating or cooling output) delivered as a ratio of the energy input (e.g. electricity) to deliver that useful output. The higher the COP, the more efficient the device. For ACs, the CoP usually exceeds 1, as ACs mechanically transfer more energy from a heat source (indoor air) to a heat sink (the exterior) than the amount of energy that is used in mechanical the process.

- *Energy efficiency ratio or rating (EER):* A specific ratio used for cooling equipment that, similar to a CoP, is the ratio of the output of cooling energy (measured in British thermal units in the United States and kilowatt-hours [kWh] elsewhere) to input energy (in kWh). It can equally be measured in terms of capacity (for example, Watt of output per Watt of input). In the United States, it is generally calculated using an outside temperature of 95°F (35°C), an inside temperature of 80°F (27°C) and relative humidity of 50%.

- *Seasonal energy efficiency ratio (SEER)*. The EER adjusted for the overall performance of the equipment for the weather over a typical cooling season. It is calculated with the same indoor temperature, but over a range of outside temperatures, with a certain specified percentage of time in each of the temperature categories.

Because climatic conditions vary considerably across the world, these metrics have often been adapted to the conditions prevailing in specific regions or countries.

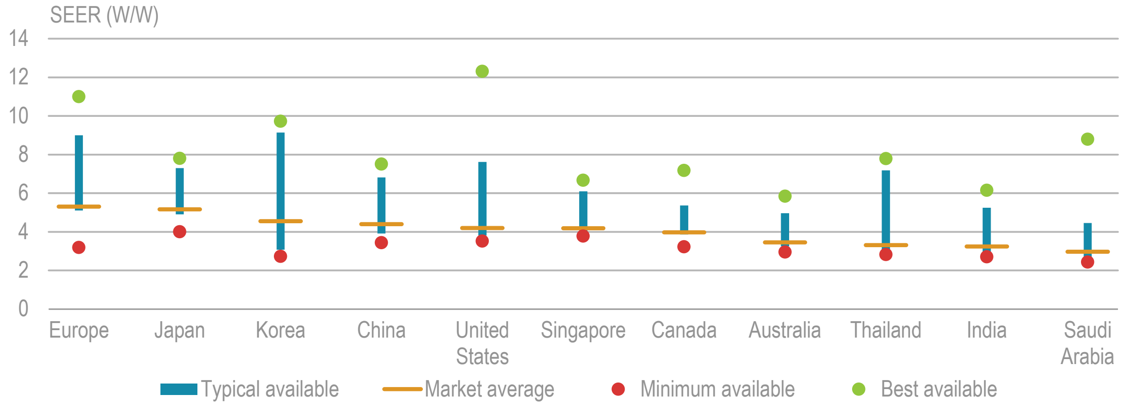
Given differences in test conditions, it is generally not possible to convert between any of these cooling equipment efficiency metrics. As a result, one can have an AC that has a higher EER than another one, but a lower SEER. In addition, the metrics used in practice are not always appropriate to operating conditions. Larger temperature reductions also lower efficiency, as the AC's compressor has to work harder. This makes it difficult to compare ratings across regions with very different climates, even when using SEERs.

The use of generic terminology has given rise to a great deal of confusion and difficulty in comparing efficiency estimates across countries. Efforts in recent years have tried to increase clarity by introducing more specific metrics, such as the cooling seasonal performance factor, which can be used to measure the efficiency of reversible heat pump ACs or other equipment. Like SEERs, this factor is meant to be the cooling equivalent of the heating seasonal performance factor used to measure the heating performance of a heat pump, representing the range of AC or heat pump operating conditions when in cooling mode. The North American Air-Conditioning, Heating and Refrigeration Institute has developed a similar metric, the integrated part load value, specifically for chillers.

Further efforts are needed to improve the measurement of energy efficiency of all types of cooling equipment in order to assess more accurately their performance under real operating conditions and to facilitate comparisons of performance within and across national and regional markets.

There are substantial variations in the efficiency of ACs currently available for purchase both within and across countries. Improved regulations and more efficient supply chains could reduce cooling energy consumption by as much as three to five times, with the SEER (which reflects the average annual energy efficiency of cooling equipment) of available ACs significantly more efficient than the market average energy efficiency (Figure 2.3).

Figure 2.3 • SEERs of available residential ACs in selected countries/regions, 2018



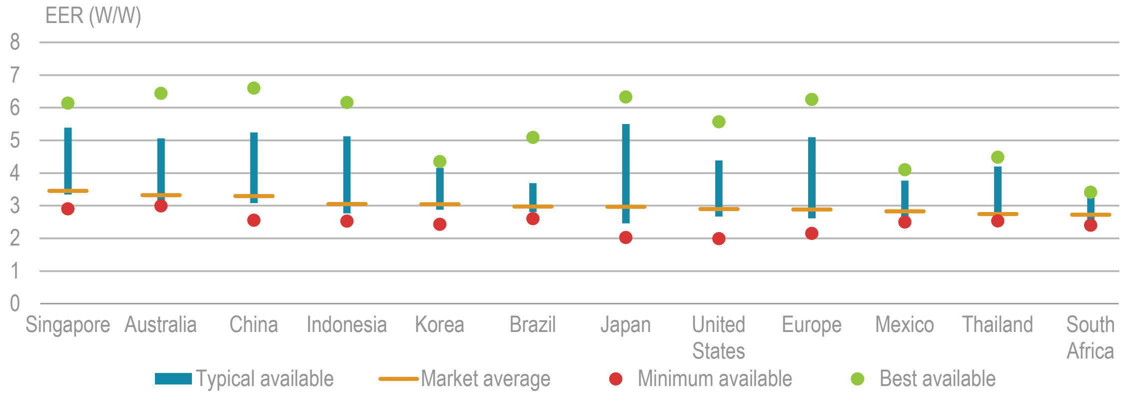
Notes: SEER = the ratio of output cooling capacity to electrical energy input, adjusted for the overall performance of the device for the weather over a typical cooling season in each given country; as the test conditions differ across countries, the average ratios are not strictly comparable; W/W = watt per watt.

Source: IEA Global Exchange on Cooling and national product registry information, www.iea.org/exchange/cooling/.

Key message • Global best available air-conditioning equipment is up to five times more energy efficient than the least efficient ones currently available.

Enhancing the efficiency of AC sales globally would also help reduce the impact of cooling on peak electricity demand. The EER (which better reflects the operational efficiencies of ACs during peak demand) of the most efficient units available in most markets is typically twice as energy-efficient as the market average in those same countries (Figure 2.4).

Figure 2.4 • EERs of available residential ACs in selected countries/regions, 2018



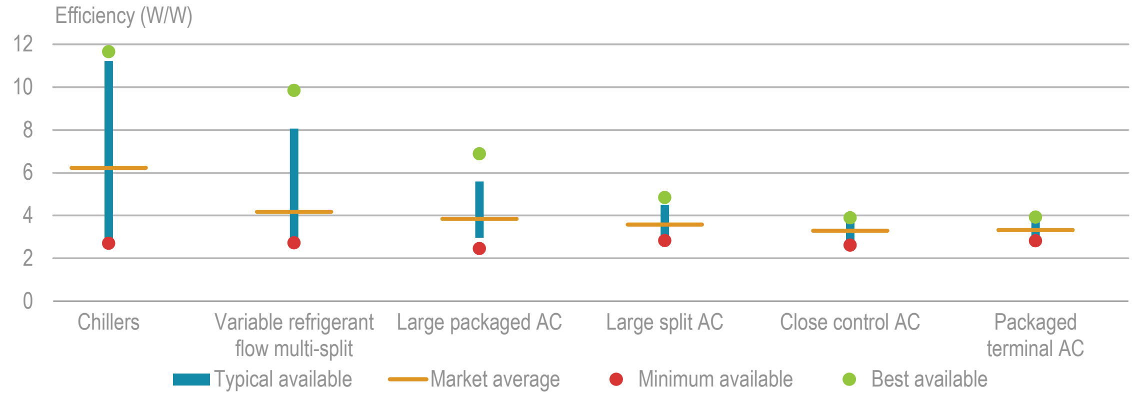
Source: IEA Global Exchange on Cooling and national product registry information, www.iea.org/exchange/cooling/.

Key message • Global best available technology is typically twice as efficient as the market average and would help reduce the impact of cooling demand on electricity grids during peak demand.

A similar pattern is apparent in the commercial sector: significant variations within and across countries, though the differences are largely due to the type of equipment and the size of the cooling system. Large chillers and split ACs tend to be significantly more efficient compared to rooftop and packaged units (Figure 2.5).

Several factors explain why AC efficiencies diverge so much across and within countries. Consumer preferences are driven by a number of different concerns, including the upfront cost of buying the equipment and the cost of running it. Unsurprisingly, consumers – be they households or businesses – are less concerned about buying an efficient unit and using it efficiently if electricity is subsidised, which is often the case in the emerging economies (IEA, 2017f). As the most efficient devices tend to be more expensive (in part because of pricing strategies or because they incorporate additional features), consumers may decide not to purchase the more efficient equipment, even if the energy cost savings would ultimately make up for the additional upfront cost. For example, the most efficient models in China can be twice as expensive as the least efficient ones on the market, requiring more than ten years to pay back the higher upfront cost of the unit at current electricity prices (IEA, 2017e).

Figure 2.5 • Energy efficiency of available commercial ACs, 2018



Note: Efficiency represents the ratio of output cooling capacity to energy input at a set peak temperature point.

Source: IEA Global Exchange on Cooling and national product registry information, www.iea.org/exchange/cooling/.

Key message • Global best available technology is more than twice as energy efficient as market averages and more than three times more efficient than the most inefficient models currently available.

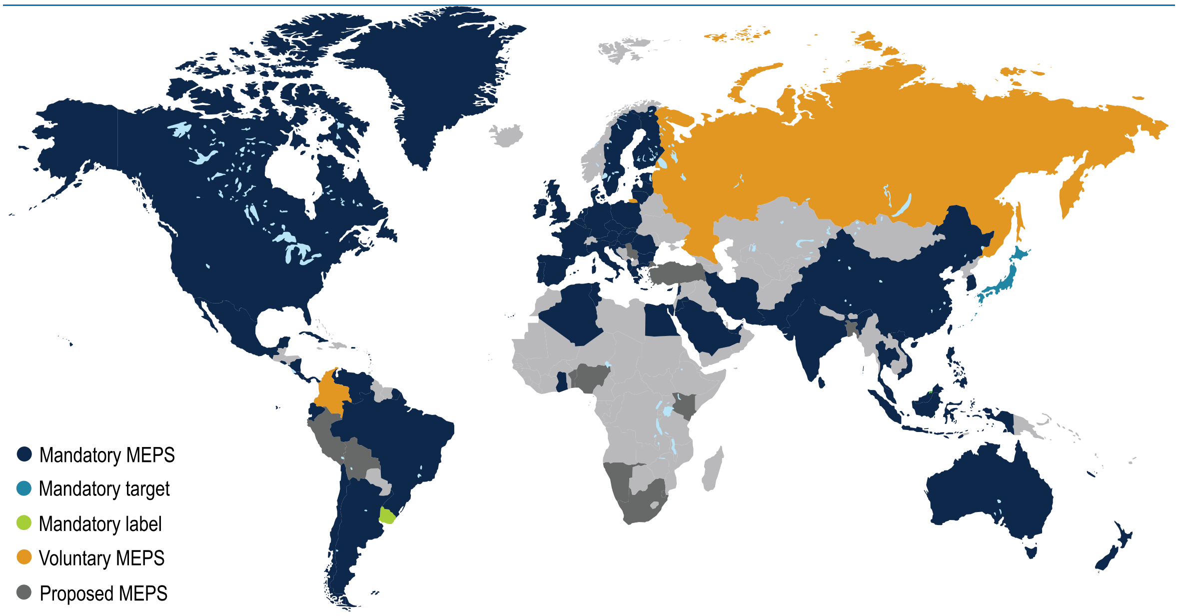
Another factor influencing the efficiencies of available equipment is policy – principally minimum energy performance standards (MEPS) and energy labelling. MEPS, which may be voluntary or mandatory, have been effective in many countries in driving out the least-efficient models and encouraging manufacturers to develop and market ones that are more efficient. They have also helped drive the price of efficient units down, with increased production creating economies of scale. Most countries that have sizeable cooling loads have introduced MEPS, with 85% of the ACs sold worldwide in 2016 covered by MEPS (IEA, 2017e).

Nearly 55 countries today, including major cooling markets such as India, China and Indonesia, have either proposed or already have MEPS for ACs, while another 5 have targets or labelling programmes for ACs (Map 2.3). These MEPS have generally become more stringent in recent years. For example, standards for ACs were tightened in the United States in 2017. Yet AC MEPS still differ markedly across countries: in general, they are most stringent in the richest countries and are weakest or absent in hot or humid countries with rapidly growing demand for ACs. In addition, they are not always mandatory.

In general, standards are more stringent in the richest countries, where consumers are more able to afford the more expensive but more efficient models. In some cases, they take account of the efficiency of the models being manufactured domestically; some countries, such as Indonesia, have adopted relatively weak standards out of misplaced concern for the effect on national manufacturers. In most countries, MEPS have been tightened progressively in recent years, though at differing rates. For example, India's MEPS for ACs have been tightening since 2008 and rose again at the beginning of 2018 from 2.7 W/W in 2016 (using the Indian SEER [ISEER]) to 3.1 W/W, becoming mandatory at the same time.

Further improvements in the maximum efficiency of ACs as well as the average efficiency of all the models sold can be expected through research and development efforts and further innovation in air-conditioning technologies. The sustained efficiency improvements over the last 25 years are not due to any single technology, but rather the steady evolution of several technologies that have collectively increased the efficiency of ACs (Navigant Consulting, 2016). This will undoubtedly continue well into the future, though the rate of improvement is likely to slow over time because the energy performance of vapour compression refrigeration cycles is ultimately limited by the laws of thermodynamics.

Map 2.3 • Map of MEPS and labelling for air conditioners



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Key message • Most of the major cooling markets today have mandatory MEPS, although the required efficiency levels are typically far below those of the most efficient products available.

There are several areas where efficiency of existing AC technologies could be improved, including aerodynamically efficient fan blades, more efficient compressors, improved inverter technology to control the speed of the compressor motor, and the use of variable speed drives on fan motors. In the longer term, research, development and demonstration is expected to focus on reducing the cost of highly efficient advanced vapour-compression systems and emerging non-vapour-compression systems that do not use refrigerants (Navigant Consulting, 2016).

The energy needed to operate air-conditioning systems can be reduced in other ways:

- *Thermal zoning* within buildings using room systems such as mini-split ACs or variable volume controls, dampers and valves enables the temperature within a building to vary from one zone to another, providing an opportunity to reduce significant energy use compared with ACs that deliver the same temperatures throughout the entire building.
- *Enhanced controls and predictive control* can minimise the energy used to achieve thermal comfort within buildings. Enhanced controls, using programmable and smart thermostats, enable ACs to turn off when additional cooling is not required. Predictive controls use sensors and weather data to estimate how to cool the building in the most efficient manner.
- *Better sizing, installation and maintenance* can ensure that air-conditioning equipment and controls work as intended, by making sure that right amount of refrigerant is circulating, by cleaning the fans and filters, and by optimising control settings.

Energy performance of buildings

The energy performance of buildings is one of the most important drivers of the demand for mechanical space cooling. The design of a building and the materials and construction techniques used for its envelope are of particular importance.

Building design

The design and architecture of buildings has a major impact on the need for mechanical cooling and other energy services. For instance, traditional building structures such as awnings, overhangs, porticos and trellises provide shading to buildings and help reduce solar heat gain, but there is a trend in many parts of the world away from such features, typically on the grounds of cost.

In practice, energy is but one of several factors taken into consideration when design and construction decisions are taken. Cost is often the main concern: lighter materials are usually cheaper, and the most effective insulation more expensive. Space-use design, which affects the building aspect ratio (the ratio of interior space to the surface area of the building), is another important factor, as it affects the rate at which heat is transferred between the interior and exterior, as well as the amount of building area that is subject to solar heat gains.

Aesthetic design is very often given priority over energy efficiency. For example, shades over windows can cut the need for cooling, but may affect the look of a building. All-glass façades and the removal of visual clutter such as radiant panels, fans or in-room ACs can also boost space-cooling needs. For example, ducted ACs are often preferred for aesthetic reasons, but are generally less energy efficient than a liquid cooling system based on a chiller.

Buildings designed with controls and sensors that enable smart control of ACs can provide comfort for the building occupant while also allowing demand-side response to reduce the impact of space cooling on peak electricity loads. At the basic level, adding more controls and sensors can enable more efficient temperature settings without harming occupant comfort. While advanced systems are typically costly, best practice in advanced building design and operation illustrates the potential to reduce and manage space-cooling demand in buildings with smart controls (Box 2.3).

Box 2.3 • The Edge building in Amsterdam: An example of smart space-cooling technology

The Edge – a 40 000 square metre (m^2) office building in the Zuidas business district in Amsterdam – is widely considered to be the smartest and greenest building in the world. The Building Research Establishment Environmental Assessment Methodology (BREEAM) gave the Edge, which was completed in 2014, a score of 98.36% – the highest sustainability score ever.

The building incorporates a range of energy-efficient building envelope components, including dynamic windows, automatic shades and displacement ventilation. It is also fitted with 28 000 sensors which track movement, lighting levels, humidity and temperature. These data enable the building to respond and use resources more efficiently. For instance, when areas are not being used, heating, air conditioning and lighting can be adjusted or switched off.

Workers in the Edge are also connected to the building via a smartphone app, which they can use to adjust temperature and lighting levels around them. The app remembers their preferences, which helps the heating, cooling and ventilation systems to optimise energy use.

In addition, the building uses energy from solar panels installed on the roof and side of the building as well as from panels located nearby. Water for cooling and heating is piped to and from an aquifer beneath the building, and excess heat from the building is removed by a heat exchanger. Thanks to these energy-saving measures, controls and building design, the Edge building actually produces more electricity with its solar panels than it consumes.

Sources: www.bloomberg.com/features/2015-the-edge-the-worlds-greenest-building/; www.breeam.com/index.jsp?id=804.

In addition to the technology used in the building, the design of materials used around and outside buildings can impact both the felt temperature and impact the solar heat gain in the building. The use of landscape and plants in architecture can improve airflow, while seasonal solar shading with deciduous trees can reduce the solar heat gain on buildings, reducing the heat island effects around a building. In residential applications, it is estimated that well-designed landscapes could save 25% of the energy used for heating and cooling (NREL, 1995). While the growing trend of urbanisation has reduced the number of trees and plants that are near or within buildings, increasingly, some local authorities are encouraging building owners and occupants to adopt green roofs to save energy and increase sustainability. For example, Chicago's Green Roof Grant programme has resulted in more than 500 vegetated roofs and more than 500 000 m^2 of green roof coverage within the City of Chicago (City of Chicago, 2018).

Building envelopes

The building envelope – the roof, floors, ceilings, external walls, doors, windows and foundations – has an enormous impact on the need for space cooling and ventilation. The choice of materials is of particular importance. In many countries, there is currently a move away from the use of traditional, heavy materials such as stone and brick, which have heavy mass that reduces thermal fluctuations, towards lighter materials such as wood, aluminium and composite materials that do not always offer the same insulating properties.

Thermal mass is important for space cooling (and heating), as it holds temperature longer and creates a natural barrier between indoor and exterior temperatures, increasing thermal comfort. Traditional buildings with thick earthen or stone walls with light colours, such as those in relatively hot Mediterranean and North African climates, rarely need to be cooled artificially. Insulation can compensate for the use of lighter materials with less thermal mass. Energy-efficient roofing, doors and windows and the reduction of uncontrolled air flow and leaks can also have a big impact on the amount of heat that enters a building and, therefore, the need for mechanical cooling.

A range of both high-tech and low-tech solutions that affect energy use for space cooling can be incorporated during building construction or added by the occupants or owners of the building later on. When they are designed and operated correctly, these technologies, which often draw on the wisdom and experience of cooling buildings in times before mechanical cooling was invented, can both increase comfort and reduce energy use. These include technologies that:

- Reduce the heat entering a building, including materials with high thermal resistance (e.g. fibreglass insulation and high-performance windows), thermal mass (e.g. green roofs and rammed earth walls), air sealing (i.e. air-tight envelopes with no uncontrollable vents), solar protection (e.g. low-emissivity window films, shutters and overhangs) and cool roofs (Box 2.4).
- Remove heat from interior spaces through mechanical and natural ventilation. Mechanical ventilation typically uses less energy than mechanical air conditioning, and if designed and operated properly, can remove the hottest air in a space to lower the average temperature.
- Store cold to reduce or displace energy needs for mechanical air conditioning, including thermal mass (e.g. ceramic tiles and stone) and phase-change materials. Materials that absorb heat when a space is hot can re-emit the heat when the space is cold; they can also be used mechanically (e.g. with a heat pump) to provide cooling at a later time.
- Affect perceived thermal comfort, including air movement (fans and natural ventilation) and humidity management (dehumidification in hot humid climates and water evaporation in hot dry climates). They do not significantly change the average air

temperature within the space, but provide improved comfort to occupants without the use of mechanical space cooling.

Box 2.4 • Cool roofs

In hot climates, it is best to reject as much heat as possible from the roofs and exterior surfaces and prevent any heat build-up from migrating to the attic or conditioned spaces. For instance, more than 60% of the roof surface in urban India is covered with galvanised metal, asbestos and concrete, which can exacerbate the heat island effect in cities and drive greater cooling needs in buildings (ORGCC, 2017; NRDC, 2017). Yet, cool roofs, which can be simply white or light in colour, can reduce heat gain and provide greater thermal comfort by reflecting visible and near-infrared light.

Recently, the concept of a cool roof has included detailed roofing rating requirements that provide performance criteria of solar reflectance and thermal emittance after a roof sample has been aged (weathering tests in a variety of climates) for a specified period, such as three years. The highest-quality aged white roofs can reflect 80% of the sun's energy compared to black roofs that reflect only 5% to 10% (CRRC, 2013). There are also cool-coloured roofing products that visibly look the same as typical roofs, but which reflect the near-infrared portion of sunlight. Depending on colour and performance, these products reflect about 30% to 50% of the sun's energy. Roof performance (i.e. the capacity to reflect solar heat) degrades over time with soiling and biological growth, so to ensure accurate energy-saving measurements, aged ratings are specified in policy programmes.

Reflective urban landscapes including cool pavements (e.g. light-coloured roads and sidewalks) can mitigate the heat island effect and reduce urban temperatures by between 2°C and 4°C. Several studies have been conducted to predict global cooling potential, with conservative estimates for total global urban land area and modest improvements in the albedo effect from installing cool roofs and improving the reflectivity of roadways and parking lots. These studies conclude that rejected heat from the planet could have the cooling effect of approximately 1.5 years of global man-made carbon emissions, or around 44 gigatonnes of carbon dioxide (CO_2) (GCCA, 2013). However, this is a one-time effect of converting urban landscapes to more reflective surfaces.

Sources: CRRC (2013) *Rated Products Database*, www.coolroofs.org/index.html; GCCA (2013), *Cooler Planet*, www.globalcoolcities.org; IEA (2013a), *Technology Roadmap on Energy-Efficient Building Envelopes;* IEA (2013b), *Transition to Sustainable Buildings*; NRDC (2017), "Cool Roofs: Protecting Local Communities from Extreme Heat", https://www.nrdc.org/sites/default/files/cool-roofs-extreme-heat-ib.pdf; ORGCC (2017), "Distribution of Census Homes by Predominant Material of Roof," http://censusindia.gov.in/Tables_Published/H-Series/H-Series_link/S00-004.htm.

The appropriate choice of building envelope technologies must take into account affordability and lifecycle costs, whether it concerns new construction or renovations of existing buildings.[5] Building energy codes, where they exist and are enforced, also influence the quality of building construction (see Chapter 4). In combination with MEPs for ACs, such codes are the basic policy lever for space-cooling energy demand (see Chapter 3).

Demand-side management

Space cooling can account for a sizeable chunk of overall electricity load, especially at peak (see Chapter 1). Demand-side management (DSM) can play an important role in both accommodating and dampening electricity peak loads for cooling and other electricity end uses, as well as facilitating the integration of variable renewables-based generation. DSM, which has been in widespread use around the world since the 1970s, refers to activities aimed at encouraging electricity consumers to reduce their electricity consumption (load shedding) and/or modify their pattern of electricity usage (load shifting) as a way of lowering the overall cost of providing

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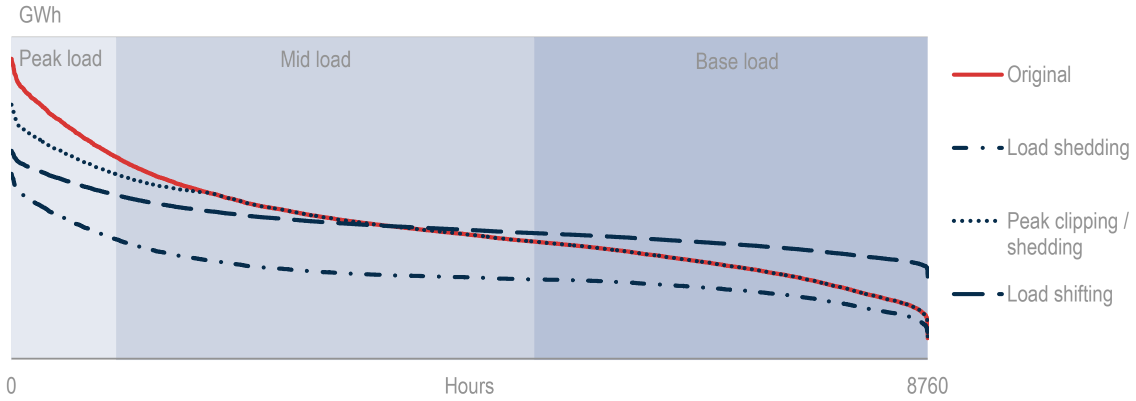
[5] Further information on building envelope technologies can be found in IEA (2013a), *Technology Roadmap on Energy-Efficient Building Envelopes*.

electricity and ensuring reliable service. In most cases, the goal of DSM is to reduce overall system load during peak hours, or to move the time of energy use to off-peak times such as night-time and weekends (Figure 2.6). This reduces the need for installing and maintaining additional capacity to meet peak load.

Figure 2.6 • Illustrative example of demand management and the annual load duration curve



Note: The load duration curve plots load in each hour of the year sequentially from the highest to the lowest level.

Key message • DSM programmes can target space cooling to reduce peak load temporarily or permanently, or shift it to off-peak periods.

DSM can include a wide range of actions designed to reduce or shift electricity demand. For example, many utilities, especially in the United States, promote the sale of efficient ACs and other electrical equipment through information or awareness campaigns, which can be highly cost-effective. In some cases, subsidies for the equipment itself are also provided. Utility-sponsored energy audits of large commercial and industrial consumers can provide a detailed assessment of electricity usage and identify energy-saving options or opportunities to shift demand away from peak periods when electricity prices are highest. Utilities and electricity suppliers may be subject to energy-efficiency obligations, which specify annual percentage reductions in electricity sales to end-use customers. DSM can be used to meet these targets.

Tariff structures can also encourage consumers to change their behaviour or shift their electricity consumption, most commonly by using peak and off-peak pricing. Differentiated tariffs require special time-of-use meters but are becoming increasingly common in many countries. For example, more than half of all households in Scandinavian countries have hourly meters.

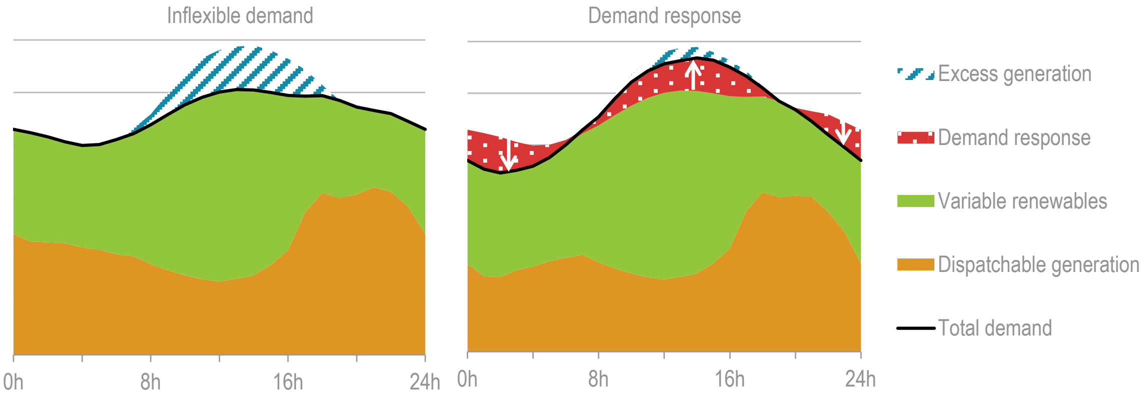
Impact of demand response on cooling demand

Among the different types of DSM, attention is increasingly being focused on demand response, as utilities seek to minimise the cost of meeting increased load and integrate growing supply from variable renewables. Private companies are increasingly offering demand response, using computing power and algorithms to efficiently allocate demand reductions. They sign up customers, usually large industrial or commercial businesses, who are paid for switching off or turning down their electric appliances and equipment on request, and sell these peak load savings on the hourly wholesale market at the prevailing price.

Demand response has developed most in North America, where it is normally used in conjunction with pricing mechanisms to better manage buildings loads and overall electricity demand. At the global level, demand response remains very limited in scale: today, only 1% of total electricity demand worldwide, or about 40 gigawatts (GW) of capacity, is able to directly respond to shortages or excess supply (Navigant Research, 2016). But interest in demand response is increasing with advances in digital (information and communication) technology and the rapid growth in variable renewable power, especially in Europe.

Demand response can be particularly valuable in systems with large amounts of variable renewables-based generation. Maintaining the ability to quickly ramp up supply from other generating plant in response to a sudden dip in output from wind turbines when the wind drops or from solar plants when the sun goes in, or when load suddenly surges due to a heatwave, can be expensive. Encouraging consumers to cut their load at such times through dynamic energy pricing, for example by turning down their ACs, or doing this automatically with digital controls, can be cheaper (Figure 2.7).

Figure 2.7 • Impact of demand response on the daily load curve



Source: IEA (2017a), *Digitalization and Energy*.

Key message • Demand response, facilitated by digital technology, can shift consumption to those hours with a surplus of electricity supply.

Most ACs are suitable for demand response as peak electricity loads typically match well with high cooling loads in summer, especially as availability of solar power falls in the evening as the sun goes down (Kärkkäinen, 2012). ACs can be turned down or switched off completely using remote controls or smart building management systems. Lowering space-cooling loads through demand response at times of peak electricity demand is often a primary objective of DSM programmes in the United States – the pioneer of DSM and the world's leading AC market. Digitalization is likely to expand opportunities for space cooling to contribute to demand response (Box 2.5).

Box 2.5 • Demand response, digitalization and cooling

Digitalization allows for a greater number of electricity consumers to participate in demand response. Digital connectivity allows appliances and equipment to be monitored continuously and connected to the grid. The information is collected and then used to shape demand so as to match it with available supply. During the hours when supply is scarce or electricity networks are congested, connected devices such as smart ACs can be switched off or run at lower load automatically. These connected devices can reduce or shift consumption to other periods when supply is abundant, for example, when the sun shines, the wind blows or when there are no technical problems with the electricity grid. Sophisticated new digital technologies allow this to be done in a way that does not affect significantly the comfort of the consumer. The end user is typically compensated for the break in service through a price incentive.

A combination of technologies at the intersection between digitalization and energy can help demand response penetrate to a larger share of consumption. Greater automation, the diffusion of Internet-connected devices in the residential and commercial sectors (such as smart thermostats directly connected to the power market and to weather forecast providers), and higher deployment of electric vehicles and smart charging systems will all allow further integration across demand and supply, and unlock greater cost savings for individual consumers and the system overall (Gils, 2014; O'Connell et al., 2015). Artificial intelligence could potentially greatly enhance the efficiency and effectiveness of demand response in the longer term.

Sources: Gils (2014), "Assessment of the theoretical demand response potential in Europe", *https://doi.org/10.1016/j.energy.2014.02.019*; O'Connell et al. (2015), "On the inclusion of energy-shifting demand response in production cost models: Methodology and a case study", http://orbit.dtu.dk/files/118476222/NREL_Official_Report.pdf; IEA (2017a), *Digitalization and Energy*.

Other cooling solutions

District cooling

District heating and cooling (DHC) systems exist in many cities around the world, although district heating is far more common than district cooling, given the historically greater need for heating in the northern hemisphere. District cooling networks supply chilled water produced in a central plant to buildings and industrial sites through a network of insulated pipes. The chilled water is typically produced using the same technologies as air conditioning in commercial buildings (i.e. electric chillers or heat pumps using a refrigerant cycle), but generally at a much larger scale. In some locations, the water may be chilled in part or in full using heat exchange with natural sources, such as groundwater, rivers and the sea if environmental conditions and costs permit – a method known as "free" or natural cooling. Heat, for example from industry, geothermal or even solar thermal sources, can also be used with absorption chillers.

District cooling systems often incorporate storage in the form of cold water, slurry or ice. This can help to reduce the need for capacity and reduces the time the system runs below full load, which improves energy efficiency and allows for more flexibility – for example, by generating chilled water when electricity prices are low. Integrated designs – for instance, combining heating and cooling with thermal storage in the Katri Vala DHC network in Finland[6] – can also take advantage of various synergies throughout the network to achieve high system efficiencies.

The principal advantage of district cooling is that the buildings supplied in this way do not require their own ACs, which can save space and also reduce need to create surplus (i.e. peak) cooling generation capacity). Costs can also be lower thanks to economies of scale, especially if it makes use of a low-cost source of energy, such as industrial excess heat or geothermal energy.

District cooling is still a relatively uncommon method of providing cooling, and information on district-cooling installations and energy consumption worldwide is limited. It generally makes economic sense only in places with the right scale and density of cooling loads, as increased throughput improves the economics of such systems. Advanced DHC networks can pair heating and cooling services to increase the net efficiency and flexibility of the entire energy system, for example by augmenting district heat for water heating by capturing heat in district cooling return lines.

District-cooling networks today exist in a range of climates and countries. Qatar has the world's largest district-cooling system, comprising three cooling plants covering the West Bay and the Pearl-Qatar districts in Doha with a combined capacity of 197 000 tonnes of refrigeration (690 megawatts [MW]) and a fourth plant under construction. There are two district cooling systems in the Paris region of France (Box 2.6) and similar networks in Barcelona, Helsinki and Lisbon. Combined district heating and cooling systems are used in several other countries,

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[6] www.helen.fi/en/company/energy/energy-production/power-plants/katri-vala-heating-and-cooling-plant/.

including Denmark, Finland, Austria, Canada, South Korea, the Netherlands, Sweden, the United Kingdom and the United States. In Stockholm, for example, the DHC system uses free cooling from seawater.

Box 2.6 • District cooling in Paris, France

Climespace, a subsidiary of the French energy company Engie, operates the largest district cooling network in Europe, including six large plants in the central district cooling network (with a combined capacity of 215 MW) and four additional plants outside the central network, for a total cooling capacity of 285 MW. The Climespace network supplies water taken from the River Seine and chilled to an average temperature of 5°C through 71 km of pipelines to five million m^2 of space in hotels, offices, government buildings, theatres and museums.

The network incorporates a storage system, including tanks of cold water at 2-5°C and six ice storage units, which is capable of delivering up to 140 megawatt hours of cooling capacity per day. The cold water and ice are produced during the night and distributed at peak hours during the day. This reduces the need for chiller capacity (a large capital cost) during peak demand hours and reduces operating costs, as electricity is cheaper and ambient temperatures are lower at night. The ice storage is also used to reduce the temperature of the cold water distributed throughout the network, as low as 2.2°C when needed, in order to increase the density of the energy transported by the existing network and, thereby, increase its effective capacity. It also serves as standby in case a chiller fails.

The business district of la Défense, just outside central Paris, also has a district cooling system operated by the Société Urbaine de Climatisation, a subsidiary of Dalkia. It serves 70 high-rise offices and hotels with 1 million m^2 of space through 6 km of pipes with water taken from the River Seine. Electric chillers are used to provide additional cooling during periods of peak demand. Storage capacity, such as chilled water or ice storage in the central Paris district cooling network, could help to provide this additional capacity during peak demand.

Source: Di Cecca, Benassis and Poeuf (2017), *Energy Storage: the Parisian District Cooling System*.

As global energy systems become more complex, district cooling networks with storage could form part of a broader integrated energy system. For instance, district cooling networks could "charge up" cooling capacity during periods of surplus electricity generation, allowing for greater integration of variable renewable energy sources such as solar photovoltaic (PV) into the electricity network and reducing the risk of curtailment – the forced disconnection of capacity due to a lack of network capacity.

Some existing district cooling networks already make use of storage, which can lower substantially the cost of supply and prices to end users. For example, the Lusail City district cooling system being developed by Marafeq in Qatar will use electric chillers and thermal energy storage to supply chilled water. Two storage plants, each with 47 500 tonnes of capacity, have been built and a third is due to be commissioned in 2018. Those plants will be able to supply around 140 000 tonnes of chilled water during the daily peak period on top of the 360 000 tonnes of chiller production capacity. It is estimated that storage will enable savings of around 1 000 gigawatt hours (GWh) per year and avoid the need for around 35 MW of capacity compared with conventional air–conditioning systems using either air-cooled chillers or split AC. The Climespace network in Paris also makes use of thermal storage.

Solar cooling

Solar cooling is an emerging technology that holds the promise of providing an economically attractive source of cooling with zero or very low emissions, with a number of attractive features when compared with other cooling alternatives. It can also help to alleviate peak power load associated with cooling. Solar cooling can include the direct use of solar PV with a heat pump or

AC as well as solar thermal collectors that use a thermally driven cooling device such as a sorption chiller. Both types can also be adapted to produce space or water heating during the winter (either directly through solar thermal or by using a reversible heat pump) and can likewise be combined with excess heat, geothermal, DHC and co-generation plants.

Solar PV applications using a chiller are still a rather niche market, although this is changing as PV panel costs have decreased substantially in recent years. One barrier – as described in Box 3.1 – is the potential mismatch of peak solar PV generation relative to peak cooling demand, especially in the residential sector where peak cooling demand load is often in the evening. As electric battery technologies and other storage mediums (e.g. compact phase-changing materials) continue to improve and come down in costs, solar PV for space cooling in buildings will likely become more common.

Solar thermal cooling technologies uses heat obtained directly from the sun (using different types of collectors) in a thermally driven cooling process (e.g. as opposed to using electricity generated by solar PV panels). Solar thermal cooling systems using sorption chillers are to date relatively niche technologies, but the market is growing as costs come down. At the end of 2015, an estimated 1 350 solar thermal cooling systems had been installed worldwide – around 80% of them in Europe, mainly in Spain, Germany and Italy (Weiss, Spörk-Dür and Mauthner, 2017). Costs have fallen by more than half since 2007, largely because of the standardisation of the equipment, although they have not come down as quickly as solar PV.

The majority of the solar cooling systems make use of flat plate or evacuated tube collectors. They represent a tiny fraction of the total number of solar thermal energy systems in place globally, most of which are used for supplying heat. Further cost reductions and improvements in the thermal efficiency of sorption heat pumps are also needed for the technology to be deployed on a much larger scale than is currently the case. Additionally, further innovation and cost reductions are needed to provide integrated cooling solutions using solar thermal technologies when the sun goes down.

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3. The outlook for cooling

There are few certainties when it comes to energy. But one thing to be very confident about is that global demand for space cooling and the energy needed to provide it will continue to grow for decades to come – mainly the result of rising incomes and the associated increase in demand for greater thermal comfort, population growth in the hottest parts of the world and climate change. What is much less certain is exactly how quickly cooling-related energy demand will grow and how it will be met, in part because we do not know for sure how governments will act to influence underlying market trends. The consequences, notably for the environment, if governments do not act to curb energy demand for cooling are likely to be severe.

Methodology

Modelling approach

In keeping with the International Energy Agency (IEA) tradition, this report adopts a scenario approach to assessing the long-term global prospects for energy demand for cooling. Two scenarios are presented to illustrate the consequences of differing degrees of policy action through to 2050 to address the threat of a "cold crunch". One focuses on the growth in people desiring and being able to afford air conditioning systems (ACs) and paints a picture of rampant growth in demand for space cooling with far-reaching implications for emissions, energy security and electricity costs – the result of an absence of any additional policy push beyond that which has already been announced by governments around the world. The other illustrates how more rigorous policies and measures could steer the world onto a much more sustainable path characterised with more moderate rates of growth in cooling demand. In this way, the report assesses the range of possible outcomes according to the degree of policy effort that may be forthcoming in the years and decades to come.

The primary tool for producing quantitative scenario-based projections of space cooling-related energy use and emissions is the IEA *Energy Technology Perspectives* (*ETP*) model. The buildings sector component of the model uses a global simulation stock accounting framework, split into the residential and non-residential subsectors across 35 countries and regions. The residential subsector includes all energy-using activities in apartments and houses, including space cooling (air conditioning, fans and ventilation). The non-residential, or commercial, subsector includes energy consumption for space cooling and other end uses in buildings used for commercial services.[1] The projection period runs to 2050.

The principal inputs into the buildings sector model fall into two main categories: demand-side drivers (economic and demographic factors, energy performance indicators and the building stock) and supply-side or technological variables (including the prices and energy performance of appliances and equipment). Combining the demand for energy services with the technological inputs yields a set of energy demands by fuel for each end-use application, including space cooling.

Within the buildings sector model, cooling demand is driven by the quantity, efficiency and usage patterns of ACs. The cost-effective supply of electricity to meet that energy demand is determined based on assumptions such as the techno-economic characteristics of power technologies, renewable resource characteristics, load profiles for ACs and policies. This then

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[1] More details of the ETP model, including the approach to modelling energy use in buildings, can be found in Annex A of the 2017 edition of *ETP* (IEA, 2017b).

determines, for each region/country, the investment choices about the type of capacity to meet electricity demand and the fuel mix for baseload and peak load in a cost-effective manner, as well as the resulting emissions and cost of electricity supply.

The scenarios

The ***Baseline Scenario*** is the baseline against which we assess the potential for saving energy for space cooling and curbing the carbon dioxide (CO_2) that is emitted because of that demand. It is driven by assuming that those who require cooling, for climatic reasons, and become able to afford it, will buy and use ACs, and that generation capacity to power them will have to be built. However, it also takes into account not just the policies and measures that governments around the world have already put in place to curb the growth in energy use, limit energy-related emissions and improve energy efficiency, but also the likely effects of announced policies, as expressed in official targets or plans. Those plans include the nationally determined contributions (NDCs) pledged under the 2015 Paris Agreement, although in some cases they have been supplemented or superseded by more recent announcements, including the decision by the United States administration in 2017 to withdraw from the agreement. Policies and targets adopted by subnational authorities, such as state governments in federal countries, cities and municipalities, as well as the commitments made by the private sector, are also taken into account. This means that the Baseline Scenario already represents a major shift from historical "business-as-usual" trends, which incorporate no meaningful climate policy action.

The second scenario – the ***Efficient Cooling Scenario*** – considers energy efficiency as a critical tool to address rapidly growing space-cooling demand. It considers first and foremost the implications of much tighter minimum energy performance standards (MEPS) for air-conditioning equipment, and the role those could play in supporting broader ambitions around energy-efficient and sustainable development. In particular, MEPS are increased in all countries in an assertive and progressive manner, which drives up the average efficiency of equipment installed. Nonetheless, in no country do those MEPS exceed the efficiency of the most efficient devices already available today. In other words, the Efficient Cooling Scenario does not intrinsically assume any need for further technological advances in the future, even though they will undoubtedly occur and help push up the average efficiency of new models.

The focus on equipment efficiency is in no way to suggest that this is the only policy action that should be taken.[2] In particular, as will be seen, combined action on equipment efficiency and building efficiency, together with a set of wider policy actions, offers the best path to maximising overall efficiency and minimising the negative consequences of cooling growth. The Efficient Cooling Scenario illustrates this by putting a focus on what is probably the easiest and fastest-acting area of policy action – enhanced equipment efficiency.

Both the Baseline and Efficient Cooling Scenarios adopt the same socio-economic and demographic assumptions, described in detail in Chapter 2. The assumptions about cooling degree days (CDDs) differ slightly between the two scenarios according to the different outcomes for climate change and temperature increases across the world (which vary to some degree between regions). On average, CDDs increase globally by nearly 25% between 2016 and 2050 in the Baseline Scenario and 20% in the Efficient Cooling Scenario (without taking into account movement in populations within countries).

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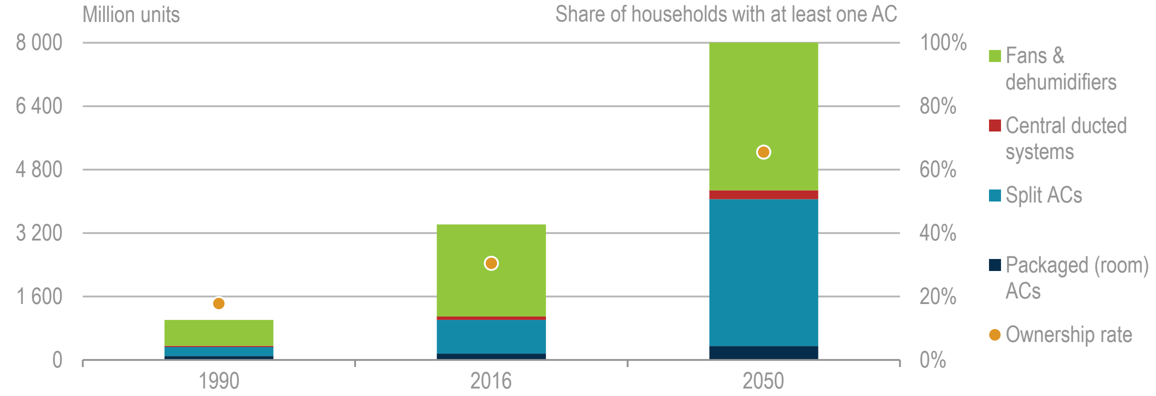
[2] The Efficient Cooling Scenario applies an assumption of cleaner power generation, which is enabled, in part, by greater deployment of energy efficiency measures. Further information on power sector outlooks and the broader role of energy efficiency can be found in the most recent edition of the *Energy Technology Perspectives 2017* (IEA, 2017b), which can be found at www.iea.org/etp2017.

Baseline Scenario trends

Ownership and energy efficiency of space-cooling equipment

The extent of ownership of space-cooling equipment and the energy efficiency of that equipment are the principal underlying drivers of energy demand for cooling. In the Baseline Scenario, it is broadly assumed that all those who wish to, and can afford to, buy such equipment will do so. The number of individual cooling units or systems (including ACs, fans and dehumidifiers) in use in the residential sector worldwide rises from just above 3.4 billion in 2016 to more than 8 billion (Figure 3.1). The biggest increase in absolute terms is for split ACs, the number of which rises from just over 850 million today to over 3.7 billion. Central ducted split ACs, which are generally larger, also see rapid growth, tripling to around 225 million units. Electric fans (including a small number of dehumidifiers), which consume far less power than ACs, remain the leading type of cooling equipment, though their number grows less rapidly, from 2.3 billion to 3.9 billion over 2016-50. The global average rate of household ownership of ACs surges from just over 30% in 2016 to almost two-thirds in 2050.

Figure 3.1 • Household ownership of cooling equipment by type in the Baseline Scenario



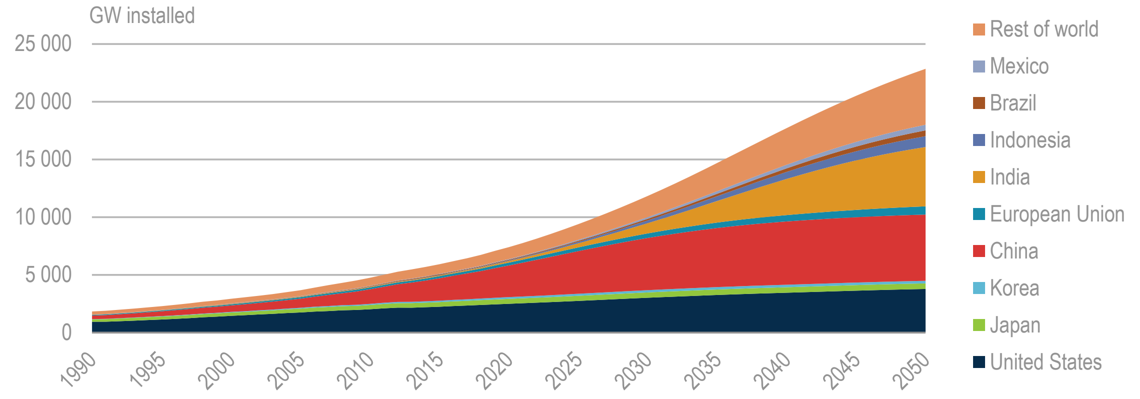
Key message • Household ownership of ACs is set to soar as, in many hot and humid countries, rising incomes make them more affordable and a warmer climate makes them indispensable.

The total space-cooling output capacity of residential ACs worldwide increases in line with the number of units brought into service over the projection period, growing from around 6 200 gigawatts (GW) in 2016 to nearly 23 000 GW in 2050. Unsurprisingly, the biggest increases occur in the emerging economies with the hottest climates. India sees the biggest growth in absolute terms, followed by the People's Republic of China (hereafter, "China") (Figure 3.2).

Together, these two countries account for around half of the total increase in the household ownership of ACs worldwide, with over 2 billion residential ACs installed in China and India by 2050. There is also significant growth in Africa, where there are currently very few units, and likewise in the Middle East.

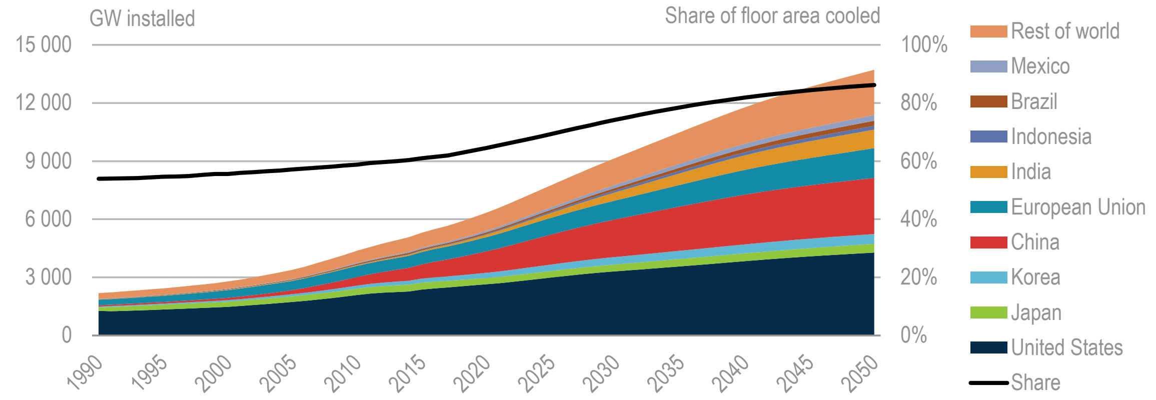
It is a similar story in the commercial sector, where the total number of pieces of space-cooling equipment grows from nearly 530 million in 2016 to over 1.3 billion in 2050, with cooling capacity rising from 5 500 GW to slightly less than 14 000 GW (Figure 3.3). Split ACs contribute the overwhelming bulk of this growth, though the number of chillers (mostly electric) grows more rapidly to 105 million units, a 260% increase. The share of floor surface cooled also rises from 60% to more than 85% over the same period. The biggest increases are in China (2 100 GW) followed by the United States (1 850 GW), together contributing almost 50% of the global increase in commercial space-cooling capacity.

Figure 3.2 • Residential AC cooling capacity in the Baseline Scenario by country/region



Key message • China and India account for more than half of the global expansion in the number and capacity of residential air conditioners.

Figure 3.3 • Commercial AC cooling capacity in the Baseline Scenario by country/region

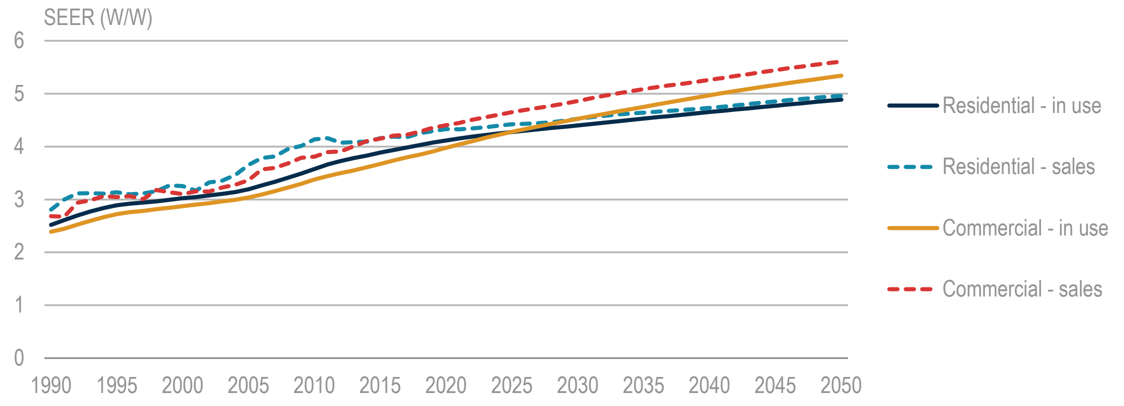


Key message • Globally, the total amount of commercial buildings floor area cooled rises from 60% to more than 85% between 2016 and 2050, with the biggest increases in the United States and China.

In the Baseline Scenario, the energy efficiency of new ACs worldwide continues to improve steadily over the projection period, driven by a panoply of current and planned policies, including MEPS, and by continuous technological advances. This is largely consistent with historical trends, whereby the efficiency of ACs has improved by roughly 1.7% per year since 1990 (as measured by the seasonal energy efficiency ratio (SEER), though this is still far from the potential that could be achieved by adopting the most efficient technologies already on the market (Figure 3.4).

In line with the trend of the past decade, the average efficiency of ACs in the commercial sector in the Baseline Scenario rises slightly faster than in the residential sector. Today, the average efficiency of the stock of ACs is more or less the same in each sector, but by 2050, it is markedly higher in the commercial sector, reflecting the fact that commercial ACs grow in size, partly due to new commercial premises shifting to chillers that cool the whole building, offering greater opportunity for deploying more efficient technologies (efficiency tends to increase with size). By contrast, the average efficiency of residential ACs decelerates without new policies as the effects of those implemented early in the projection period wear off.

Figure 3.4 • Weighted average world SEER of ACs in the Baseline Scenario

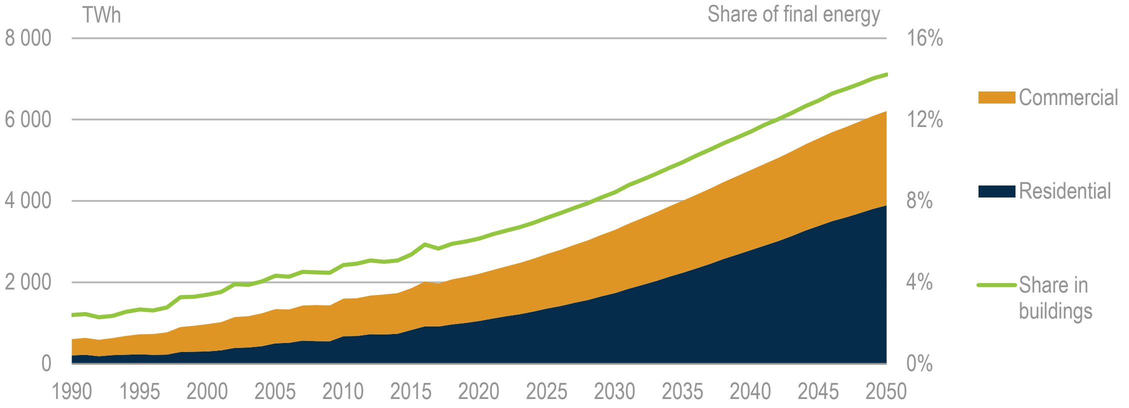


Key message • The efficiency of ACs continues to improve steadily in the Baseline Scenario, but falls far short of the potential available, with SEERs of 6 or higher already in most markets today.

Energy use for space cooling

The projected improvements in the energy efficiency of ACs brought into use over the projection period only partially offset the impact of soaring ownership of that equipment on energy consumption. Global energy use for space cooling is projected to jump from 2 020 terawatt hours (TWh) in 2016 to 6 200 TWh in 2050 – an astounding threefold increase (Figure 3.5). Nearly 70% of this increase comes from the residential sector, where the potential today for more space cooling is greater (many offices, shops, hospitals and public buildings already have air conditioning); the share of the residential sector in total space cooling energy demand climbs from 45% to nearly 65%.

Figure 3.5 • World energy use for space cooling by subsector in the Baseline Scenario

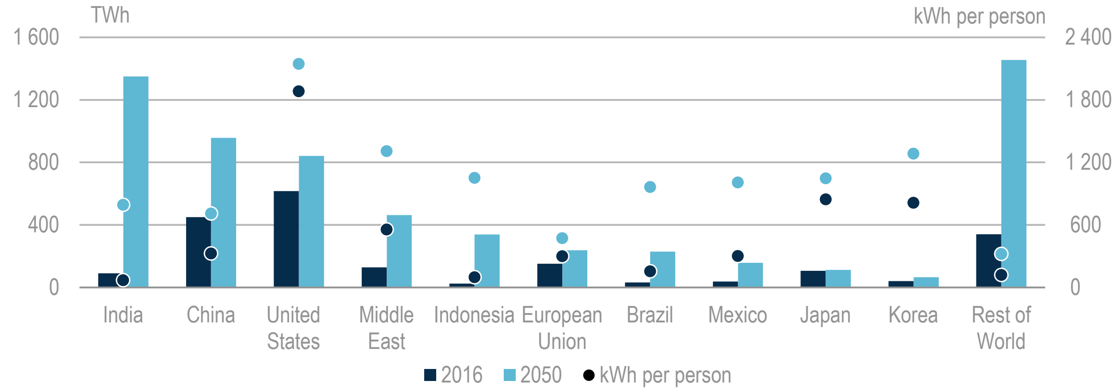


Key message • On current trends, energy needs for space cooling – almost entirely in the form of electricity – will more than triple between 2016 and 2050, driven mainly by the residential sector.

Because of the strong growth in energy use for air conditioning, the share of cooling in total energy consumption in buildings more than doubles, from 6% to 14%. All of the increase in energy use for cooling is in the form of electricity. As a result, space cooling's share of total buildings electricity use jumps from 18% to just under 30% by 2050; its share of global electricity use rises from 10% to 16% over the same period.

The lion's share of the projected growth in energy use for space cooling comes from the emerging economies, with India, China and Indonesia alone contributing half (Figure 3.6). India's cooling-related energy demand soars from just 90 TWh in 2016 to 1 350 TWh in 2050 – a 15-fold increase. The next-biggest increase in volume terms is in China, where demand more than doubles to 960 TWh, followed by Indonesia, which sees a near 13-fold increase to 340 TWh in 2050. Demand in the United States also climbs by 40%, but it is still overtaken by both India – which becomes the world's largest energy user for cooling – and China. Cooling energy use more than triples in the Middle East. Brazil and Mexico also see rapid increases.

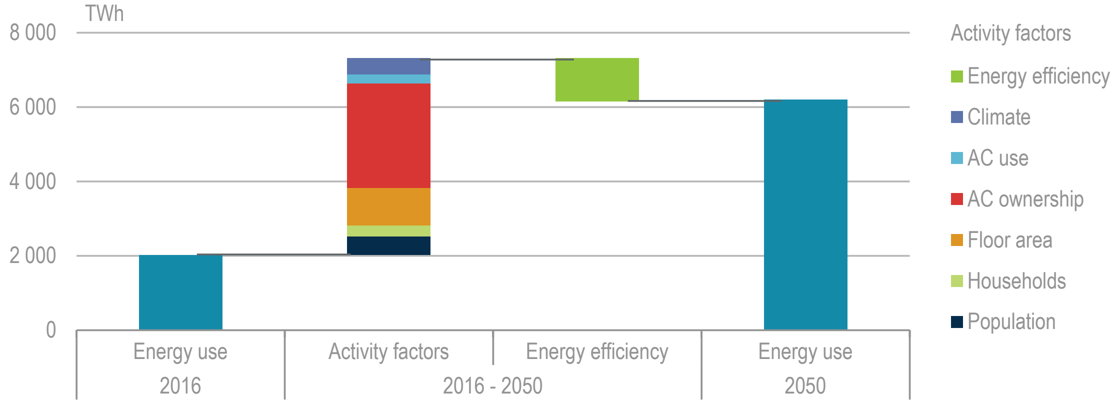
Figure 3.6 • Energy use for space cooling by country/region in the Baseline Scenario



Key message • Most of the projected growth in energy use for space cooling is set to come from India, China and other emerging economies.

The increase in global energy use for space cooling is largely the result of the increased ownership of ACs, but increases in how much each unit is used and the size and number of buildings also contribute, as does climate change. All these factors combine to drive up energy use for cooling (Figure 3.7).

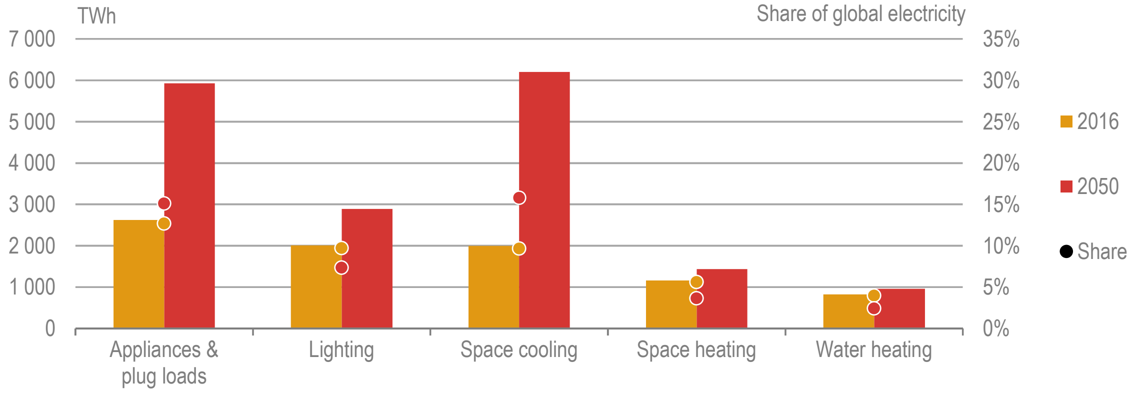
Figure 3.7 • The role of drivers of energy demand for space cooling in the Baseline Scenario



Key message • Booming sales of ACs more than outweigh the impact of continuing gains in energy efficiency.

The global use of electricity in buildings and other sectors grows significantly over 2016-50, but no end use grows as fast as space cooling. As a result, cooling becomes the single largest user of electricity in buildings, ahead of appliances and other "plug loads" (small electrical or electronic devices) (Figure 3.8).

Figure 3.8 • Building electricity demand by end-use application in the Baseline Scenario

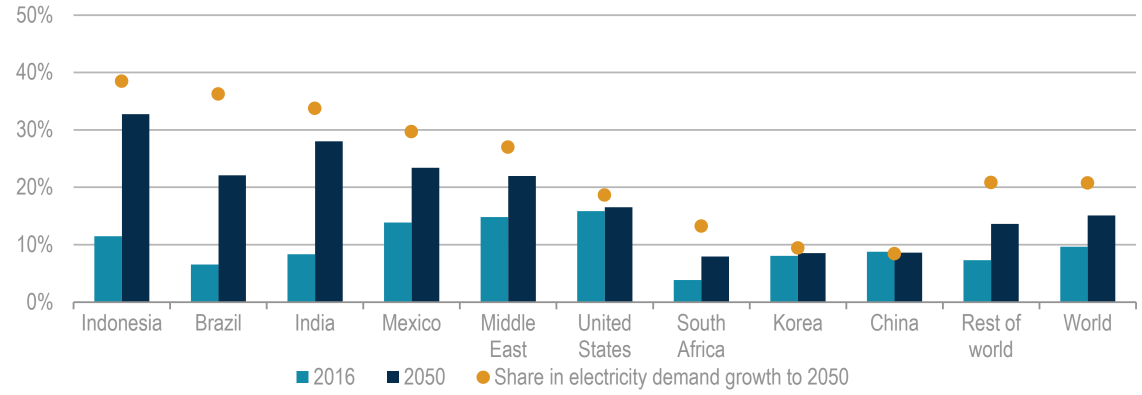


Key message • Space cooling is set to overtake appliances and plug loads to become the single largest user of electricity in buildings, and account for 16% of global electricity demand in 2050.

Implications for electricity systems

The projected increase in space cooling demand will have a major impact on the electricity system in most regions. The share of cooling in electricity demand increases sharply in all hot regions, most notably in large countries such as Brazil (where CDDs are expected to increase by a staggering 25% between now and 2050), and India (Figure 3.9). Worldwide, cooling accounts for 21% of the total increase in final electricity consumption between 2016 and 2050; by country, the range is from 8% in China to nearly 40% in Indonesia. The total increase in cooling demand is equivalent to more than 20% of total global electricity consumption in 2016.

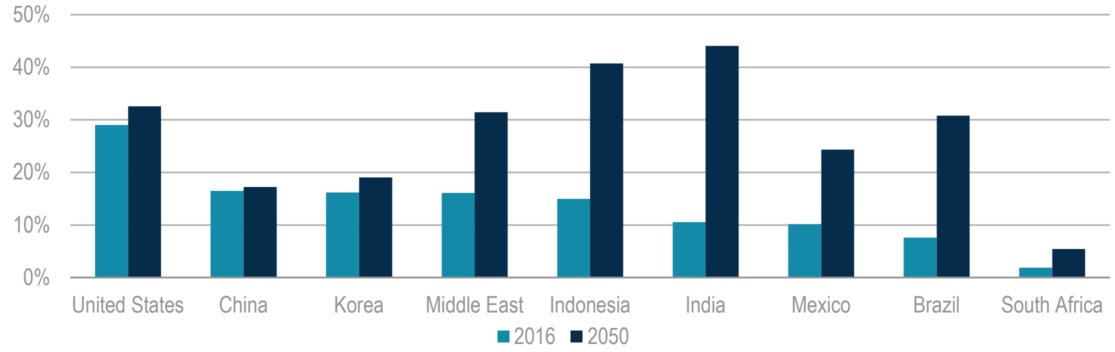
Figure 3.9 • Share of space cooling in total electricity demand and in the growth in electricity demand by country/region in the Baseline Scenario



Key message • The share of space cooling in electricity demand increases everywhere bar China, notably in Indonesia, Brazil and India, where the potential for increased use of ACs is greatest.

The critical factor for electricity systems is the extent to which space-cooling demand increases the need for power generation and network capacity. As explained in Chapter 1, the daily and seasonal profile of cooling demand is such that increased load will accentuate peak demand. The extent to which this occurs varies across countries according to climatic factors, the overall structure of electricity demand and consumer behaviour. The increase is most pronounced in India, where the share jumps from just 10% to 45%. Brazil, Indonesia and the Middle East also face a big increase (Figure 3.10).

Figure 3.10 • Share of space cooling in peak electricity load by country/region in the Baseline Scenario

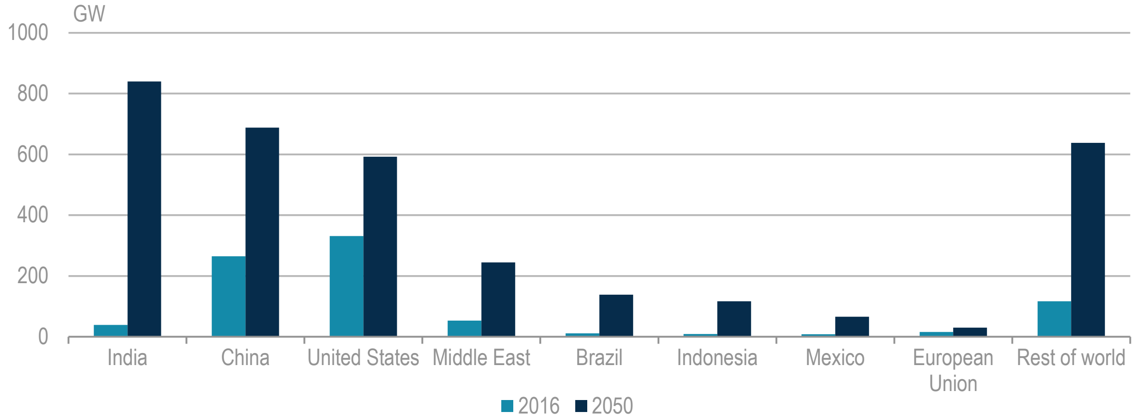


Note: The shares have been calculated for the time within the year at which the peak load of overall electricity demand occurs.

Key message • The share of space cooling in peak electricity load worldwide is projected to rise sharply in many countries, with the biggest increase occurring in India.

Globally, the total amount of capacity needed to meet space-cooling demand, taking account of the variability of renewables-based generating capacity, is projected to jump 395% from 850 GW in 2016 to 3 350 GW in 2050. To put this into perspective, the 2 500 GW of additional capacity is bigger than the total generating capacity of the United States, Europe and India combined today. India sees the biggest increase, given its large population and hot climate (Figure 3.11).

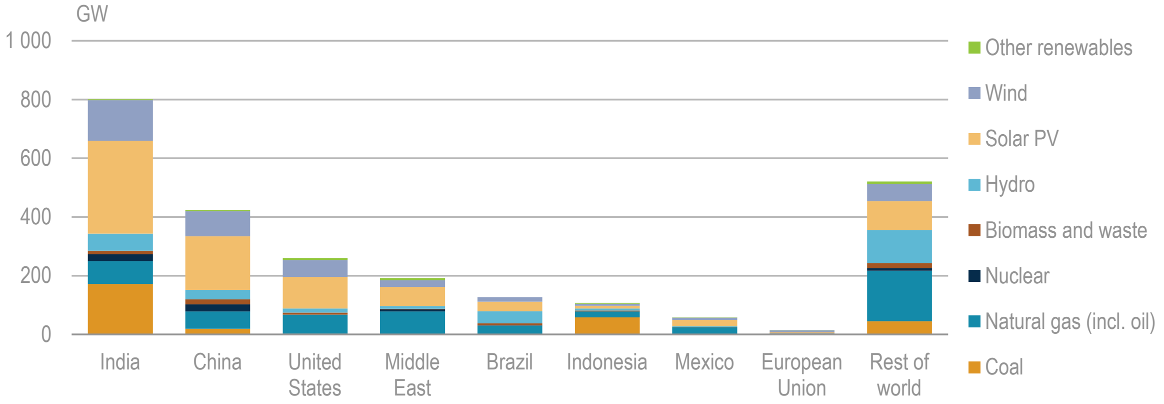
Figure 3.11 • Power generation capacity required for cooling by country/region in the Baseline Scenario



Key message • Globally, the capacity needed for space cooling jumps from 850 GW in 2016 to 3 350 GW in 2050 – an increase equal to the total generating capacity of the United States, Europe and India combined today.

With lower costs, renewables meet most of the global increase in capacity needs for space cooling to 2050 in the Baseline Scenario, though coal and gas account for a sizeable share in India, Indonesia and other developing Asian countries (Figure 3.12). Solar photovoltaic (PV) accounts for more than 835 GW, or one-third, of the generating capacity additions needed globally to meet the growth in cooling demand. India is the biggest contributor, accounting for almost 40% of the global solar PV capacity increase for cooling. India also drives nearly 60% of the 300 GW increase in global coal capacity for cooling between 2016 and 2050. The shares of natural gas in incremental capacity are generally highest in countries where the shares of variable solar PV and wind power are relatively high, including the United States and the Middle East, where natural gas (and sometimes diesel) is typically the preferred back-up fuel.

Figure 3.12 • Power generation capacity additions to meet the growth in space-cooling demand in the Baseline Scenario by country/region and fuel, 2016-50

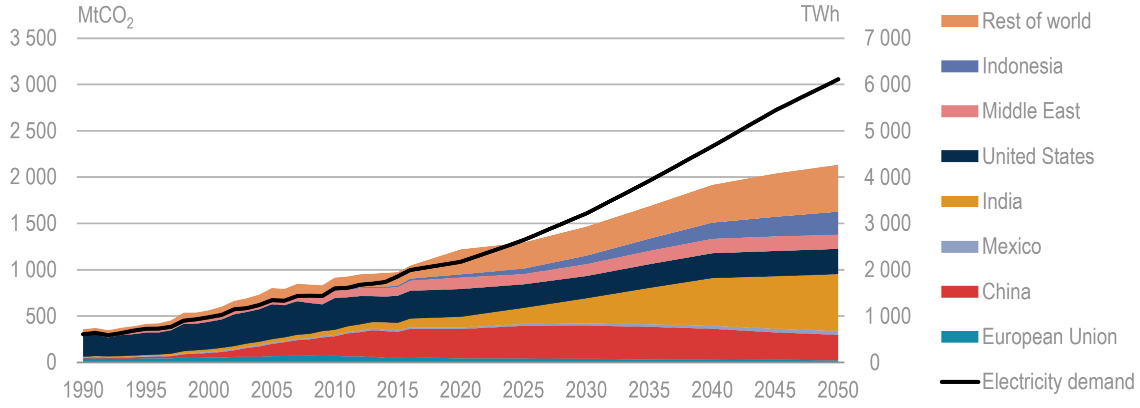


Key message • Renewables meet almost two-thirds of the global increase in capacity needs for space cooling to 2050, though coal and gas account for a sizeable share in India and Indonesia.

Space cooling-related CO_2 emissions

The huge projected increase in electricity consumption for space cooling to 2050 in the Baseline Scenario inevitably results in a substantial rise in CO_2 emissions associated with the fossil fuels used in power generation. The pressure to provide power to meet the energy demands of the scenario makes it harder to decarbonise electricity systems. Emissions almost double from 1 135 million tonnes (Mt) in 2016 to 2 070 Mt in 2050. This increase is equivalent to the total CO_2 emissions of Africa today. Nonetheless, emissions rise much less than electricity demand. This is because the average carbon intensity of electricity falls as reliance on coal (the most carbon-intensive fossil fuel) declines in favour of natural gas (the least intensive) and renewables, driven to a large degree by policy action (Figure 3.13). Globally, generating 1 kilowatt hour (kWh) of electricity emitted on average 505 gCO_2 in 2016, but this falls to 270 g in 2050 in the Baseline Scenario. Yet, despite the partial decoupling with electricity use, emissions associated with cooling still double by 2050. The share of cooling in total power sector CO_2 emissions worldwide rises from 8% to 15%.

Figure 3.13 • Electricity demand from space cooling and resulting CO_2 emissions in the Baseline Scenario

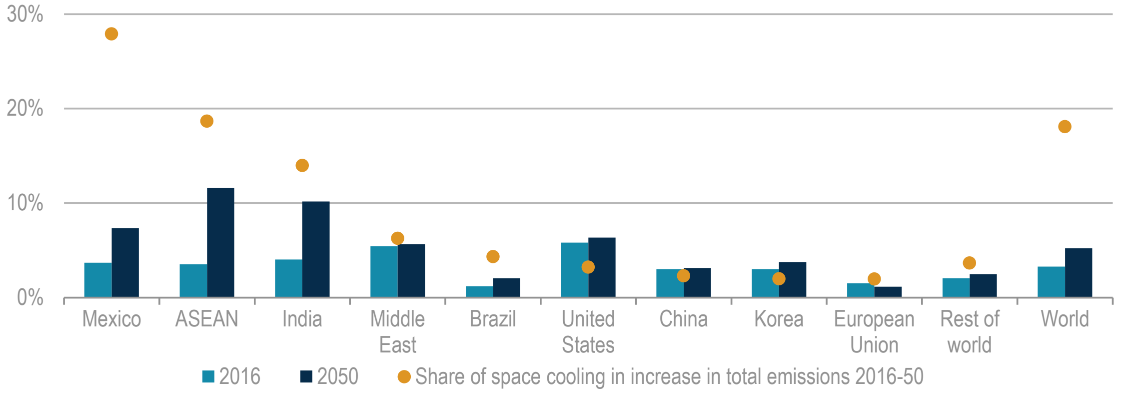


Key message • India and Southeast Asia account for the largest shares of the growth in CO_2 emissions from air conditioning, due to demand growth and reliance on coal-fired generation.

Most of the growth in space cooling-related emissions comes from India as its power generation remains heavily reliant on coal. By contrast, emissions in China fall thanks to the steady decarbonisation of its power sector in the Baseline Scenario. By 2050, India accounts for 30% of global emissions from space cooling in 2050, compared with just 8% in 2016.

The share of space cooling in total CO_2 emissions rises in almost all countries. The increase is largest in India, where it grows from just over 4% in 2016 to more than 10% in 2050; for the world as a whole, it increases from 3% to 5% (Figure 3.14). As a share of the increase in total world emissions, cooling is responsible for about 18%. In Mexico, cooling accounts for more than 25% of the increase in total CO_2 emissions – the highest share of any country – reflecting the strong growth in cooling demand relative to other end uses.

Figure 3.14 • Share of space cooling in total CO_2 emissions of the energy sector by country/region in the Baseline Scenario



Note: Energy sector emissions include CO_2 from industrial processes; ASEAN = Association of Southeast Asian Nations.

Key message • The share of space cooling in total CO_2 emissions rises in all regions, accounting for 18% of the total increase in global emissions between 2016 and 2050.

Efficient Cooling Scenario trends

The story of the Baseline Scenario is a truly depressing one: if the world decides collectively not to expand upon the energy and climate policies that have already been put in place or announced, then energy use for space cooling will explode, driving up electricity supply costs and CO_2 emissions. But the good news is that there is another plausible story to be told.

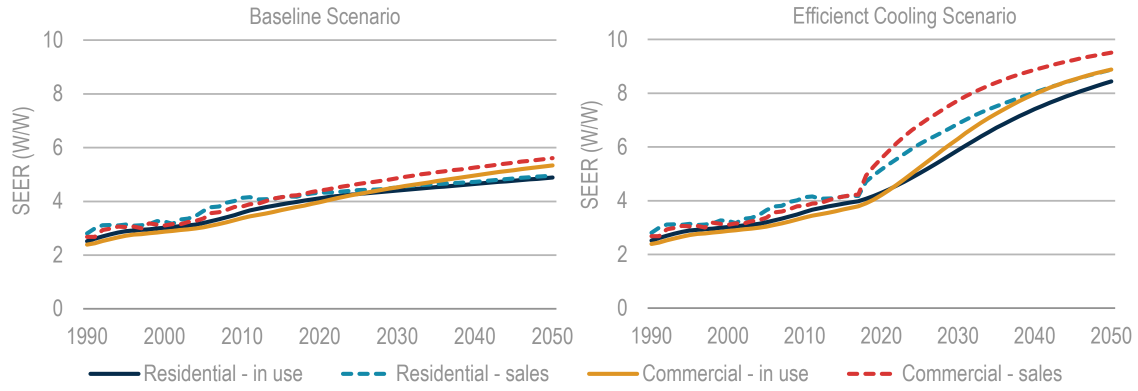
There is a lot more that governments can do to get us onto a much more sustainable track that involves a more moderate rate of increase in cooling-related energy needs and which is compatible with the ambitious goals to limit climate change that were agreed in Paris in December 2015. That is the purpose of the Efficient Cooling Scenario. It describes an energy pathway that involves much stronger policy action to limit energy needs for space cooling, which can combine with wider efficiency and decarbonisation policies to create a much better future.

Energy savings from rapid energy efficiency gains

The Efficient Cooling Scenario focuses on making ACs more efficient, thanks mainly to the impact of much more stringent MEPS, to reduce the amount of energy required to meet future cooling needs. The average energy performance of the stock of ACs worldwide, as measured by the SEER, more than doubles between 2016 and 2050 to around 8.5. Efficiency is 50% higher in 2030 and 80% higher in 2050 than in the Baseline Scenario (Figure 3.15). Yet, the average efficiency reached in 2050 in the Efficient Cooling Scenario is still 40% below that of the most efficient ACs on the market today.

This shift to higher AC efficiencies is eminently achievable, and there have been several cases in the past of MEPS driving up the energy performance of electrical appliances dramatically. For example, it has happened on two occasions – in 1993 and 2001 – in the United States, where newly announced MEPS for refrigerators were higher than any products on the market at the time, driving much more energy-efficient models. Perhaps surprisingly, the average price of refrigerators in constant dollars actually decreased on both occasions (IEA, 2013b). A detailed assessment of higher MEPS for household refrigerators in Australia also shows there was no observable increase in average prices (Lane and Harrington, 2010).

Figure 3.15 • Average global SEER of ACs by scenario



Key message • The efficiency of ACs captures major jumps in energy efficiency potential through a combination of international co-operation, market regulation and incentives.

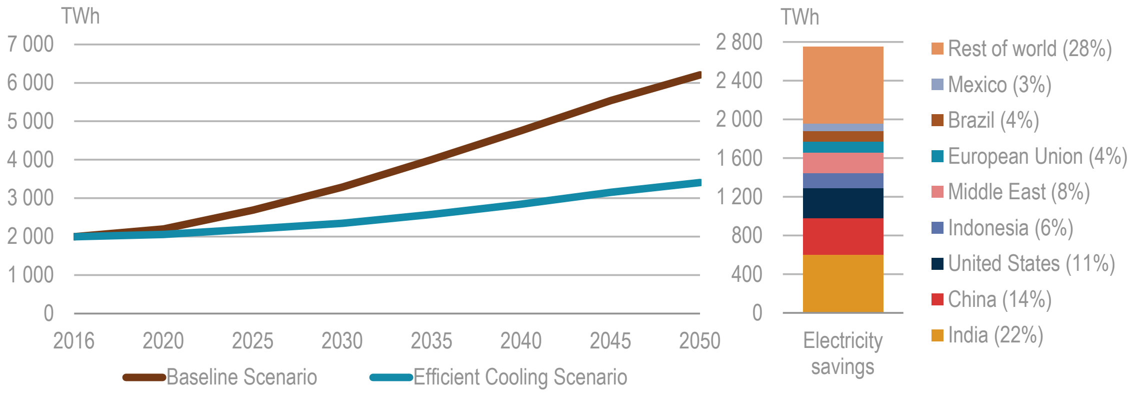
AC learning rates – the expected reduction in purchase prices for each doubling of production – suggest the major jump in energy performance in the Efficient Cooling Scenario is feasible, with the right policy push. MEPS have been shown to be highly effective at improving the efficiency of products on the market, with a recent study noting that the extra cost for efficiency can be overestimated by a factor of 10 (Nadel and deLaski, 2013). Given the quadrupling of global AC sales by 2050 compared to today, there is considerable scale to improve AC energy performance without raising costs to consumers. The Efficient Cooling Scenario assumes a marginal increase in the early 2020s from higher MEPS, but this quickly comes back down as market demand drives greater production at lower costs. Overall, the Efficient Cooling Scenario only sees a net increase of USD 70 billion (United States dollar) to 2050 (or 1%) compared to the Baseline Scenario – a drop in the ocean, given the USD 6.9 trillion that will be spent on ACs over that period. The value of the energy savings (see below) would also be substantially greater than any marginal increase in purchase price.

The result of the AC energy efficiency drive in the Efficient Cooling Scenario starts to take effect immediately, and the gains are substantial by the early 2030s – illustrating the benefits of acting today. Most ACs, especially in the residential sector, have short lifetimes compared with buildings or power sector infrastructure, so mandating improvements in the efficiency of products sold today quickly leads to an improvement in the average efficiency of the stock of ACs. By contrast, the Baseline Scenario, with less stringent standards, effectively locks-in inefficient products.

The impact of these energy efficiency gains on energy use for space cooling is rapid and substantial. Globally, the use of energy continues to grow in the Efficient Cooling Scenario, but much less rapidly than in the Baseline Scenario. Cooling-related electricity consumption climbs to 3 400 TWh in 2050 – 70% up on 2016 but 45% lower than the level in the Baseline Scenario (Figure 3.16). Those energy savings – 2 800 TWh in 2050 – are equivalent to all the electricity consumed by the

European Union in 2016. India and China account for more than one-third of the energy savings, mirroring their contribution to global growth in cooling demand in the Baseline Scenario.

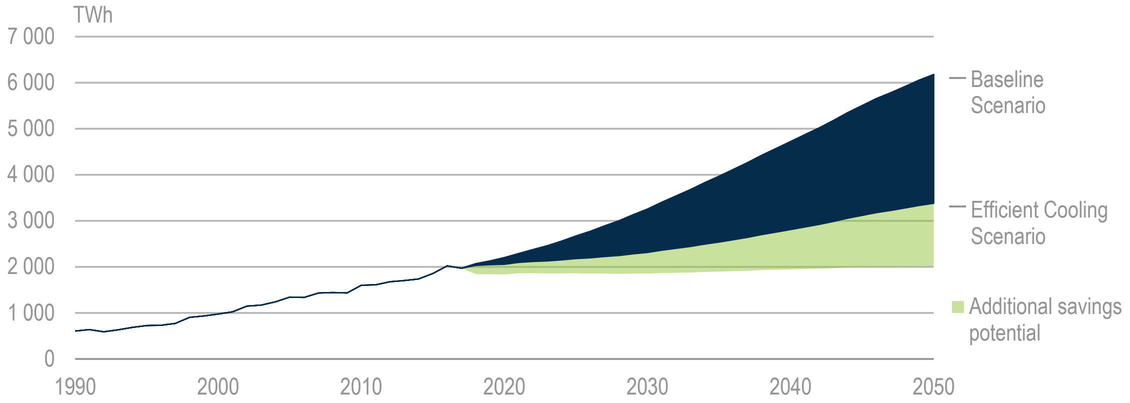
Figure 3.16 • World electricity consumption for space cooling in the Baseline and Efficient Cooling Scenarios and energy savings in 2050 by country/region



Key message • The increase in electricity demand for space cooling in the Efficient Cooling Scenario is less than half that of the Baseline Scenario, saving 2 800 TWh of electricity in 2050.

The deployment of more efficient ACs is just one step that can be taken to address rapidly growing space-cooling demand. Other important measures, such as building envelope improvements and even low-tech solutions such as increasing the indoor temperature setting on ACs by 1°C (either through behaviour change or thermostatic controls), could contribute to even further potential energy savings when combined with high-performance equipment (Figure 3.17). Additional measures not included in this analysis, such as the installation of direct renewable cooling generation, could also lower energy demand for cooling. All of these measures offer significant potential, but the Efficient Cooling Scenario focuses on the biggest and most readily achievable area – the efficiency of AC equipment.

Figure 3.17 • Contribution to world energy savings from energy-efficient ACs and additional potential energy demand reductions beyond the Efficient Cooling Scenario



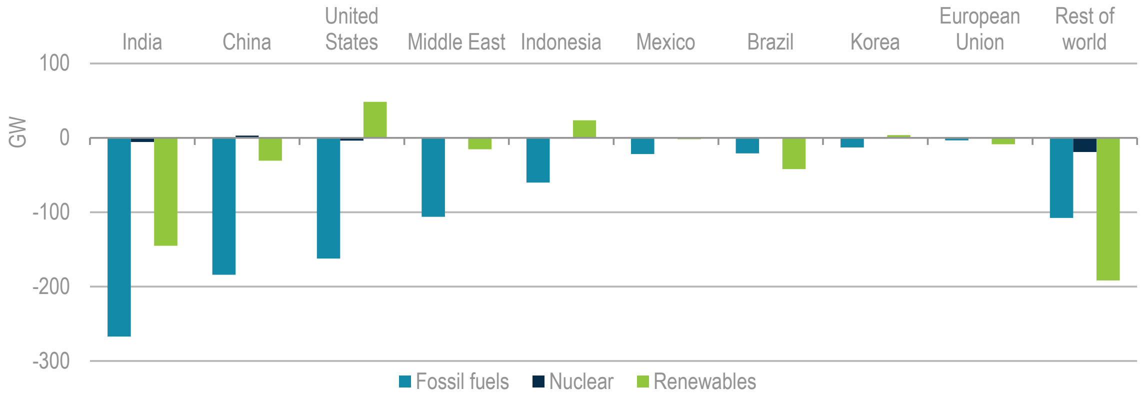
Key message • More efficient ACs in the Efficient Cooling Scenario reduce energy needs for space cooling by more than 45% compared with the Baseline Scenario in 2050, with other measures such as building envelope improvements leading to even greater savings.

Electricity system benefits

A major benefit of the Efficient Cooling Scenario is a much lower cost of supplying electricity to all end users thanks to less need for investing in peak capacity. The much smaller increase in electricity needs for space cooling results in a similar reduction in the need for overall power generation and network capacity to meet cooling demand in relation to the Baseline Scenario.

Worldwide, the need for additional capacity between 2016 and 2050 just to meet the demand from ACs is 1 170 GW in the Efficient Cooling Scenario, compared with 2 500 GW in the Baseline Scenario. In China, for example, only 215 GW needs to be added compared with 420 GW in the Baseline Scenario. In most countries and regions, the reduction in capacity needs is in the form of coal and natural gas, while renewables-based capacity additions in some cases are actually higher in the Efficient Cooling Scenario due to stronger climate policies, enabled by less pressure to expand electricity systems (Figure 3.18).

Figure 3.18 • Difference in power generation capacity needs for space cooling in 2050 between the Baseline and the Efficient Cooling Scenario



Note: Negative numbers refer to reduced capacity needs from more efficient ACs in the Efficient Cooling Scenario.

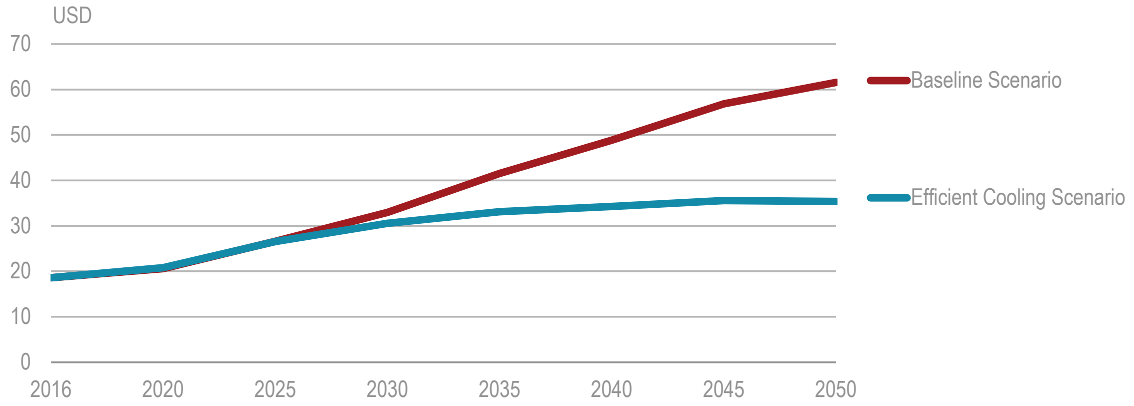
Key message • The Efficient Cooling Scenario results in capacity savings of 1 330 GW by 2050, corresponding to the installed capacities of Canada and the United States today.

Lower electricity capacity requirements also mean less need to invest: worldwide, the cumulative savings on capital spending on power generation capacity to meet space-cooling loads amount to USD 1.2 trillion over the period 2017-50. India accounts for USD 295 billion, or over a quarter of the global investment savings.

Taking into account operating and fuel costs in power generation, as well as transmission and distribution costs, the Efficient Cooling Scenario leads to total cumulative cost savings of USD 2.9 trillion compared with the Baseline Scenario – USD 1.6 trillion in generation and USD 1.3 trillion in transmission and distribution. This translates into lower costs per kWh of electricity used for space cooling and per person. The average cost of supplying electricity to end users for cooling rises from around USD 20 per person in 2016 to USD 35 in 2050 in the Efficient Cooling Scenario, averaged across the global population (Figure 3.19). But this is far below the cost of USD 62 in 2050 in the Baseline Scenario for a more-or-less equivalent degree of thermal comfort. It would be expected that these savings would be largely passed onto end users in the form of lower electricity prices regardless of whether the system is competitive or regulated.

One consequence of the combination of lower space cooling-related electricity needs and the much higher penetration of solar PV in the power generation fuel mix is that a higher share of cooling needs can be met by solar PV worldwide. In 2016, around 12% of cooling electricity load coincided with solar PV generation, thanks to the high degree to which the load profile of cooling matches that of solar output.[3] That share rises to 70% in 2050 in the Efficient Cooling Scenario, due to higher solar PV deployment, which is driven by the strong climate policies assumed in this scenario, as well as more efficient ACs, leading to lower cooling peak loads.

Figure 3.19 • Annual electricity costs per capita to meet space cooling needs by scenario



Note: Electricity costs are averaged across the entire population.

Key message • In 2050, people have to spend on average 45% less on electricity for space cooling in the Efficient Cooling Scenario thanks to the greatly reduced capacity needs to meet peak space-cooling load.

Integrating storage (e.g. batteries or thermal storage mediums such as chilled water or ice) could equally support greater use of renewables to meet growing, but energy-efficient cooling demand (Box 3.1). Such measures, either applied locally – for instance using a battery pack or water tank – or through district energy solutions, could take advantage of synergies across energy supply and demand to achieve affordable, low-carbon cooling (and heating) for buildings (IEA, 2017b).

Box 3.1 • Systems integration of renewables and thermal storage on peak cooling in India

The deployment of solar PV in India is expected to grow strongly, up to 1 000 GW of installed capacity by 2050. This means there will more often be times when more power is being generated than is required, leading to curtailment of excess PV generation during the sunniest times of the day. At the same time, cooling demand is expected to grow substantially, typically peaking in the early evening around 7pm, when the sun has gone down and solar PV is no longer providing its full capacity.

One potential way to address this mismatch is to store cold and then distribute it to buildings through district cooling networks. For instance, heat pumps could produce chilled water or ice when the solar electricity is available, and then use that storage to meet cooling loads later in the evening.

To demonstrate the potential benefits of using thermal storage with solar PV and integrated district cooling, the operation of the Indian power system was modelled during a peak cooling week in 2050.[4] The simulation considers a scenario in which India's cities – where the expected growth of cooling demand will be concentrated – would use district cooling networks with thermal storage to partially meet cooling loads from ice or chilled water produced using daytime solar PV. The scenario does not suggest that district cooling would be economically viable in all Indian cities; rather, it provides a sense of the potential and magnitude of the thermal storage needs to meet rapidly growing peak cooling demand in India through the country's large solar generation potential (Figure 3.20).

The model assumes a total thermal storage of 2 400 $\text{GWh}_{\text{thermal}}$, corresponding to an equivalent of about 600 gigawatt hours (GWh) of electrical storage. The IEA estimates that roughly one-fifth of the

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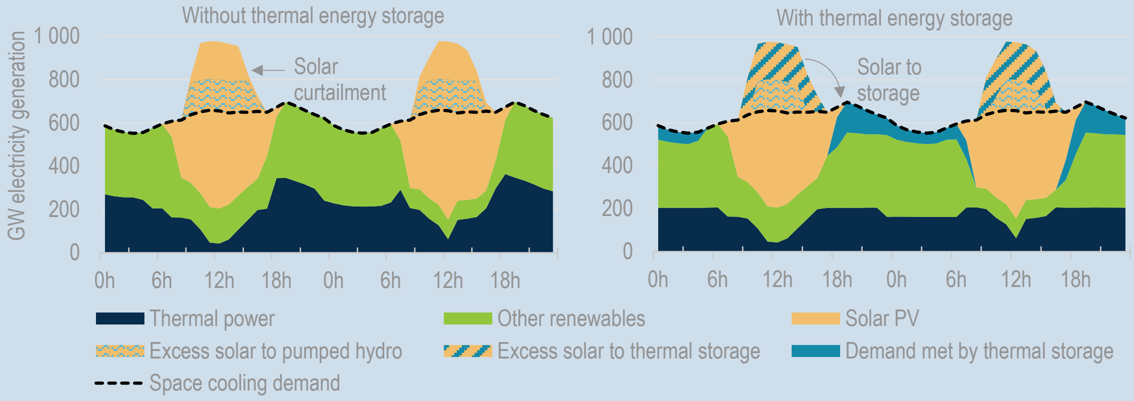
[3] This does not mean that this share of AC demand is exclusively covered by solar PV.

[4] Simulation performed in PLEXOS using a Unit Commitment Economic Dispatch model, modelling operating costs (e.g. fuel, operations and maintenance) and operational constraints (e.g. minimum generation and forced outages).

total solar PV output could be stored during the day as chilled water or ice, which otherwise would be curtailed and hence lost. That cold storage could then be discharged later in the evening, meeting around 15% of space cooling demand after the sun goes down. The required volume would be comparable to around 20 000 Olympic-sized swimming pools (if the storage medium were ice).

Figure 3.20 • Illustrative analysis of the potential role of storage using solar PV for district cooling over two days in April 2050 during the peak cooling period in India



Notes: Thermal power includes coal- and gas-fired power generation as well as nuclear electricity generation; other renewables include wind, concentrated solar power and hydro power, which includes pumped hydro produced using excess solar generation.

Key message • Thermal storage could take advantage of surplus solar output to alleviate the strain of peak cooling demand on the electricity system in the evenings.

Discharge from such a system could meet peak cooling demand between 5pm and 7pm, while equally reducing the need for peak generation capacity (e.g. using coal- or gas-fired thermal power generation, shown in dark blue). The model results show a reduction in peak residual demand of 11%, or 80 GW. In addition, the thermal storage adds system flexibility through balancing of supply and demand, which allows provision of electricity from cheaper generation sources throughout the year.

Estimates of total system costs reveal a net savings from the use of energy storage to meet cooling loads through excess PV generation, compared to a scenario without storage requiring more peak power generation (Table 3.1). The estimated annual system savings are higher for thermal storage (USD 9.7 billion) than battery storage (USD 7.5 billion). This is the result of lower costs for thermal storage capacity at around 10 USD per $\text{kWh}_{\text{thermal}}$ (ETSAP and IRENA, 2013) compared to targets of around USD 300 per $\text{kWh}_{\text{electric}}$ for battery storage in 2050 (Schmidt et al., 2017). Those savings would likely outweigh additional costs for the district cooling system (e.g. network pipes and substations), given the long life of typical district energy networks and investments that can be amortised over time. Of course, the more efficient the AC stock is, the lower the investment is required.

While this analysis does not provide a detailed assessment of the specific local conditions or system dynamics that would be required for sound energy system planning and investments, it does suggest that combining different supply- and demand-side elements could offer cheaper, cleaner and more flexible solutions to meet space cooling demand in India. These types of integrated solutions, allowing for greater use of renewable energy sources, could also compliment broader economic and social policy objectives – for instance, cutting local air pollution from electricity generation (see below).

Table 3.1 • Key power system parameters for a scenario without and with thermal storage

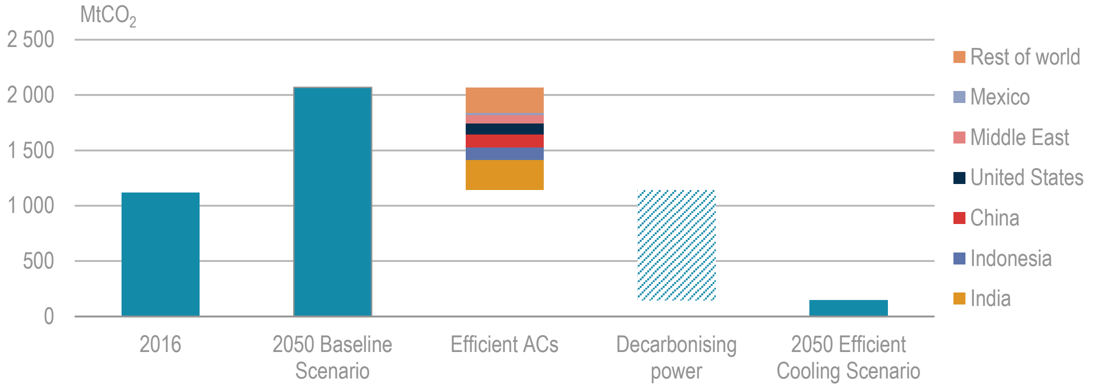
	No Storage	Thermal Storage
Peak residual demand (GW)	715	633
Curtailment (TWh)	50	0.5
Total system cost savings (USD billion per year)	-	9.7 (7.5 with battery storage)

Sources: ETSAP and IRENA (2013), www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E17%20Thermal%20Energy%20Storage.pdf; Schmidt et al. (2017), http://dx.doi.org/10.1038/nenergy.2017.110,

Emission reductions

The measures to make ACs more energy efficient, coupled with decarbonisation of fuel mix in power generation as assumed in the Efficient Cooling Scenario, lead to a huge reduction in CO_2 emissions related to space cooling in the power sector. By 2050, those emissions drop to just 150 Mt – a mere 7% of those in the Baseline Scenario and 13% of their 2016 level (Figure 3.21). This is obviously driven by the decline in fossil fuel use, but more efficient ACs account for around half of the CO_2 reductions in 2050 between the two scenarios.

Figure 3.21 • Contribution to the global reduction in CO_2 emissions from space cooling by country/region in the Efficient Cooling Scenario

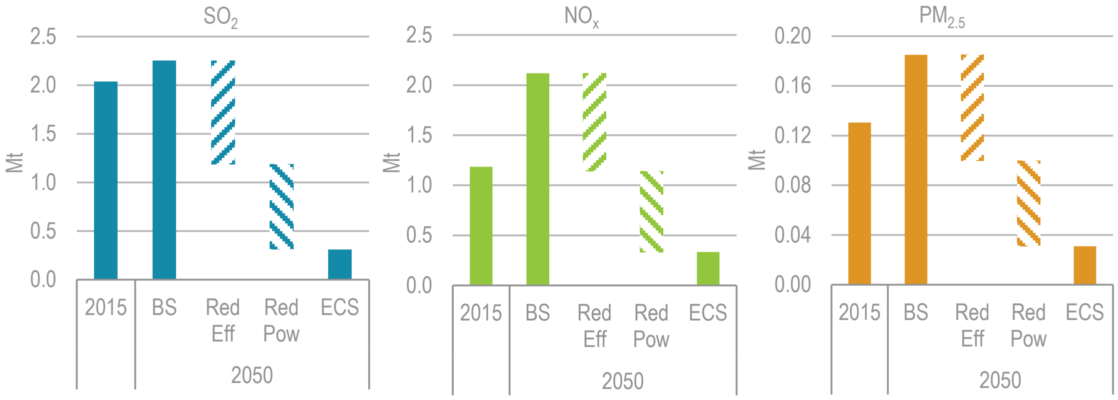


Key message • Global CO_2 emissions from space cooling double by 2050 in the Baseline Scenario, while efficient ACs cut those emissions almost to 2016 levels in the Efficient Cooling Scenario, with cleaner power further reducing CO_2 emissions.

Energy efficiency offers a cheaper path to a sustainable energy solution for growing cooling demand, rather than thinking simply in terms of building additional clean power supply to meet inefficient AC demand. For instance, meeting all the additional demand via additional solar capacity rather than efficient ACs would require an additional 2 200 GW of solar PV capacity globally in 2050 – 40% more than in the Efficient Cooling Scenario. In addition, electricity storage requirements would almost double to around 1 400 GW. In practice, it may not even be technically feasible to build all this extra capacity by 2050, given the already challenging task of decarbonising the power sector – a critical component to reach ambitious climate goals. The message is clear: policy efforts to raise the energy efficiency of ACs must go hand in hand with policies to encourage clean power technologies.

Another major environmental benefit of reduced demand for electricity for space cooling in the Efficient Cooling Scenario is improved air quality and fewer related adverse health effects. The power sector is a major source of air pollution, accounting for around one-third of all sulphur dioxide (SO_2) emissions in the energy sector in 2015, 15% of its nitrogen oxides (NO_x) emissions and 6% of its fine particulate matter ($PM_{2.5}$) emissions. Space cooling was responsible for 9% of global emissions of SO_2 in the power sector and 8% of NO_x and $PM_{2.5}$ emissions. In the Baseline Scenario, these shares increase to 15% for SO_2, 16% for NO_x and 15% for $PM_{2.5}$ in 2050 (Figure 3.22). In absolute terms, emissions fall in the period to 2035 thanks largely to more stringent emission limits in the power sector that lead to more investment in clean energy technologies like solar PV, but they then rebound as air-conditioning demand surges. By contrast, in the Efficient Cooling Scenario, emissions fall drastically over 2015-50 – by as much as 85% for SO_2. Roughly half of the reduction in the Efficient Cooling Scenario versus the Baseline Scenario is due to slower growth in cooling demand; the other half is due to switching from polluting technologies and fuels to emission-free ones, such as solar PV or wind power.

Figure 3.22 • Reductions in air pollutant emissions linked to space cooling by type of pollutant



Note: BS = Baseline Scenario; ECS = Efficient Cooling Scenario; Red Eff = reduction in emissions thanks to improved efficiency of air conditioners; Red Pow = reduction in emissions through measures in the power sector.

Key message • Emissions of air pollutants related to space cooling rise substantially in the Baseline Scenario but fall in the Efficient Cooling Scenario thanks to a combination of more efficient ACs and a shift to less-polluting power generation technologies.

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4. Policy action to curb cooling-related energy

Rigorous action by governments will be critical to curb the potentially huge growth in demand for cooling in order to achieve the kind of outcomes described in the Efficient Cooling Scenario. Left to their own devices, it is unlikely that manufacturers will produce the most energy-efficient cooling equipment. Nor will builders and architects put up the most thermally efficient structures designed to minimise cooling requirements. It is the responsibility of the public authorities at national, regional and local levels to enable and encourage investments and mandate improvements in the energy performance of buildings and cooling equipment that are needed to bring about a lasting reduction in the demand for cooling (and the need for energy to meet that demand). And such policy action works: efficiency standards for air conditioning systems (ACs) and building codes that reduce cooling (and heating) needs, have been in place for many years in many countries and have delivered large and cost-effective energy savings. Strengthening and broadening the use of such measures hold the key to meeting the world's space-cooling needs in a truly sustainable fashion.

The need for a holistic approach to cooling policy

In broad terms, the ultimate goal of cooling policies is clear: meet the legitimate needs of consumers for thermal comfort while using the smallest amount of energy and keeping emissions and costs to a minimum. But translating this goal into specific targets or outcomes – and developing a coherent policy for achieving them in the context of broader energy and environmental policies – requires a holistic approach.

A cooling policy strategy needs to account for national circumstances – the current state of the market, the outlook for cooling demand and energy use, economic drivers, social and cultural considerations, and national traditions surrounding policy making. Effective policies often start by involving stakeholders through public consultations on the development of a long-term vision and strategy aimed at achieving stated policy goals. For example, within the Kigali Cooling Efficiency Program (K-CEP), 27 countries are developing holistic approaches with cooling plans that will examine and document methods and ambitions to make cooling more efficient and sustainable.

The basic formula for an effective policy suite to drive energy efficiency improvements includes a combination of regulation, information and incentives. The principal regulations include minimum energy performance standards (MEPS) and building energy codes; incentives include taxes and subsidies; information measures include equipment energy labels and capacity-building programmes. But national governments also need to support energy efficiency policies at the local level, where investment decisions are taken and implemented. An effective policy suite should include local policies for land-use planning and enforcing building energy codes, as well as targeted financial incentives for buildings, equipment and pilot and demonstration projects (IEA, 2016; IEA, 2017d; U4E 2017).

Integrating cooling into policies on sustainable buildings

Cooling is just one aspect of energy use in buildings that needs to be addressed in integrated energy policy planning to achieve sustainable, low-carbon energy use in buildings. This process includes considering buildings within the broader context of local and regional energy communities, where cost-effective, low-carbon synergies often depend on attaining a scale and density of supply and demand.

The adoption and proper enforcement of mandatory building energy codes and MEPS for equipment and appliances must be at the heart of policies aimed specifically at energy use in buildings. Standards need to be expanded and strengthened as quickly as possible across all countries, drawing on extensive international experience and knowledge. Policies should account for capacity building, including appropriate training for skilled labour in the buildings sector to design, sell, install and operate more efficient cooling equipment. Capacity building within governments and public bodies is also important. Policies need to take into consideration the opportunities that are arising from the emergence of digital technologies that can make cooling and other buildings-related energy services more sustainable (Box 4.1).

Box 4.1 • Policies to encourage digitalization of cooling and other building technologies

Advances in digital technologies are resulting in improvements in the quality of cooling services and opportunities for conserving energy and using energy more efficiently. For instance, the roll-out of smart thermostats can reduce energy consumption by automatically adjusting temperature settings according to the precise needs of occupants and in response to real-time price signals. However, there are obstacles to realising the benefits of widespread digitalization in buildings, including data security, privacy and technical and economic considerations. There may be a case for electricity utilities to offer financial incentives and introduce innovative tariff structures to encourage building owners and occupants to adopt digital technologies, given the potential cost savings to utilities from optimised energy use in buildings. Greater effort is also needed to communicate the benefits of digitalization to end users in the form of improved comfort and cost savings.

Standards for connected devices will be crucial to the prospects for digitalizing buildings. Policy makers and companies need to ensure that devices are able to provide and receive information using open source or compatible software to allow for interoperability across technologies. Common technical standards for connected devices will help ensure their interoperability (e.g. with other devices, with building management systems and with the grid). Standards could also help ensure user-friendliness.

New business models for energy services could also help overcome barriers to digitalization in buildings. Traditionally, building owners, operators and occupants purchase appliances and equipment such as ACs to provide a specific energy service, such as space cooling. In the digital future, as energy systems in buildings become more complex, new business models that provide a set of energy services rather than an amount of energy are becoming more viable. The emergence of energy service companies (ESCOs) or similar business models creates opportunities for the provision of comprehensive energy packages, such as smart controls combined with heat pump technologies and appropriate building renovation measures, aimed at delivering thermal comfort and saving energy. Supportive policy frameworks, such as bulk procurement of energy-efficient technologies and white certificates* can help in this regard by driving down the cost of products and ensuring those technologies actually produce the targeted energy savings.

* A tradeable instrument issued by an authorised body guaranteeing that a specified amount of energy saving has been achieved.

Source: IEA (2017a), *Digitalization and Energy*, www.iea.org/publications/freepublications/publication/DigitalizationandEnergy3.pdf; www.iea-ebc.org/.

Policy should also give attention to financing – a crucial element in consumer decision making regarding purchases of new cooling equipment or renovating a building, especially if more efficient equipment or building materials are more expensive.

Policy support for local energy communities

Policy makers also need to consider what measures might be introduced to promote the development of efficient local energy communities – neighbourhoods that take collective action to reduce, purchase, manage and generate energy. For example, renovations to energy systems across entire building blocks can help lower the cost of both energy efficiency measures and sustainable energy supply by creating sufficient economies of scale (IEA, 2016).

Economies of scale can also be applied across building energy communities to take advantage of changing energy flows through better management and optimisation of energy loads in buildings. Additional work is needed to address policy and market barriers that typically treat buildings, district energy and power generation separately (IEA, 2014). Energy policies and programmes can support this process through multiple measures, including:

- Rewarding flexibility, energy efficiency and low-carbon technology solutions within energy policy frameworks.
- Supporting the development of smart business models that increase opportunities to improve energy performance and reduce carbon footprints across energy communities.
- Continuing research to bring forward cost-effective, integrated and smart district cooling solutions.
- Sharing experience and best practices that enable efficient systems and businesses in an increasingly complex energy system.

Policy measures focused on cooling

Policy in all countries should focus on two main areas, whatever the overall approach to buildings and space-cooling policy: the energy efficiency of the new cooling equipment that is offered for sale; and the thermal performance of the buildings that need to be cooled. Demand-side management, which hinges on an appropriate policy and regulatory framework, is another measure that can help. In the longer term, policy could also play a role in encouraging the development of new technologies that promise to supply cooling services in a more sustainable way, including solar cooling and integrated solar photovoltaic (PV) and cooling storage systems.

Boosting the energy efficiency of cooling equipment

The main policy measures aimed directly at raising the energy efficiency of ACs and other cooling equipment are labelling programmes and MEPS. This is the essence of the Efficient Cooling Scenario presented in this report. Governments everywhere need to expand, extend and strengthen these policies in a progressive manner. Governments should complement these with a package of other measures that accelerate the transformation of the AC market towards high-efficiency products, including targeted programmes and research, development, demonstration and deployment.

Labelling of ACs has proven its worth

Promoting energy-efficient products through voluntary or mandatory labelling is the most widely used and longest-running policy measure in the buildings sector. Labelling programmes are the primary mechanism to educate the public when they make purchasing decisions. In addition to energy performance, labels for ACs may indicate the amount of cooling the unit can produce, the associated power input required and details of the physical equipment, such as whether the system includes an inverter compressor or variable-speed fans. As product performance continues to improve, labelling programmes should be designed with a mechanism that allows for re-scaling to enable consumers to identify the more efficient products (IEA, 2013b).

There are numerous examples of successful labelling programmes, including ENERGY STAR in the United States, Top Runner in Japan (which combines voluntary labelling with mandatory standards), and energy labelling in the European Union. These and most other labelling programmes in operation cover ACs, along with other appliances, equipment and buildings.

MEPS need to be continually strengthened

MEPS have proved themselves the single most effective policy measure for boosting the efficiency of new appliances and equipment, including ACs. Most of the leading energy-consuming countries have already introduced MEPS for ACs. Globally, there is considerable scope for tightening MEPS without increasing the cost to end users (see Chapter 2).

MEPS contain performance requirements for an energy-using device, which effectively limits the maximum amount of energy that may be consumed by a product in performing a specified task. In setting and applying MEPS, policy makers need to take into consideration the actual energy efficiency of ACs on the market and use accurate energy performance measurement standards, protocols and testing procedures. In some countries, current standards are set too low to have any major impact on the market. In others, MEPS cover only a small proportion of the products available on the market. MEPS that specify internationally co-ordinated testing procedures and requirements for verifying that models comply can reduce industry compliance costs and improve the quality of products, as well as ultimately lower the cost of products for consumers.

Two important lessons can be learned from successful MEPS programmes: market scale; and the benefits of complementary policies. In the case of ACs, market scale already exists: as many as 2.4 billion ACs could be sold in the coming decade as new demand comes online and older equipment is replaced. Wider policies, including labelling, market incentives and other regulatory measures, and government-funded research, can all enhance the effectiveness of MEPS. And the fruit is ripe for picking: with the 197 parties to the Montreal Protocol agreeing to the Kigali Amendment in 2016, there is considerable room for international co-operation, across governments, industry and working with partners – notably under the K-CEP launched in 2017 and the Mission Innovation Challenge on Affordable Heating and Cooling.[1]

In addition, the Clean Energy Ministerial, with the support of the governments of the United States, India, the People's Republic of China (hereafter, "China", Canada, and Saudi Arabia, launched in 2016 an Advanced Cooling Challenge, which aims to encourage the development and deployment of super-efficient, smart, climate-friendly and affordable cooling technologies; the goal is to improve average AC efficiency by 30% by 2030.[2]

Improving the energy performance of buildings

The way buildings are designed, built and operated can have a huge impact on the need for heating and cooling, and the need for energy to provide those services. Once a building is erected, the amount of active cooling needed to provide a given level of thermal comfort is effectively locked in. This makes it all the more important that the thermal performance of a building, including opportunities for passive cooling, is taken fully into consideration when it is being designed, built or renovated.

Building energy codes work – if they are well-thought-out and enforced

The main purpose of building codes is to protect public health, safety and general welfare. Increasingly, codes also incorporate standards for building materials, systems and construction practices to ensure that the energy used in the building for heating, cooling, ventilation and lighting is kept to a minimum. Ideally, building codes set out the standards that must be

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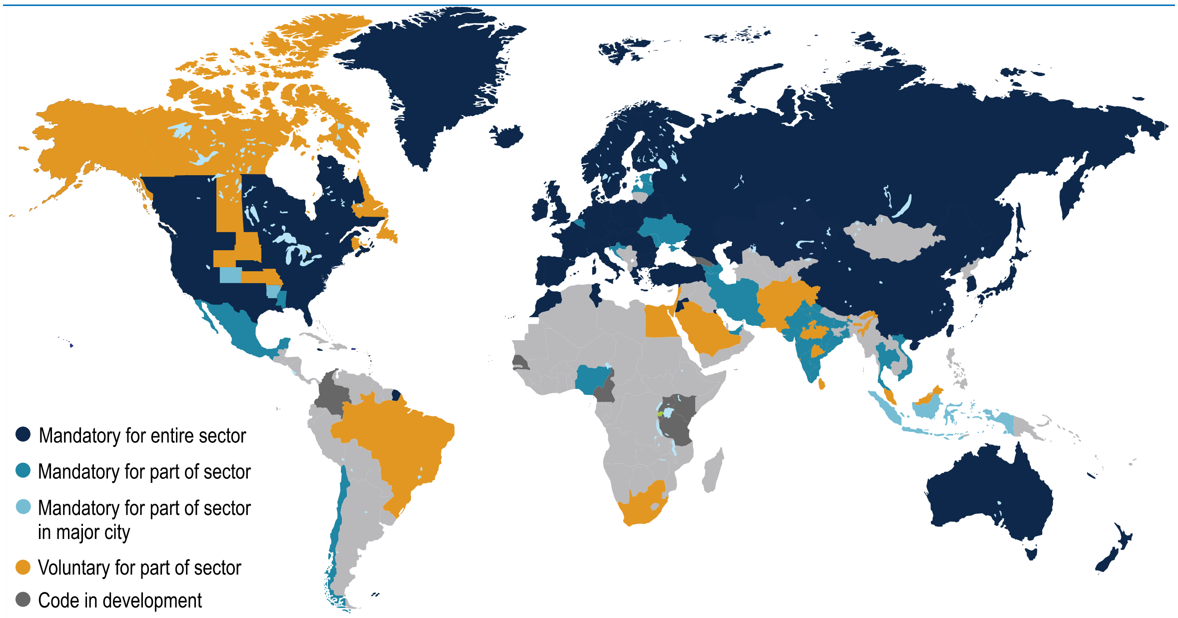
[1] http://mission-innovation.net/.

[2] www.iea.org/cem/AC-Challenge/.

conformed to in order to obtain planning permission and, in some cases, to obtain occupancy permission. In practice in many regions such codes are either voluntary or are not well enforced.

Building energy codes work – at least if they are well-thought-out and properly enforced. This is perhaps easier said than done, especially in less-developed countries that struggle to enforce law and order generally. But building energy codes have been widely pursued by many countries (Map 4.1) and continue to hold enormous potential for reducing energy consumption in buildings, notably for air conditioning in most developing countries, where space cooling demand will grow rapidly in the coming decades. Several countries are working on revising their building energy codes to make energy efficiency provisions more stringent, while other countries are planning to introduce their first building energy codes. Yet, broadly speaking, there is a growing urgency to address building envelope energy performance and its subsequent impact on cooling demand: of the 130 billion square metre (m^2) of new buildings construction anticipated over the next 20 years, two-thirds are expected to occur in countries that do not currently have mandatory building energy codes in place (IEA, 2017b).

Map 4.1 • Map of building energy codes by country, state and province, 2017



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Key message • Most hot countries with growing cooling demand do not have mandatory building energy codes for all buildings.

Building energy codes are the most effective policy instrument to influence energy use in new buildings and for major retrofits. For each type of building, energy codes can take multiple forms – most commonly as either prescriptive- or performance-based. Increasingly, the traditionally rigid prescriptive-based codes are becoming more flexible with the inclusion of trade-offs that enable designers to select more cost-effective materials and systems. Policy makers are also developing a new generation of performance-based codes that are "outcome-based", which essentially require minimum energy performance in the actual operation of the building – often delivered through energy performance certificates of buildings (IEA, 2010).

Climatic considerations are important when establishing building codes, especially for space cooling. The suitability and importance of particular specifications and technology choices are highly dependent upon the climate. For example, standards for windows, such as low solar heat gain and shading, roof reflectivity, insulation and sealing are extremely important to limit the need for air conditioning in hot and humid countries. Detailed analyses must be carried out when formulating the requirements of the building energy codes (IEA, 2013b).

Enforcement is critical to the effectiveness of building energy codes. In reality, the energy elements of codes are rarely respected fully and, in some cases, are all but ignored if the code is not enforced. Simplification is one way of making it easier (though not necessarily less costly) for architects and builders to comply, and several countries have made efforts along these lines.

Significant progress has been made recently in developing and strengthening building energy codes in a number of countries. Mexico took two major steps recently, including publishing the first national building energy conservation code and launching a building energy code roadmap that provides national targets in three-year increments to 2050. California is leading the way in the United States, with the latest 2016 Building Energy Efficiency Standards estimated to exceed the energy savings of the 2015 International Energy Conservation Code (CEC, 2017). In June 2017, India released a much-anticipated update to the Energy Conservation Building Code, a national model code that can be adopted and enforced by state and local governments to improve the efficiency of non-residential buildings (BEE, 2017).

Demand-side management policies to enable further operational energy savings

Many countries continue to have considerable potential to implement comprehensive Demand-side management (DSM) programmes that can, among other things, help curb the impact of cooling on electricity load, especially at peak. Where the electricity sector is being opened up to wholesale and retail competition, the regulatory framework can be reformed to ensure that DSM, as a market-based offer, is adequately compensated so as to provide an incentive for proposing demand-side and supply-side solutions to meet an impending shortfall in capacity. In particular, a combination of market liberalisation and technological advances provide increasing opportunities for regulators to introduce demand-side bidding mechanisms, which allow end users to participate in market trading, including offers to reduce cooling loads.

Public programmes for efficiency improvements to buildings

Public programmes can also drive efficiency improvements in buildings. For example, in the United States local and state jurisdictions administer a national weatherisation assistance programme funded by the federal Department of Energy that subsidises the cost of improvements to building envelopes for low-income households; the programme has upgraded seven million low-income homes since the programme started in 1976.[3] Reducing the need for space cooling is often a central component of weatherisation. Several other countries provide grants or tax credits for home improvements that lower energy needs for ventilation and cooling.

There is growing interest in programmes to encourage construction to be “net zero”, including zero-energy buildings, zero-carbon buildings, passive architecture or in some cases nearly zero-energy buildings. The core objective of these programmes is to reduce significantly the energy consumption inside the building by implementing advanced technologies, including those related to the building envelope, with any remaining energy needs met by on-site renewable energy production, such as from solar PV and small wind systems, or by distributed energy systems using low-carbon waste heat or cooling. Net-zero buildings are technically viable, but they can cost a lot more than traditional buildings depending on the cost of the efficient technologies. Upgrading existing homes or commercial buildings to meet net-zero criteria is often very costly due to the inefficiencies inherent in existing buildings. Strong policy support is needed to ensure that energy

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[3] https://energy.gov/eere/wipo/weatherization-assistance-program.

prices reflect the true costs of energy, and public subsidies that reflect the multiple benefits of energy efficiency can stimulate investment in such buildings.

Improving cooling technology through research and development

Strong public support for cooling-related research will be needed to ensure the rapid development and deployment of increasingly energy-efficient AC equipment, as well as efficient building solutions. Private-sector activity in this area is low: the majority of equipment and building material manufacturers have a very low research-to-investment ratio (the share of investment spent on research) compared with other sectors of the economy, mainly due to the commodity-based nature of building materials and products, the time it takes to change to new technology and relatively low profit margins (IEA, 2013b). Public research related to cooling needs to aim to develop higher-performance technology solutions for meeting space-cooling needs, such as: higher performance of heat pumps and air-conditioning systems; lower costs for high-performance building envelope components; reduced costs of solar thermal cooling technology; and boosted development of solar PV coupled to ACs (IEA, 2017b):

The potential economic and environmental benefits of technological advances in cooling justify a substantial increase in research spending by countries. Many countries contribute to such efforts specifically related to cooling technology through the International Energy Agency (IEA) Technology Collaboration Programmes (TCPs) for District Heating and Cooling, Heat Pumping Technologies, Solar Heating and Cooling and for Energy Efficient End-Use Equipment (Box 4.2):

Box 4.2 • IEA Technology Collaboration Programmes with research projects on cooling

The **IEA Technology Collaboration Programme for District Heating and Cooling (DHC TCP)** including Combined Heat and Power is a co-operative platform that aims to advance innovation in, and improve the economics of, district energy solutions and technologies. Much of the programme's work has focused on achieving an optimal match between energy supply and demand, including by developing a roadmap on district energy system optimisation to integrate renewable energy and excess heat. The TCP is interested in expanding on research for district cooling technologies and solutions.

The **IEA TCP for Energy-Efficient End-use Equipment (4E TCP)** seeks to share information and transfer experience in order to support good policy development in the field of energy-efficient appliances and equipment, including ACs. It also initiates projects and studies designed to meet the data needs of participants, enabling better-informed policy making.

The **IEA Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)** aims to advance research on heat pumps through the creation of research opportunities, networking possibilities and meeting places for academia, industry, private-sector markets and policy makers to collaborate. The strategy of the TCP includes research, development and demonstration activities on heating, cooling and refrigeration for buildings, transport and industry. In a recent update of the strategy, the scope was widened to include more efficient air conditioning, especially in warm and humid climates.

The **IEA Technology Collaboration Programme on Solar Heating and Cooling (SHC TCP)** is working to enhance collective knowledge and application of solar heating and cooling through international collaboration. The TCP aims to promote the use of all aspects of solar thermal energy and increase the global market share of related technologies by engaging in research and development of components, materials and design as well as raising political and public awareness. One on-going project (Task) is working to assist a strong and sustainable market development of solar PV or other new innovative thermal cooling systems.

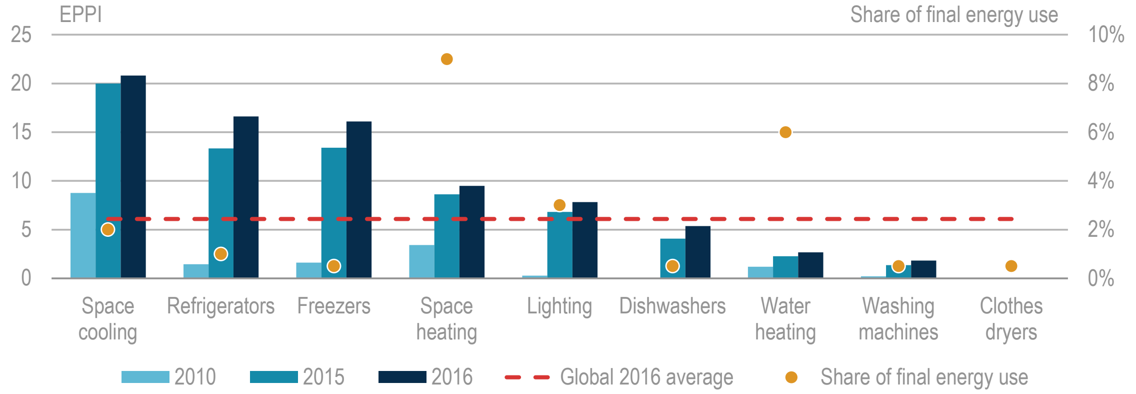
Sources: www.iea-dhc.org; www.iea-4e.org; www.heatpumpingtechnologies.org; www.iea-shc.org.

Measuring progress in cooling efficiency policies

Recent years have seen some significant progress in AC standards and building codes, though far more remains to be done. The IEA tracks the progress of policy in cooling and six other end uses using an Efficiency Policy Progress Index (EPPI) that measures the combined effect of the strengthening of codes and standards across the world's leading energy-consuming countries (Box 4.3). For many end uses, progress was made between 2010 and 2016. Space cooling made the most progress of all end uses between 2010 and 2016 (Figure 4.1).

Policies requiring new buildings to keep out heat, by improving the building envelope, are now substantially more stringent, as are new AC standards. Standards for space cooling in the United States carry particular weight, given its market size today. In some countries, such as Denmark and Germany, building envelope policy has been the key driver for policy progress, while in other countries, such as Japan and Korea, heating, ventilation and air conditioning (HVAC) equipment has been a key driver. This progress establishes the precedent for stronger policy action and forms the foundations on which such action could build.

Figure 4.1 • EPPI and share of global energy use by end use



Source: IEA (2017c), *Energy Efficiency 2017*.

Key message • Considerable policy progress has been made in recent years in pushing more energy-efficient air conditioning, but enormous scope remains to tighten policy.

Box 4.3 • The IEA EPPI

The IEA Efficiency Policy Progress Index (EPPI), introduced for the first time in the 2016 edition of the *Energy Efficiency Market Report*, combines coverage and strength of energy performance codes and standards into a single index for measuring overall policy progress. Space cooling is one of seven end uses covered. The countries included in the EPPI account for two-thirds of global energy use. The index tracks country-specific and global efficiency policy progress since 2000.

To calculate an EPPI score at country level for each end use, the increase in the strength of codes and standards enacted or updated since 2000 is multiplied by policy coverage. Since codes and standards apply to specific products and building types, and not to all the energy used by a country, the individual end-use scores are then weighted by total country energy use to produce a country-level EPPI score. If a country has an EPPI score of 1, broadly this means codes and standards implemented since 2000 are designed to improve the minimum energy efficiency performance of the entire country by 1% relative to 2000. The global EPPI score is the sum of the country-level EPPI scores weighted by country total energy use. A global EPPI score of 1 means that the codes and standards implemented since 2000 are designed to improve global energy efficiency by 1%.

Source: IEA (2017c), *Energy Efficiency 2017*, www.iea.org/publications/freepublications/publication/Energy_Efficiency_2017.pdf.

Recommendations

Governments of countries with large or potentially large cooling demand need to take urgent action to rein in the growth in energy use for that purpose and limit the potentially large economic and environmental costs that would ensue. Well-defined policy actions can deliver significant energy savings and emissions reduction by stimulating the widespread deployment of energy-efficient ACs, including the appliances and systems themselves, and, in the longer term, more efficient buildings technologies that limit the need for mechanical air conditioning.

Achieving the energy and carbon dioxide (CO_2) emissions reductions envisioned in the Efficient Cooling Scenario will require strong, consistent, stable and balanced policy support. The investments required to put the world onto a sustainable cooling path will need to be made primarily by private actors, but the role of government in setting out the policy and regulatory framework to make those investments happen will be critical. The following actions should be considered by governments wishing to firmly address growth in cooling energy demand in an equitable, cost-effective and sustainable manner:

Develop and implement a comprehensive national policy on cooling

- Introduce a stable, long-term policy framework incorporating regulations, information programmes and incentives to reduce both cooling-related energy consumption and refrigerant emissions.
- Involve stakeholders from government, industry and consumer groups in the development of such a framework.
- Ensure that the framework takes account of the multiple benefits of energy efficiency, lifecycle energy use and carbon emissions.

Develop and enhance regulatory measures

- Introduce or strengthen MEPS for air-conditioning equipment.
- Introduce or strengthen building energy codes for new buildings construction.
- Introduce or strengthen codes and standards for existing buildings, including requirements for maintenance and operation that improve demand-side management.
- Modify existing regulatory, fiscal or local planning policies that inhibit the uptake of energy-efficient and renewable energy solutions for buildings.
- Ensure regulations are enforceable and enforcement mechanisms are properly funded.

Improve information availability, quality and impact on consumers

- Introduce or strengthen air-conditioning equipment and buildings labelling policies and make them mandatory.
- Support information and capacity-building efforts that encourage consumers to opt for energy-efficient products and services.
- Support information and capacity-building efforts on issues such as AC maintenance, behaviour and building management that can enhance the efficiency of equipment use.

Improve information availability, quality and impact on professional decision makers

- Harmonise international test procedures, labelling and reporting requirements to make transparent comparisons between cooling technologies possible.
- Support information and capacity-building efforts in educating architects, engineers and cooling-system installers.
- Improve data collection and statistics on energy efficiency indicators.

Bolster incentives and funding for energy efficiency

- Develop financial incentives for energy efficiency, including financial backing for banks, ESCOs and other organisations that supply or finance the purchase of efficient materials, cooling technologies in efficient buildings and district-cooling systems.
- Develop non-financial incentives for energy efficiency, including the use of innovative mechanisms for bulk purchase to increase the market availability of efficient best available technology in the market.

Bolster international collaboration on cooling-related research

- Step up funding for cooling research, focusing on emerging technologies that have the potential to lower drastically emissions from cooling in the long term.
- Promote collaboration between utilities, industry, government and university researchers on cooling research to help to use scarce financial resources effectively and accelerate learning through shared experiences while avoiding the need to "reinvent the wheel".
- Support international collaboration in cooling research and the transfer of technical knowledge between countries and regions, including through the IEA Technology Collaboration Programmes.

Priority must be given to MEPS and labelling for ACs. These measures hold the potential to make the biggest dent in rising cooling demand in the coming decades, given the significant difference between minimum and best available technologies globally. With respect to building envelopes, improving adoption and enforcement of mandatory policies for low-energy building construction is a necessary first step for all countries, and improved capacity building (including education and training) is needed in many countries to ensure that efficiency standards and building energy code compliance is standard practice. Renovations of existing buildings are also needed in countries where the bulk of buildings that will be in use in 2050 are already standing today. A global "race to the moon" approach is needed to bring deep energy renovation and "net-zero" buildings from small-scale demonstration to mass-market penetration. Taken together, a well-designed and properly implemented set of policies can redirect every country from a path of unsustainable and unmanageable cooling energy demand growth, to a sustainable and affordable alternative.

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Acronyms, abbreviations and units of measure

Acronyms and abbreviations

AC	air conditioner or air-conditioning system
BREEAM	Building Research Establishment Environmental Assessment Methodology
BS	Baseline Scenario
CAAGR	compound average annual growth rates
CDD	cooling degree days
CFC	chlorofluorocarbons
CO_2	carbon dioxide
COP	coefficient of performance
DHC	district heating and cooling
DSM	demand-side management
ECS	Efficient Cooling Scenario
EER	energy efficiency ratio or rating
EPPI	Efficiency Policy Progress Index
ESCO	energy service company
ETP	IEA *Energy Technology Perspectives*
GDP	gross domestic product
GHG	greenhouse gas
HCFC	hydrochlorofluorocarbons
HFC	hydrofluorocarbon
HVAC	heating, ventilation and air conditioning
IEA	International Energy Agency
ISEER	India seasonal energy efficiency ratio
K-CEP	Kigali Cooling Efficiency Program
MEPS	minimum energy performance standards
NDCs	nationally determined contributions
NO_x	nitrogen oxides
$PM_{2.5}$	fine particulate matter
PPP	purchasing power parity
PV	photovoltaic
SEER	seasonal energy efficiency ratio
SO_2	sulphur dioxide
TCP	IEA Technology Collaboration Programme
USD	United States dollar
WEO	*World Energy Outlook*

Units of measure

°C	degree Celsius
°F	degree Fahrenheit
g	gramme
GW	gigawatt
GWh	gigawatt hour
gCO_2/kWh	gramme of carbon dioxide per kilowatt hour
km	kilometre
kWh	kilowatt hour

m^2	square metre
Mt	million tonnes
MW	megawatt
TWh	terawatt hour
W	watt

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