Annual Review of Environment and Resources

Greenhouse Gas Emissions from Air Conditioning and Refrigeration Service Expansion in Developing Countries

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Annu. Rev. Environ. Resour. 2021. 46:59–83

First published as a Review in Advance on June 3, 2021

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-012220-034103

Keywords

cooling services, Sustainable Development Goals, emerging technology, climate policy, space cooling, cold chain, developing countries, sustainability, clean technology

Abstract

Air conditioning and refrigeration services are increasing rapidly in developing countries due to improved living standards. The cooling services industry is currently responsible for over 10% of global greenhouse gas (GHG) emissions, so it is critical to investigate how the expansion of cooling services will impact future GHG emissions. In this article, we first examine the current status and expected expansion of cooling services worldwide and the associated GHG emissions. Then, we review potential improvements and innovations that could reduce future GHG emissions. Three approaches to reduce GHG emissions within the cooling sector include converting to alternative refrigerants, improving energy efficiency, and moving toward a lower-carbon electricity grid. In addition, we identify eight interventions that apply to the built environment or the food supply chain that would lead to additional GHG reductions in the cooling sector.

Contents

1. INTRODUCTION

The demand for space cooling and product refrigeration is increasing, driven by a warming climate, economic growth, population growth, and urbanization (1, 2, 3). As global temperatures rise, it is estimated that there will be a 25% increase in cooling degree days throughout the world by 2050, with greater distribution in regions that already have warm climates and where income and population are increasing quickly (1, 4). Urbanization is increasing across the globe but is especially prominent in developing countries such as China, India, and Nigeria. Increased temperatures and the resultant demand for space cooling are more pronounced in cities due to the urban heat island effect (5, 6). In addition to increased demand for space cooling, the capacity of facilities and equipment to refrigerate perishable products has increased in the past decade and will continue to increase in the future with the most significant growth expected in developing countries (7, 8).

Despite recent growth in the sector, much of the world still lacks basic cooling technology in the form of space cooling and refrigeration. For example, in 2016 the household ownership rate of air conditioners in India and Indonesia was less than 10% compared with 90% ownership in the United States (9). As the world gets warmer and nations become wealthier, demand for cooling services is expected to rapidly increase. Access to cooling services affects the health and well-being of the global population, in terms of accessibility of health services (i.e., medicines and vaccines), food preservation and security, the ability of individuals to cope with the risks of increasing temperatures, and the functioning of modern society (e.g., maintaining operation of information technology). Although cooling services provide numerous societal benefits, the sector is also responsible for significant environmental impacts. In addition to consuming large amounts of energy, cooling services have historically used refrigerants with global warming potentials (GWPs) that are many orders of magnitude greater than carbon dioxide. Despite the significant contributions to greenhouse gas (GHG) emissions, cooling services often do not receive much attention from the environmental community, possibly due to the distribution of cooling services across the building, transportation, and food sectors. A more specific and holistic focus on cooling services may lead to more effective interventions than exploring cooling service contributions in isolation for each of the major sectors.

Although beyond the scope of this article, we note that there are numerous equity considerations associated with cooling services. The United Nations Sustainable Development Goals (SDGs) aim to provide a framework to reduce the environmental burdens of society while enhancing peace and prosperity of people. SDG 7, Affordable and Clean Energy, aims to "ensure access to affordable, reliable, sustainable, and modern energy for all" (3, 10). Specifically, SDG Target 7.2 focuses on increasing international cooperation in support of clean energy research, renewable energy production, and investment in energy infrastructure in developing countries that can aid in the environmentally responsible expansion of cooling in developing countries (10, 11). For instance, in 2016, China and India received international investment to support clean energy research from the Organisation for Economic Co-operation and Development and the International Renewable Energy Agency totaling 1.1 billion and 2.05 billion US dollars, respectively (12).

This article synthesizes knowledge associated with (*a*) the current status and expected expansion of space cooling and refrigeration services; (*b*) a review of the environmental impacts of cooling services, with an emphasis on GHG emissions; (*c*) direct mechanisms to reduce the impacts of cooling services; and (*d*) potential future technological and nontechnical innovations that can provide access to cooling services while minimizing environmental impact.

The International Institute of Refrigeration (IIR) lists multiple subsectors for cooling and refrigeration services, including domestic refrigeration, commercial refrigeration, refrigerated transport, air conditioning, and mobile air conditioning (MAC), as listed in **Figure 1** (13). This article uses the term cooling services sector to refer to the two main categories in **Figure 1**: (*a*) space cooling and (*b*) products refrigeration. Cooling for large-scale machinery and industry

Global warming potential (GWP): a measure of the greenhouse effect; expressed in carbon dioxide equivalent (CO_2eq)

Greenhouse gas (GHG): gases that trap heat in Earth's atmosphere that absorb and emit radiant energy causing the greenhouse effect

Sustainable Development Goals (SDGs): 17 goals created by the United Nations to address global environmental, economic, and social issues

Mobile air conditioning (MAC): air conditioning systems installed in vehicles

	Categories	Subcategories
Cooling refrigeration services	Space cooling	Room air conditioning
		Mobile air conditioning
		Other space cooling (e.g., data center)
	Products refrigeration	Commercial refrigeration
		Household refrigeration
		Refrigerated warehouse
		Refrigerated transportation

Figure 1

The applications of cooling and refrigeration services considered in this article (see also 13). The cooling and refrigeration services are divided into two categories: space cooling and products refrigeration. In the space cooling category, room air conditioning, mobile air conditioning, and other space cooling (e.g., data center) are considered. In the products refrigeration category, commercial refrigeration, household refrigeration, refrigerated warehouse, and refrigerated transportation are considered.

units (e.g., boilers, turbines) are not included in this review due to the unique properties and specifically designed technology for those applications. Regarding terminology, the acronym RAC has been used in the literature to refer to room air conditioning, residential air conditioning, and the entire sector of refrigeration and air conditioning. To minimize confusion and improve clarity, we refrain from using the RAC acronym.

Heating, ventilation, and air conditioning (HVAC): systems that provide cooling and heating to residential and commercial buildings

2. CURRENT STATUS AND EXPECTED EXPANSION OF SPACE COOLING AND REFRIGERATION SERVICES

There are approximately 3 billion refrigeration, air conditioning, and heat pump units worldwide as of 2015, and the industry is projected to expand rapidly in the next 50 years, especially in developing countries (13). The cooling services sector is best measured in terms of degree-volume, which is the total volume of air that is cooled a given number of degrees. Unfortunately, it is difficult to estimate total cooling demand in terms of degree-volume due to data limitations. Nevertheless, there are several studies that have estimated the growth potential of the sector in terms of per-unit growth and projected energy demand.

The cooling services sector consumed approximately 17% of global electricity use in 2018, the equivalent of approximately 3,900 TWh/year of electricity, with the majority of this consumption occurring in the residential sector (5, 13). Space cooling consumed approximately 2,000 TWh/year (5), generating 1,135 metric megatons (Mt) of CO_2 in 2016 when considering both energy-related emissions and emissions from refrigerant leakage, triple the level from 1990 (1). In addition, projected electricity demand for space cooling is expected to triple from current levels by 2050 (5).

2.1. Expansion of Space Cooling Systems

Space cooling, also referred to as comfort cooling, reduces the ambient temperature of an environment and may also control humidity. Space cooling occurs in residential and commercial buildings, mobile vehicles, and data centers and encompasses traditional air conditioning units, heat pumps, and other heating, ventilation, and air conditioning (HVAC) technologies. The energy used to cool buildings has more than tripled between 1990 and 2016 and continues to grow faster than any other energy-consuming building service (2).

Room air conditioning represents a large portion of the space cooling sector and includes individual mini-split air conditioners or self-contained air conditioning window units designed to cool one room; it does not include central air conditioning systems intended to cool an entire residence (2, 5). Although centralized units tend to be more efficient, they are more costly and require retrofitting existing structures. Therefore, room air conditioning units are expected to see significant growth. The global demand for room air conditioner units is estimated to grow exponentially from 1.2 billion units installed in 2018 to 4.5 billion units installed by 2050 (2). Importantly, these estimates only take into account the expected market of customers who are willing and able to pay for cooling services. When including all those who need access to expanded space cooling services regardless of ability to pay, 14 billion space cooling appliances would be required to meet untapped demand by 2050 (6). Approximately 70% of projected growth in the space cooling sector will be in developing countries in the tropics and subtropics, with developing countries expected to see a fivefold increase in the number of room air conditioning units by 2050 (2, 6). For example, air conditioning sales in Brazil, India, and Indonesia have increased by 10–15% per year (2). In India, air conditioner ownership grew from 2 million total units in 2006 to 14 million total units in 2016, with an expected ownership of 200 million units by 2030 (6).

Space cooling in passenger transportation, or MAC, is another subsector expected to experience significant growth. MAC refers to all road vehicles including cars, vans, trucks, and buses. It does not include refrigerated freight cooling, which is categorized under refrigeration services. Without significant policy intervention, global energy use from MAC is expected to triple by 2050 (14, 15). Personal motor vehicles emit roughly 10% of global CO_2 emissions and the road transport sector (including both personal and commercial vehicles) emitted roughly 5.2 $GtCO_2eq$ in 2010 (16, 17). The installation rate of MAC in vehicles in developed countries is close to 100%, whereas it is closer to 60% of the vehicle fleet in developing countries, although 100% of new vehicles include MAC as part of standard equipment (15). MAC usage depends on many factors including climate, length of trip, season, and vehicle type. On average, MAC operates 43–49% of the time a vehicle is in use (107–121 of 249 h of use annually) (14, 15), although that estimate is expected to vary greatly according to local conditions.

In addition to residential and mobile applications, increased demand of space cooling services is needed to support the information communications technology (ICT) sector. Data centers require energy-intensive cooling operations to maintain equipment function (18). The ICT industry has grown rapidly over the past 20 years, along with the infrastructure needed to cool the equipment. Electronic equipment produces a great deal of heat while storing, processing, and retrieving data. Data facilities must be maintained within a specific temperature and humidity range to prevent equipment damage and loss of data (19). Cooling services comprise approximately 40% of the total energy consumed by data centers (18). Put another way, for every 1,000 kWh consumed by a data center, 600 kWh is consumed by electronic equipment while 400 kWh is consumed to provide a climate-controlled environment (18). Electricity consumption by data centers in the United States increased 35% between 2013 and 2020 with a projected increase to approximately 140 billion kWh annually by 2020 (19, 20). Even more rapid growth in this sector is occurring in developing countries, illustrated by a 255% increase in mobile cellular subscriptions and 235% increase in Internet users per 100 habitants between 2000 and 2010 (20).

2.2. Expansion of Refrigeration Systems

Refrigeration services to preserve perishable products are also increasing rapidly. Space cooling and refrigeration have many technical similarities, although refrigeration services generally require significantly lower temperatures for the preservation of goods. Cooling services that provide access to an appropriate climate-controlled environment continuously throughout a product's entire supply chain is referred to as a cold chain. Access to an unbroken cold chain is crucial for certain goods such as vaccines and meat products for both quality and safety considerations. The cold chain is also important to preserve the quality and shelf life of other perishable foods and temperature-sensitive goods to reduce wastage (21). From production to consumption, cold chain facilities include refrigerated warehouses, refrigerated vehicles, refrigerators used in retail operations, and refrigerators used within commercial food providers and households (8, 22, 23). Globally, the cold chain is a fast-growing industry valued at more than $160 billion in 2018 and is projected to have an approximately 16% compound annual growth rate until 2026 (24, 25).

Globally, refrigerated warehouse capacity was 616 million m^3 in 2018, unevenly distributed throughout the world (7). India, the United States, and China had the three largest refrigerated warehouse capacities with 150, 131, and 105 million m^3, respectively, in 2018, comprising nearly 63% of the world's capacity (7). Industrialized countries tend to have a much higher capacity per capita than developing countries, however. For instance, the refrigerated warehouse per capita in New Zealand, the United States, and the United Kingdom are 0.42, 0.40, and 0.36 m^3/person, respectively (7). In contrast, India, Brazil, and China have capacities of 0.11, 0.09, and

0.08 m^3/person (7). Between 2014 and 2018, Turkey and Mexico experienced explosive expansion in refrigerated warehouse capacity, increasing by 110% and 208% in those four years. In the same period, the capacity also increased by 14%, 18%, and 38% in India, Brazil, and China, respectively (7). Meanwhile, the capacity growth in most developed countries is less than 10%, with slight decreases in refrigerated warehouse capacity seen in Australia and the United Kingdom (7).

Chlorofluorocarbon (CFC): chemicals containing atoms of carbon, chlorine, and fluorine, used in the manufacture of aerosol sprays and as refrigerants

Hydrochlorofluorocarbon (HCFC): chemicals containing carbon, hydrogen, chlorine, and fluorine, used as a replacement for CFC

Hydrofluorocarbon (HFC): chemicals containing carbon, hydrogen, and fluorine, used as an alternative of CFC and HCFC

At the consumer end of the supply chain, which includes retail, restaurants, other commercial food providers, and households, there are approximately 90 million commercial refrigeration installations, including condensing units, stand-alone equipment, and centralized systems, and 1.5 billion household refrigerators operating in the world (26). The annual unit sales of household refrigerators worldwide increased steadily from 177.9 million in 2014 to 201.1 million in 2016, and are expected to increase to 235.5 million in 2025 (9). The ownership of a household refrigerator, a major appliance, is above 90% in developed countries (27). In some developing countries (e.g., China), the penetration of refrigerators is also approximately 90%; however, in other developing countries (e.g., India), less than 60% of households own a refrigerator (27, 28).

Additionally, refrigerated vehicles are responsible for connecting the upstream and downstream storage facilities. The market size for refrigerated trucks is anticipated to exceed $13 billion by 2027 (29). The emerging cold chain industry in developing countries is the major driver of the refrigerated transport market. For instance, the number of refrigerated vehicles in China increased by more than 20% per year from 2014 to 2018 (30). The Asia-Pacific accounts for the largest market share of refrigerated transportation in 2019, a trend that is expected to continue in the future (30).

3. ENVIRONMENTAL IMPACTS OF COOLING AND REFRIGERATION SERVICES

Space cooling and refrigeration equipment are responsible for numerous environmental impacts, particularly with respect to overall contribution to GHG emissions (31). GHG emissions occur due to refrigerant leakage as well as emissions associated with the generation of electricity to provide the cooling service. In addition, a variety of impacts can occur as a result of infrastructure changes induced by the cooling services. Examples might include changes in building design due to the presence of an HVAC system or changes in the modes and distances a food product travels when refrigeration is available (22). Researchers use inconsistent terminology regarding direct and indirect emissions in this regard, with some researchers referring to refrigerant loss as direct impacts and emissions associated with energy use as indirect impacts. Meanwhile, those in the life cycle assessment community consider both refrigerant loss and energy-associated emissions as direct impacts, whereas changes associated with cooling service adoption are considered indirect impacts.

3.1. Refrigerant Properties

Most cooling services use a refrigerant to remove heat from an environment via a variety of technical mechanisms (32). **Table 1** lists typical refrigerants and common current applications throughout the world. R12 and R22, the most common representatives of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), were widely used as refrigerants until they were discovered to be responsible for ozone depletion (33, 34). The Montreal Protocol (35) phased out the use of CFCs and HCFCs. According to the Montreal Protocol, all developed countries should phase out HCFCs by 2030 and all developing countries should phase out HCFCs by 2040 (36). As a substitute for CFCs and HCFCs, hydrofluorocarbons (HFCs) became popular. Although HFCs do not cause ozone depletion problems, many HFCs have significant GWP (see **Table 1**). Therefore, in

Table 1 List of typical refrigerants, properties regarding their environmental impacts, and notes on their current applications

Refrigerant	Properties[a]	Notes on the current application
R11 (CFC)	ODP = 1.0; GWP = 4,750	Phased out in 1996 due to severe ozone depletion effects
R12 (CFC)	ODP = 0.82; GWP = 10,900	Phased out in developed countries in 1996 and in developing countries in 2010 according to the Montreal Protocol due to its ozone depletion effects
R22 (HCFC)	ODP = 0.055; GWP = 1,800	One of the most popular refrigerants; used as an alternative to R11 and R12 due to lower ODP in the cooling and refrigeration sector; phased out according to the Montreal Protocol; production banned or cut significantly in most countries but still has widespread use in equipment that has not yet been retired
R123 (HCFC)	ODP = 0.012; GWP = 76	Used as an alternative to R11 in low-pressure HVAC systems; phased out according to the Montreal Protocol due to ozone depletion effects
R134a (HFC)	ODP = 0; GWP = 1,340	Widely used in commercial refrigeration systems globally and also on refrigerated vehicles in high- and medium-temperature conditions; being phased down according to the Kigali Amendment
R404a (HFC)	ODP = 0; GWP = 3,940	Widely used in industry and commercial refrigeration systems worldwide, as well as refrigerated vehicles in medium- and low-temperature conditions; being phased down according to the Kigali Amendment
R407C (HFC)	ODP = 0; GWP = 1,770	Used as a replacement to R22 in HVAC systems; being phased down according to the Kigali Amendment
R410a (HFC)	ODP = 0; GWP = 2,100	Widely used in building and vehicle HVAC systems as an alternative to R22; being phased down according to the Kigali Amendment
R600a (HC)	ODP = 0; GWP = 3	Mainly used in domestic refrigerators in Europe, Asia, the Middle East, and Africa
R717 (NH_3)	ODP = 0; GWP = 0	Used in industry refrigeration systems (e.g., refrigerated warehouses, process cooling)
R744 (CO_2)	ODP = 0; GWP = 1	Mainly used in industry and commercial refrigeration systems (e.g., supermarkets) in Northern Europe

Abbreviations: CFC, chlorofluorocarbon; GWP, global warming potential; HC, hydrocarbon; HFC, hydrofluorocarbon; HCFC, hydrochlorofluorocarbon; HVAC, heating, ventilation, and air conditioning; ODP, ozone depletion potential.
[a]Both ODP and GWP are approximate values, as different sources have slight differences in data (36, 38, 43–48).

2016, the Kigali Amendment to the Montreal Protocol (35) put in place targets to phase down high-GWP HFCs, with a goal of 80% reduction in the consumption of HFCs by 2047 (37).

Even though it is being phased out, R22 is still the most common refrigerant in all types of cooling and refrigeration services due to its presence in existing installed infrastructure. In 2015, R410a and R22 were the largest two refrigerants in HVAC systems by consumed volume (183 kton and 159 kton used globally), and R22, R404a, and R134a were the top three refrigerants in refrigeration systems worldwide by consumed volume (203 kton, 80 kton, and 31 kton used) (38). As alternatives to R22, R134a and R404a are commonly used in refrigeration equipment, and R407C and R410a are implemented in HVAC systems (38–40). Ammonia (R717) and carbon dioxide (R744) are natural refrigerants that possess low ozone depletion potential and GWP and are also used in industrial and commercial refrigeration systems (e.g., cold food storage, processing, supermarkets) (38, 41). In a 2015 study by the United Nations Environment Programme (UNEP), refrigeration, air conditioning and heat pumps (RACHP) represented 86% of the HFC use in GWP-weighted tonnes of CO_2eq—far and away the largest use of any single market (42). Of this HFC use, it is estimated that 65% of the global GWP-weighted HFC consumption is utilized for

Refrigeration, air conditioning and heat pumps (RACHP): acronym for heating and cooling sector air conditioning and that 35% is for refrigeration (42). Within the space cooling sector, a main use of HFCs is in the MAC sector, with MAC-related HFC emissions accounting for an estimated 170 Mt of CO_2eq in 2013, approximately one-third of GWP-weighted global HFC emissions (5).

3.2. Greenhouse Gas Emissions of Cooling and Refrigeration

When discussing the GHG emissions of the cooling and refrigeration services sector, one must differentiate between total GHG emissions, leakage-associated GHG emissions, and energy use–related GHG emissions. Total GHG emissions are the sum of leakage-associated and energy use–related GHG emissions. We discuss these three types of emissions in detail. The total GHG emissions associated with space cooling and refrigeration are approximately 4,400 Mt CO_2eq in 2020, corresponding to over 10% of global GHG emissions (1, 49, 50). Although individual projections vary due to data uncertainty and differing assumptions, GHG emissions associated with cooling services are expected to grow. **Figure 2*a*** shows the estimated global emissions of the refrigeration and air conditioning sector from 2020 to 2050, assuming business as usual (50). Emissions are expected to grow rapidly between 2020 and 2040, and the growth rate is slower after 2040. The majority of these increases are expected to occur in developing countries (51), and the behavior of the trend is the combined results of the growth within the refrigeration and cooling sector, the expected improvements in efficiency, and better compliance with phaseouts of high-GWP refrigerants.

With regards to relative contribution to total GHG emissions, **Figure 2*b*** shows the total GHG emissions from space cooling was more than 3,000 Mt CO_2eq and that the total GHG emissions from products refrigeration was approximately 1,250 Mt CO_2eq in 2020. In the space cooling sector, approximately 2,800 Mt CO_2eq total GHG emissions are from the unitary and mobile air conditioning systems, whereas in the product refrigeration sector, commercial refrigeration and household refrigeration contribute to nearly 1,000 Mt CO_2eq.

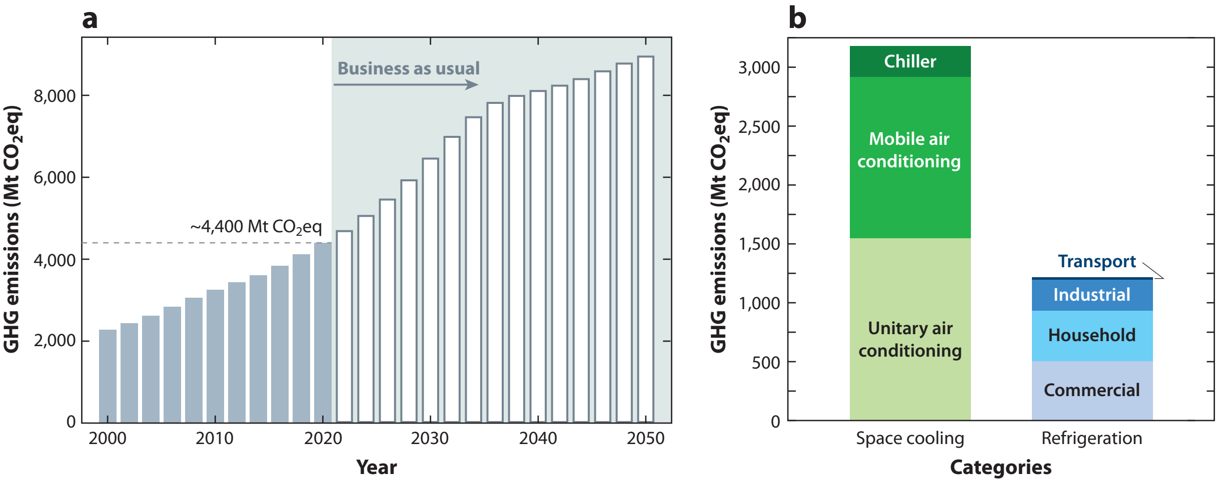

Figure 2

Greenhouse gas (GHG) emissions of the cooling and refrigeration industry (50). Emissions are measured in metric megatons of CO_2 equivalent (Mt CO_2eq). (*a*) Trend of GHG emissions and business as usual future forecast. GHG emissions of the cooling and refrigeration industry are expected to increase in the business as usual scenario. (*b*) 2020 cooling services sector GHG emissions breakdown into subcategories. GHG emissions from space cooling were more than double of that from refrigeration applications in 2020 with mobile and unitary air conditioning comprising the majority of emissions.

3.2.1. Leakage-related greenhouse gas emissions. Refrigerant leakage can occur during the normal operation of cooling equipment as well as when these units are assembled, are repaired, and at end-of-life during recycling or disposal. **Figure 3*a*** illustrates that refrigerant leakage is responsible for 29.7% of total global GHG emissions in the cooling services sector and more specifically refrigerant leakage comprises 30.7% of the total GHG emissions in the space cooling sector and 27.4% of the total GHG emissions in the refrigeration sector (50). In the realm of space cooling systems, GHGs are emitted when refrigerants leak or are improperly disposed (1). It is challenging to determine an exact leakage rate in the cooling service sector due to the variability in models and lack of data. However, one study conducted in 2007 in the United Kingdom found that the air conditioning sector experienced between 4 and 22% annual leakage (52). Data from the Green Cooling Initiative, reported in **Figure 3*a*,*b***, show the variability associated with refrigerant leakage for various applications.

MAC is responsible for a large portion of refrigerant leakage in space cooling; one study estimates that in 2015 total GHG emissions from MAC amounted to approximately 420 Mt CO_2eq, 30% of which were attributable to refrigerant leakage (15), whereas the Green Cooling Initiative estimates leakage for MAC to be 37%, as shown in **Figure 3*b***. These emissions from refrigerant leakage happen at different phases in the vehicle's life with the largest loss happening during the manufacturing process, in which an estimated 5kg of CO_2 equivalent per kg of R134a is emitted (15). During the use phase, different types of vehicles have different leakage rates, with smaller vehicles having an annual leakage rate of 30–83 g of refrigerant per year, trucks with an annual leakage rate of 60–100 g per year, and buses with the highest annual leakage rate of as much as 2.4 kg per year (15). The gap in available data between leakage rates in the mobile versus residential sector is apparent and worth noting (52).

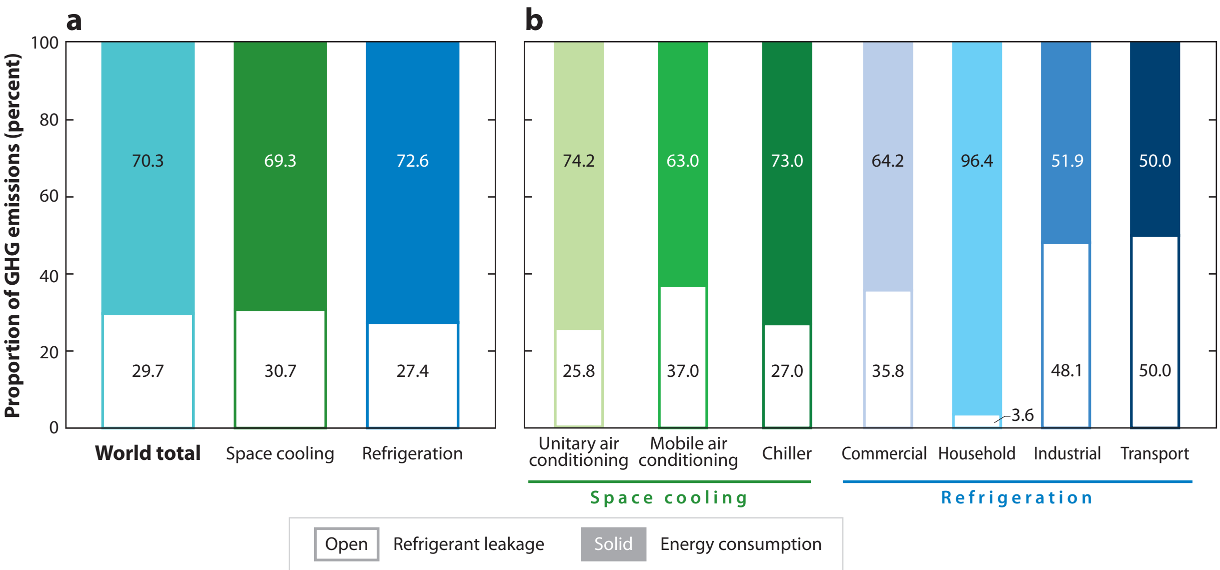

Figure 3

The percentage of greenhouse gas (GHG) emissions from refrigerant leakage and energy consumption (50). (*a*) World total emissions, space cooling emissions, and refrigeration emissions. GHG emissions from energy usage contribute approximately 70% in each group. (*b*) The emissions from subcategories of space cooling and refrigeration. Energy usage is also the main emission source in all space cooling applications, as well as commercial and household refrigeration, whereas refrigerant leakage accounts for a larger portion in industrial and transport refrigeration.

Regarding perishable products refrigeration, it has been found that the annual refrigerant leakage is approximately 8–10% in medium and large industrial and commercial refrigeration systems, approximately 8% in refrigerated transported vehicles, and less than 1% in domestic refrigerators (26), which are significantly lower than the values reported in **Figure 3*b*** and indicative of the large uncertainties associated with estimating leakage. Due to the highest overall GHG emission, significant leakage rate, and high-GWP refrigerant used, commercial refrigeration systems have the highest leakage emissions in the refrigeration sector (53). In fact, more than 20% of refrigerant leakage in the refrigeration sector is from commercial refrigeration (53–55).

3.2.2. Energy use–related greenhouse gas emissions. Current and future projections for energy use–related emissions associated with space cooling and refrigeration represent a significant environmental impact. According to the IIR, the cooling and refrigeration sector uses approximately 17% of global electricity (13). The International Energy Agency estimates that 10% of global electricity is consumed by air conditioners and cooling fans (1). Considering that 65% of world electricity is produced via fossil fuels, energy use–related GHG emissions comprise a majority of the total GHG emissions in the cooling services sector (49). The IIR estimates that the emissions due to energy consumption are responsible for approximately 80% of total GHG emissions in the cooling and refrigeration sector, whereas the Green Cooling Initiative estimates that energy-related emissions comprise approximately 70.3% of total emissions in the sector, as illustrated in **Figure 3*a*** (13). Within cooling and refrigeration services, 45%, 40%, and 15% of electricity consumption is attributable, respectively, to the residential, industrial, and service sectors (13). On average, 440 kWh per capita electricity is spent for cooling and refrigeration annually in the world; however, there are major disparities across the globe. In North America, cooling services are responsible for more than 2,500 kWh per capita compared with less than 100 kWh per capita in sub-Saharan Africa (13).

By some estimates, cooling services are projected to account for more than a 0.5°C increase in global temperature by 2100 (2). Almost 20% of all electricity used in buildings globally is used for space cooling (1). The energy use related to space cooling in buildings has more than tripled in the time between 1900 and 2016 and continues to grow at an exponential rate, with approximately 70% of this increase coming from room air conditioning, which is projected to continue with the increasing demand for space cooling in developing countries (2). In developing countries, energy-related emissions associated with space cooling are already high; in cities like Delhi and Beijing, half of electricity usage is dedicated to running air conditioners in the hottest season (6). Indeed, India, China, and Indonesia contribute to roughly half of the increase in projected global space cooling energy use from 2016 to 2050, with India expecting a 20-fold increase and Indonesia expecting a 15-fold increase in their energy demand from room air conditioning (2, 6). Without policies to improve the energy efficiency of room air conditioners and other cooling devices, or to slow the increase in space cooling demand, the projected growth in stationary air conditioning and refrigeration could result in energy-related emissions of 230–430 $GtCO_2$ between 2020 and 2050, not including MAC, which is projected to triple energy-related emissions by 2050 (6). These emissions are connected to not only increased use but also the varying efficiency of air conditioning units; it is estimated that globally (in all markets combined) the average efficiency of air conditioners being sold is less than half of the highest efficiency available in the market (1).

Additionally, space cooling can have an even greater environmental impact than other energy-intensive services due to the specific times of day it is most needed. Electricity grids must adapt to fluctuating power demands throughout the day, with the greatest demand generally occurring in the middle of the day, termed peak demand. In order to meet peak demand, electric utilities must deploy additional electricity generation units that are held on reserve during non-peak periods.

The mix of power sources during peak demand often has a greater GHG intensity than the electricity mix that occurs at times of day with reduced demand. Because the demand for space cooling generally occurs during these peak demand periods, space cooling can strain the electricity grid as well as increase the overall GHG intensity of the grid. Space cooling has a disproportionate impact on peak electricity loads. On average, space cooling was responsible for an estimated 14% of peak electricity demand in 2016 (1, 2). In some areas of the Middle East and the United States, space cooling can contribute to 50–80% of peak demand due to the warmer climate (5).

Within the space cooling sector, the increased need for data centers warrants specific attention due to its large energy requirements; some studies estimate that data centers use more than 100 times more energy per square meter than office spaces (19), with approximately 40% of that energy dedicated to cooling services (18). Over the past 6 years, energy use by data centers and supporting infrastructure in the United States is estimated to have doubled with 1.2% of total energy consumption attributed to server power in 2005 (18). This trend extends to developing countries as well, with an analysis in China illustrating that 1% of total electricity consumption in the country was attributed to data centers (18).

Electricity consumption and its related emissions are also significant in refrigerated warehouses. As a crucial part of the modern food system, the refrigerated warehouse constitutes roughly 20% of electricity consumption in the food industry (56). In a typical refrigerated warehouse, it is estimated that refrigeration accounts for approximately 60–70% of total electricity consumption, and a frozen cold warehouse consumes nearly 30% more electricity than a chilled cold warehouse per capacity unit (26). With the capacity of refrigerated warehouses expanding rapidly in developing countries, it can be anticipated that the emissions due to electricity usage in refrigerated warehouses will increase significantly as long as the grids remain reliant on fossil fuels. In addition, supermarket buildings are energy intensive and have a high refrigeration load. For instance, the United Kingdom uses 5% of the total produced energy to power supermarkets (54). In general, a typical supermarket consumes 500 to 2,000 kWh/m^2 electricity per year, approximately 45% of which is used for refrigeration (13, 39, 57). Additionally, GHG emissions from energy consumption are dominant in household refrigerators, with approximately 5% of residential energy use going to operation of refrigerators and freezers (58).

4. INTERVENTIONS FOR THE COOLING SERVICE SECTOR TO REDUCE ENVIRONMENTAL IMPACTS

In the next two sections, we examine various interventions that could reduce the overall environmental impacts of cooling services, both through interventions that can be applied directly to the cooling service sector as well as interventions that can be applied to companion sectors to reduce the demand for cooling services and, thus, the overall environmental impact. This section examines activities that focus on the cooling service sector itself, or the supply side, whereas Section 5 focuses on the demand side, which involves changes to the sectors that use cooling services.

4.1. Alternative Refrigerants

Many regulations to the cooling services sector have focused on reducing the impact of refrigerants, first responding to high ozone depletion potential and more recently to reducing GHG potential. There are several promising alternative refrigerants; however, as **Figure 3*b*** indicates, refrigerant leakages tend to be a smaller contributor of total GHG emissions for most cooling services relative to energy-related emissions. Therefore, the alternative refrigerants reviewed in this section are important but insufficient options to tackle the overall climate impact of cooling services. Refrigerant substitution will need to be introduced alongside policies for aggressive improvements in reducing energy-related emissions.

To respond to the Montreal Protocol and the Kigali Amendment to the Montreal Protocol, regulations have been issued to phase out HCFCs and high-GWP HFCs. In Europe, the use of new HCFCs in maintaining or servicing existing cooling systems was banned in 2010, and recycled and reclaimed HCFCs were banned in 2015 (38, 59). In addition, the use of HFCs with a GWP higher than 150 times that of CO_2 in MAC systems was prohibited since 2017 (60). Overall, the European Union has targeted a 79% reduction of HFC consumption by 2030 relative to the 2015 level (61). In the United States, the production, import, and use of R22 and other HCFCs on new equipment were prohibited in 2010 and 2015, respectively. After January 2020, all remaining R22 production was banned and the use of R22 could only depend on recycled quantity (62). Regarding the HFCs, the United States Environmental Protection Agency issued the Significant New Alternative Policy (SNAP) regulations to restrict the end use of high-GWP HFCs (63). For example, based on SNAP, California and Vermont passed mandates to reduce 40% of HFC emissions by 2030 (64). China is the largest global producer of HCFCs and HFCs, and the Chinese government and Chinese industries are actively seeking solutions to reduce the environmental impacts from the cooling and refrigeration industry (38, 65). In 2015, China succeeded in achieving the first-phase HCFC reduction target (−10% from the 2010 level) by decreasing nearly 300,000 tons of HCFC production and consumption from the 2010 baseline (44). Entering the latter stage of HCFC phaseout, China aims to reduce the use of HCFC substantially by 2030 and achieve no HCFC consumption in 2040. However, the annual HFC emissions increased significantly as a result of HCFC phaseout, and more regulations are needed on limiting the uses of high-GWP HFCs in China (66, 67).

In light of the regulations described above, alternative refrigerants have emerged as a lower GHG emitting solution and are shifting the cooling services industry. In the space cooling sector, medium- and low-GWP refrigerants (e.g., R32), natural refrigerants (e.g., R290), and the hydrofluoroolefin refrigerants (e.g., R1234yf) are promising alternatives. Regarding air conditioners, one common alternative low-GWP refrigerant is R290 (propane, a type of natural refrigerant), which has low GWP, promising cooling capacity, and high energy efficiency (45). In MAC systems, the industry began shifting from R124a to the lower GWP refrigerant R1234yf in 2013 (5, 15). By the end of 2018, 70 million vehicles worldwide used R1234yf in MAC systems, which, although a very small fraction of the estimated 1.42 billion vehicles globally, has the potential to reduce MAC GHG emissions by 90–99% compared to an R134a system (5, 68). Furthermore, the industry is shifting, as R1234yf is now the most widely used low-GWP refrigerant in the industry, and all car manufacturers are shifting to using it except Audi and Daimler, which plan to offer lower-GWP R744 systems (15). However, R1234yf is costly, which could be an obstacle to wider adoption of R1234yf in MAC systems (45). In the product refrigeration sector, natural refrigerants, R717, R744, and HC, are increasing in industrial, commercial, and household refrigeration systems. For example, it is estimated that 75% of global new domestic refrigerator production will use HC-600a by 2020 (45). In refrigerated warehouses, R717 is already one of the dominant refrigerants besides R22, due to its promising thermodynamics properties, high energy efficiency, and low global warming effects (38, 41, 45, 69). The main obstacles to expand the use of R717 from industrial refrigeration to other applications are safety concerns related to its flammability, toxicity, and corrosive properties (45). In commercial (e.g., supermarket) refrigeration systems, R744 is regarded as a promising choice. R744 has a low critical temperature (31°C), leading to low efficiency in conventional transcritical systems, and currently, R744 systems are mostly used in supermarkets in Northern Europe where the climate is cooler (38, 45). It is reported that there were 9,000 supermarkets with R744 in Europe in 2017 and the number is expected to reach 55,000 in 2025 (45). With technology improvements (e.g., using a second stage compressor, internal heat exchanger, external subcooler), the commercial applications of R744 can be expected to see more in regions with warmer climates (65, 70–73). Regarding household refrigerators, R600a, an HC refrigerant with a low GWP, is widely used outside of the United States (38).

Although the environmental impacts in developing countries can be reduced by leapfrogging to low-GWP refrigerants and high-efficiency cooling and refrigeration systems (74, 75), when implementing or upgrading the refrigerants or refrigeration systems in developing countries, there is the potential to fall into a trap of a wrong leapfrog approach (45). A wrong leapfrog approach could refer to a switch from HCFCs or high-GWP HFCs to medium-GWP HFCS, without taking advantage of the full reduction opportunity of low-GWP refrigerants, thus locking into a suboptimal solution. One specific example is countries switching from R22 to R404a in supermarkets when R744 systems are available and affordable to them (45). The first challenge is to determine the ultimate desired endpoint. Currently, natural refrigerants are expected to be widely used in the future. However, it is difficult to greatly expand natural refrigerants without sufficient technology improvements, which are not always guaranteed to happen. Hence, the definition of an ultimate solution may change over time. The second challenge is that the latest refrigeration technologies may not be affordable to developing countries. Although one opinion is that the total expenditures are higher for developing countries if they first upgrade an intermediate solution and then improve to the final solution (45), developing countries may not be able to afford the most advanced technologies for the current urgent needs. For instance, the R1234yf is a promising refrigerant in MAC, but it has a high price in the market (45, 76). Hence, a proper way to avoid the wrong leapfrog approach is that developing countries should consider the trade-off between technology availability and affordability to implement a cleaner system.

4.2. Energy-Efficient Cooling Services

Improving the energy efficiency of space cooling and refrigeration systems can mitigate energy-related emissions, which is particularly important given the high proportion of total emissions associated with electricity consumption of cooling services. UNEP reports six efficiency factors that can be implemented to improve energy efficiency, through technical improvements, design decisions, and behavior change: (*a*) minimize the cooling load, (*b*) minimize the temperature lift, (*c*) take account of the variable operating conditions, (*d*) select the most efficient refrigeration cycle and components, (*e*) design effective control systems, and (*f*) check operating performance and correct any faults of existing RACHP systems (77).

Some of the UNEP recommendations are straightforward, whereas others may not be immediately intuitive. For the first factor, there are numerous ways that cooling load can be minimized, ranging from simple to complex. For example, the UNEP report (77) illustrates that adding a door to supermarket display cases can achieve up to 50% cooling load reduction. The second efficiency factor pertaining to temperature lift suggests that there may be some scenarios where the desired final temperature can be increased in order to reduce cooling needs. The efficiency of a chiller can increase by approximately 10% if the target temperature for chilled water can be increased by 3°C (77). The third efficiency factor encourages consideration of both peak and off-peak conditions when designing and installing RACHP systems. Most cooling systems are designed to operate at peak cooling load, required for either the hottest weather conditions or when the building is fully occupied; however, systems operate the majority of the year at off-peak conditions at part load, which can be much more energy inefficient (77). The report recommends looking at both size and operating conditions to select the most efficient cooling system for a building (77). The fourth efficiency factor highlights the importance of selecting the most efficient cooling equipment components. There is not a one-size-fits-all approach to selecting cooling equipment, as each should be optimized for the specific application in which it will be used. Selection can have a large impact on energy efficiency without significant capital costs; for example, two nearly identical compressors (the main electricity component of a cooling system) could differ in energy efficiency by more than 20% with the same cost (77). The fifth efficiency factor recommends optimizing controls in cooling systems to optimize efficiency. For example, by setting correct pressure levels with a head pressure control system in refrigeration plants (which allows condensing temperature to fall to lower, more practical levels in cool weather), annual savings can amount to more than 25% (77). The last efficiency factor applies to existing equipment and highlights the importance of regular performance maintenance. Savings of 10% to 20% are commonly achieved by monitoring and correcting any performance issues (77).

Minimum energy performance standards (MEPS): voluntary or mandatory policies that aim to improve efficiency of air conditioning and refrigeration products

In addition to UNEP's guidance on technical, design, and behavior modifications for increased efficiency, energy efficiency labeling programs can improve the overall energy efficiency of the sector. There are many examples of energy efficiency labeling programs, including Energy Star in the United States, Top Runner in Japan, and energy labeling in the European Union (1). The US Energy Star program has been widely adopted across 75 different residential and commercial product categories products as of 2019 (78, 79). In the Energy Star program, products earn the label by meeting specific energy efficiency standards set by the United States Environmental Protection Agency and are required to meet the same performance and feature expectations as their counterparts in the market while still achieving this energy efficiency; for example, Energy Star–certified air conditioners should be 10% more efficient than the noncertified counterparts (78). While the Energy Star certification is a voluntary program, many manufacturers see the label as a way to distinguish a premium product in the marketplace (80). In 2013, the annual report from Energy Star stated that Energy Star–certified products and homes had avoided 158.2 million metric tons of GHG emissions that year (78). However, some critics point out that energy savings data reported by Energy Star do not account for the possibility of a rebound effect, where savings achieved through energy efficiency appliances may induce a behavioral response to use the appliance more often or at a lower temperature, causing the gains to be smaller than expected (81). One study found that an Energy Star–certified air conditioner might result in the same or increased frequency of use compared with a noncertified alternative (78). Moving forward, for maximum effectiveness, these labeling measures must be accompanied by regulations and technical approaches to making efficient cooling and refrigeration achievable.

In addition to appliance-based energy programs, another policy mechanism is the implementation of minimum energy performance standards (MEPS), which are (voluntary or mandatory) policies that aim to improve efficiency of air conditioning and refrigeration products in terms of energy efficiency and lower-GWP cooling equipment (1, 5). MEPS are most effective when used in tandem with labeling programs and/or incentive programs, like rebates, to help drive out the least efficient equipment models and encourage a market for more efficient models (1, 5). At least 50 countries, including developing countries with large projected cooling and refrigeration needs such as India, China, and Indonesia, have proposed or already have MEPS for air conditioners, and 85% of air conditioners sold worldwide in 2016 were covered by MEPS (1). However, for air conditioning MEPS differ substantially between countries (1). Generally, MEPS are more stringent in the richest countries where consumers have the ability to pay for more efficient, and more expensive, models, whereas standards are typically lower in developing countries with rapidly growing demand for air conditioners (1). Although research has shown that policy-driven incremental improvements in technology have resulted in a 1.7% increase in efficiency globally per year since 1990, this progress is not enough to offset the projected increase in energy demand for cooling services (2).

4.3. Decarbonized Electricity

Supplying lower-carbon electricity sources for space cooling and refrigeration is an obvious way to reduce energy-related GHG emissions. Currently, coal and natural gas produce 61% of electricity in the world. More specifically, 62% of electricity in the United States, 70% of electricity in China, and more than 80% of electricity in India are generated by coal and natural gas (49). As discussed in Section 2, the expansion of space cooling and refrigeration capacity will be mainly in developing countries, especially in India and China. The carbon emissions associated with coal and natural gas power generation are approximately 1,000 g/kWh and 600 g/kWh, respectively (82, 83). In contrast, producing renewable electricity (e.g., biomass, solar, wind) generates less than 100 g/kWh carbon emissions (82). Hence, innovation and intervention in power generation technologies are needed, and lower-carbon power sources will naturally mitigate the emissions associated with electricity usage by cooling services. For instance, in the food refrigeration sector, Wu has found an 8.5% emissions reduction could be achieved in an orange cold chain from South Africa to Switzerland if solar energy is used for precooling (84). Energy storage can be a solution to increase the use of renewable electricity (85, 86). Currently, industrial-scale energy storage systems have the challenge of increasing capacity, lifespan, security, and reducing costs, and future innovations are needed (87).

5. INTERVENTIONS IN RELATED SECTORS TO REDUCE ENVIRONMENTAL IMPACTS OF THE COOLING SECTOR

In addition to interventions in the cooling services sector itself (see Section 4), effective interventions to reduce environmental impacts can be implemented by the sectors that rely on cooling services, or what can be framed as demand-side management. In this section, interventions are identified that can further reduce the environmental impacts of cooling services through demand-side management.

5.1. Green Building Design and Building Codes

Beyond energy efficiency improvements of space cooling units themselves, overall cooling loads can be reduced by improving efficiency of buildings through either incorporating elements of green building design in new construction or enforcement of local or regional buildings codes. For new construction, there are many opportunities to utilize elements of green building design to reduce a building's energy consumption as it relates to cooling services such as window placement and orientation of the building to facilitate passive heating and cooling, as well as focused improvements in the energy efficiency of building envelopes in areas such as insulation, walls, roofs, and windows, which can reduce energy for cooling services in hot climates by 10–40% (5). One example is making roof surfaces and pavements more reflective or installing vegetation, which can especially help to combat the effects of the urban heat island effect (5). Complementary policies, such as financial incentives by regional or local governments, to encourage green building design in new construction are key in realizing widespread success of this element. Another tool to increase the efficiency of buildings in terms of energy usage due to cooling services is through enforceable building codes that mandate cooling efficiency for both new construction and major retrofits. Although building codes are and should be variable due to the climate and country, there are common elements that can be integrated into policies regardless of climate or country. Building codes offer a potentially large-scale lever for positive change on the demand side: Of the 130 billion m^2 of new building construction anticipated over the next 20 years, two-thirds is anticipated to occur in countries that do not currently have mandatory building energy codes in place (1). Building energy codes can reduce energy demand through prescriptive or performance-based categorization, and some policymakers are developing outcomes-based performance-based codes, which require a set minimum energy performance in the actual operation of the building rather than compliance with certain technology or design features (6, 88). Ideally, building design, building codes, and MEPS are part of an integrated approach and are far more successful in tandem than any of these individual measures in isolation (5).

5.2. District Cooling Systems

An evolving technology that has some interesting applications for reduced environmental impact is district cooling systems. This approach aggregates demand among multiple buildings—both residential and commercial—and utilizes a central plant to provide cooling services (89). When effectively applied, district cooling systems are more energy-efficient, more cost-effective, reduce peak power requirements, and have the ability to utilize renewable and free cooling technologies (89). On the energy efficiency side, district cooling systems consume 20–30% less power than an efficient conventional alternative and 60–80% less power than a conventional alternative (89). One way these efficiencies are achieved is through using a larger chiller system, which can be two to three times more efficient than smaller units in each individual building (6). Additionally, district cooling systems can contribute to peak shaving, as we discuss in detail below, by reducing peak power capacity by an average of 30%, with an additional 20% reduction that can be leveraged through thermal energy storage (89). On the cost savings side, one study estimates that with global increased adoption of district cooling services, energy consumption could be reduced by up to 5,000 TWh, achieving a cost savings of more than $1 trillion by 2035 (assuming a $0.20 per kWh price) (89). Moreover, district cooling systems illustrate promising technologies to leverage solar energy to power cooling technologies to further reduce environmental impact. Demand for cooling services typically increases with solar thermal radiation intensity, illustrating the huge potential in the marketplace for cooling and refrigeration services run by solar technologies (80).

Another innovation related to district cooling is capturing and utilizing heat and energy waste from these systems and leveraging free cooling from natural cooling sources such as rivers, lakes, and seawater, depending on the location (5, 6). Despite the numerous benefits, district cooling systems have not been widely adopted in the marketplace, with the exception of hot-climate countries in the Middle East, and will need substantial support from governments to gain wide-scale adoption (80, 89). Possible actions by governments to foster growth in the marketplace of this technology are mandating district cooling technologies in new developments and construction that meet specific criteria, setting technical specifications and design codes, and potentially regulating prices to make this technology more competitive (89).

5.3. Infrastructure Siting

Siting of industry infrastructure, particularly data centers, is a promising approach that may allow for substantially reduced energy demand. Energy demand can be lowered due to siting in specific, equipment-friendly climates (90, 91). Because approximately 40% of a data center's total energy use is attributed to air conditioning and humidity control (19), studies have shown that geographical location can result in energy savings for data centers that are sited in regions with cooler temperatures and lower humidity (90, 91). There can be further reductions when siting in geographic areas that possess electricity grids with lower GHG intensity. One technology that is particularly promising as it relates to siting is direct air free cooling, which essentially uses cooler air outside of a data center to remove the heat generated inside to reduce cooling load (91). One study examined 17 climate zones based on temperature and humidity to examine the potential for energy savings based on the use of direct air free cooling. The study concluded that data centers sited in mixed-humid (4A), warm-marine (3C), and mixed-marine (4C) climate zones achieved best energy saving potential with 33%, 32%, and 29% energy savings, respectively (92). The study notes that energy savings in the climate zones are variable based on time of year and noted that for some climate zones, energy use actually increased due to the need for humidification in some climates (92).

Cool thermal energy storage (CTES): a technology that uses off-peak power to provide cooling services through phase change materials

5.4. Energy Load Reduction

The cooling services sector has a disproportionate impact on peak electricity load in cities and regions; therefore, policies, technologies, and design approaches to reduce environmental impacts through energy load reduction and/or redistribution of the timing of demand for cooling service are important interventions to consider (5). One strategy to manage peak energy demand and achieve emissions reductions is through peak shaving, which is also referred to as peak smoothing or peak-load shifting. One example is to use energy storage systems to charge and store energy in the evening, when demand and utility costs are lowest, and then discharge this stored energy during peak demand, when utility rates are higher, thus reducing the need for additional electricity generation and "shaving" the peak demand (93). Although it is not immediately obvious how load shifting reduces emissions, there are numerous advantages to reduce major swings in electricity demand throughout the day. For example, wind resources tend to be strongest in the evening, when electricity demand is low (94). Using energy storage to capture wind resources and deploy it when needed can reduce the overall carbon intensity of an electricity portfolio, particularly if that portfolio relies on more carbon-intensive sources to meet its normal load peak (94). Air conditioning usage is one of the major drivers of peak electricity demand during summer months, in some areas representing up to 50% of power drawn during midday hours, putting a large strain on electricity grids around the world (93).

Beyond utility-scale energy storage, various technologies for peak shaving through energy storage and harnessing renewable energy sources have emerged as effective strategies to reduce impacts of cooling services. These technologies seek to solve the electrical power imbalance between increased demand in the daytime and abundance in the evening (93). Cool thermal energy storage (CTES) is one example that has demonstrated energy savings and also has potential to integrate renewable energy sources (95). CTES uses off-peak power to provide cooling services by leveraging latent heat from ice, chilled water, or other phase-change materials (93, 95). One benefit of CTES technology is increased operating efficiencies of chillers by scheduling them to fill the CTES in the evening, when temperatures are lower and machinery can operate more efficiently (95). Additionally, CTES reduces energy consumption by using off-peak electricity to store energy to use during peak hours, thereby shaving peak power consumption and preventing utilities from building new power generation plants (93). Perhaps most promising in the realm of future innovations is CTES's ability to integrate renewable energy sources and to store excess energy created by these energy sources. This integration allows buildings to achieve even greater environmental gains than with CTES alone, and studies have shown that CTES technology integrated with renewable energy sources can help to reduce the variability and intermittency problem inherent with renewables as well as provide energy storage (95). Widespread CTES technology deployment can allow for a marked increase in the use of renewables for cooling services; one study found that buildings appropriately equipped with CTES were able to increase utilization of renewable energy sources 10–50% more than buildings without these specific conditions (96). The biggest barrier to widespread implementation of these technologies and renewable energy source integration is cost. A study by Ban et al. found that even the most financially successful scenario of charging CTES in the evening and selling all energy generated by PV solar back to the grid was still economically infeasible in the study location of Croatia due to energy costs and tariffs (95). One potential solution to this barrier is for utilities to provide greater incentives or reduced electricity rates to encourage the adoption of this type of technology in either new construction or retrofits (96).

Internet of Things (IoT): a network of hardware and software to exchange data with other systems over the Internet

5.5. Food Waste Reduction

Although not intuitively obvious, reducing global food waste can lead to decreases in the demand for refrigeration services. Refrigeration services ostensibly exist to improve shelf life and product safety and to reduce waste associated with perishable products. Although estimates vary, approximately one-third of edible food produced for human consumption is wasted, regardless of whether there is an established cold chain in a country (97). By reducing food waste, less food needs to be produced to meet the overall demand, and consequently, less refrigeration services are needed. In addition, reducing food losses has the added benefit of improving the overall carbon footprint of the food system, given that food production is responsible for a large amount of embodied carbon emissions. When comparing countries with developed and less developed cold chains, food waste tends to occur at different parts of the supply chain. Within developed countries, a large percentage of food waste occurs at the consumer level, whereas food waste in developing countries without a well-established cold chain tends to occur at the preconsumer level (8). James & James (98) found that more than 200 Mt of perishable food products could be saved from wastage if developing countries had sufficient cold chain infrastructures; however, introducing refrigeration facilities has the inherent trade-off of consuming considerable energy and generating GHG emissions, despite the potential to decrease food losses. In developing countries, cold chain capacity is expanding rapidly. For example, the cold chain capacity increased by 66%, 50%, and 20%, respectively, in Brazil, India, and China from 1998 to 2008 (99). It is important to continue to reduce the impact of the cold chain and improve overall food waste rates in these countries. Heard & Miller (8, 22) modeled the changes in GHG emissions associated with introducing a cold chain into sub-Saharan African regions. They found that the postharvest emissions from refrigeration facilities are larger than avoided food losses emissions, whereas the change of system-level (including agricultural production) GHG emissions may vary between −15% and 10% depending on contexts (8). In a study investigating the cold chain environmental trade-off in China, Hu et al. (100) concluded that if the cold chain could fully cover the perishable food in China from production to consumption, the total emissions would be lower than the current level in the perishable food logistics sector. Therefore, future innovation to reduce the emissions from product refrigeration should focus on the overall food system and consider the balance of reduced food losses and increased refrigeration emissions.

5.6. Artificial Intelligence and Internet of Things

State-of-the-art artificial intelligence (AI) and the Internet of Things (IoT) could also play a critical role in the future development of cooling and refrigeration. The IoT platforms integrate sensor, control, and optimization technologies to improve the operation of space cooling and refrigeration equipment, and accordingly, help to achieve higher energy efficiency and lower emissions (101, 102). Regarding space cooling, Miqdad et al. (103) studied a space cooling load monitoring system, and they reported that wireless sensor networks and cloud storage can effectively use real-time data to reduce overall load demand. With such sensor systems recording data, the control and optimization for air conditioning equipment are made possible. Thongkaew & Charitkuan (104) studied the IoT for energy saving in the split-type air conditioners. They found that using IoT platforms to monitor and control the air-flow temperature and compressor conditions, nearly 20,000 kWh electricity could potentially be reduced annually (104). Regarding perishable product refrigeration, smart refrigerated warehouses with multiple sensors, microcontrollers, and cloud computing platforms have been investigated (105, 106) and have been shown to be able to optimize energy consumption and minimize food waste in future smart warehouses. In addition, radio-frequency identification systems, blockchain technologies, and distribution routing algorithms are under development to further reduce waste (107–109).

6. CONCLUSION

The confluence of rising temperatures due to global climate change, increasing urbanization, and rising incomes worldwide have set the stage for a global expansion in the space cooling and refrigeration sectors with a particular emphasis on developing countries, which will see some of the largest temperature increases due to climate change. Access to these services is crucial not only for thermal comfort but also for the effective transportation of vaccines, preventing food waste and associated GHG emissions, and increased economic productivity. Ensuring equity of access of these services is crucial in alleviating poverty and is encompassed as part of SDG 7.

However, these benefits from expanded cooling services have environmental impacts associated with both refrigerant leakage and energy use–related emissions. Current and projected emissions from the cooling services sector are significant and will need to be addressed if international climate goals are to be reached.

The positive news is that there are many existing and new innovative approaches to reconciling environmental protection with expanded, equitable access to cooling services. These range from existing successful mechanisms such as alternative and natural refrigerants with a much lower GWP, to more innovative approaches such as AI.

This issue will surely continue to play a prominent role in global climate change, and diverse stakeholders will need to work together to address the solutions discussed in this article to tackle this problem head on. These solutions will not occur in a vacuum; they will require collaboration across sectors, industries, and countries to be fully realized.

SUMMARY POINTS

1. Developing countries are a major market for the expansion of cooling services. With increased urbanization, rising temperatures due to climate change, and rising incomes around the world, the demand for cooling services is projected to dramatically increase in developing countries.
2. The environmental impact of cooling services can be directly or indirectly related to the cooling service sector. Direct environmental impacts are emissions related to refrigerant leakage in cooling services as well as energy-related emissions from the operation and expansion of these services. Indirect environmental impacts occur as secondary effects of related sectors, such as increased transportation distances associated with a refrigerated food supply or changes in building design when air conditioning is available.
3. Three approaches to reduce GHG emissions within the cooling sector include converting to alternative, lower-GWP refrigerants, designing more efficient refrigeration and cooling systems, and sourcing from lower-carbon power sources.

4. GHG emissions from space cooling can also be reduced through changes to the built environment that result in reduced energy use. Strategies to achieve reduction in energy use include implementation of labeling and regulatory measures, green building design, strategic siting of data centers, and shifting electricity demand to times of day when the grid has a lower GHG intensity. GHG emissions from refrigeration can be reduced by programs focused on food waste reduction, which will decrease the overall demand for refrigeration services.
5. Numerous state-of-the-art technologies have the potential to reduce GHG emissions of cooling services, although they have not yet achieved their full potential. These innovations include the application of AI and the IoT technology, as well as expansion and refinement of district cooling systems.

FUTURE ISSUES

1. How will the space cooling and refrigeration industry actually develop in new markets? In developing countries, the total number of installed units, electricity consumption, and emissions is anticipated to grow significantly. In addition to uncertainty due to imperfect data, projected scenarios vary depending on future regulations and technology improvements.
2. How will the maintenance and upgrading of cooling and refrigeration systems in developed countries affect GHG emissions? Although the growth within the sector is expected to be driven by developing countries, space cooling and refrigeration units in developed countries require maintenance, and old equipment will be upgraded to new systems. Refrigerant leakage can occur in the maintenance and disposal process, and the production of new cooling and refrigeration equipment also generates emissions; however, these are offset by improvements in efficiency of the new units.
3. What is the balance of technical and nontechnical interventions that are needed to meet the increasing demand of cooling services while reducing overall GHG emissions? Although there are various promising technological improvements to reduce overall GHG emissions, nontechnical methods (e.g., regulations, energy efficiency gains via voluntary programs) can also achieve significant emissions reductions.
4. What regulations will need to be implemented in developing countries? Potential regulations range from limiting the use of high-GWP refrigerants to improving the energy efficiency of building design.
5. How will the development of space cooling and refrigeration technologies affect economic and societal conditions in developing countries? Air conditioning provides new opportunities for urban design and changes to the workforce, and refrigerated food supply chains have the potential to transform the food and agricultural sectors. More job opportunities are expected in the cooling and refrigeration industry. Nevertheless, inequities between the rich and the poor may also be exacerbated. Hence, the technology-economy-society nexus should be investigated to support sustainable development in the future.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation Environmental Sustainability program under Grant CBET 1804287. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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