60th Technical Brief

THE ROLE OF REFRIGERATION IN THE GLOBAL ECONOMY

3RD EDITION

INSTITUT INTERNATIONAL DU FROID
INTERNATIONAL INSTITUTE OF REFRIGERATION

Please cite as:

Baha M., Hammami S., Dupont J-L. The role of refrigeration in global economy. 3rd edition. 60th Technical Brief on Refrigeration Technologies. International Institute of Refrigeration (IIR), Paris. http://dx.doi.org/10.18462/iir.TechBrief.04.2025

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FOREWORD

As the Director of the International Institute of Refrigeration (IIR), I am delighted to present this updated 2025 Technical Brief on The Role of Refrigeration in the Global Economy. The prior versions of this document have been a vital source for policymakers, industry leaders, and researchers who have used it to illustrate how the refrigeration sector sustains modern life, from the food on our tables to the vaccines in our hospitals. Today, its message is more urgent than ever, and its insights are not just relevant, but they are critical to our survival.

We stand at a crossroads, 2024 was the hottest year in recorded history and the demand for refrigeration is surging alongside global temperatures and billions of people are now at high risk from heat waves. As temperatures rise, so does the demand for refrigeration, especially in developing and emerging economies where access remains limited. Yet, while refrigeration is a lifeline for billions, it also presents a paradox of how it is both a critical solution to climate-driven crises and a significant contributor to the problem itself. Nearly 1 billion people still lack reliable access to refrigeration, exacerbating food insecurity, health inequities, and economic disparities such as those outlined in the Paris Agreement and the United Nations Sustainable Development Goals (SDGs).

The challenges are immense, but so are the opportunities. One of the most pressing issues is the transition to low-global-warming-potential (GWP) refrigerants and energy-efficient technologies. A holistic approach is essential policymakers, industry leaders, and researchers must work together to develop innovative solutions, reduce emissions, and ensure that refrigeration is accessible to all. This includes investing in infrastructure, advancing training and education, and mobilising financial mechanisms to support the phase-out of harmful refrigerants and the adoption of sustainable alternatives.

The IIR is committed to leading this effort. As the world's only intergovernmental, scientifically based organisation entirely focused on refrigeration, we are committed to evidence-based policymaking.

Refrigeration is not just about keeping things cold; refrigeration is the invisible backbone of civilisation and it's about preserving life, enhancing health, and driving economic growth. It is about securing a healthy present and building a sustainable and safe future for generations to come.

Dr. Yosr Allouche
General Director
International Institute of Refrigeration

ACKNOWLEDGEMENT

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1. INTRODUCTION

2024 was the warmest year on record, surpassing the record of 2023 with a streak of exceptionally high monthly global mean temperatures [1]. With the growing frequency and duration of extreme heatwaves and the challenges of global warming, sustainable refrigeration is a global necessity when addressing climate adaptation and mitigation. The refrigeration sector, which includes the cold chain for food and health products, air conditioning, cryogenics and heat pumps, is recognised within the United Nations as a development priority for its benefits to human life. Over 1.12 billion people globally — primarily among the rural and urban poor — face immediate risks due to a lack of access to refrigeration, which is crucial for reducing food loss and ensuring food availability to combat hunger and malnutrition. In this regard, access to refrigeration is a more sustainable solution than investing in large-scale food production, which carries significant energy and environmental costs [2].

Improving access to sustainable refrigeration solutions is also essential to mitigate the effects of severe heatwaves. Driven by a rising population, increasing incomes, and increasing global temperatures, the use of refrigeration is expanding dramatically, especially in the world's emerging economies. As an essential component in countless sectors from food to healthcare, industry, information communication technology (ICT), and energy, refrigeration plays a key role in the economic and social development of every country. Refrigeration also contributes significantly to countries' economic growth and global trade through sales of refrigeration equipment and the substantial workforce employed in the manufacturing, installation, maintenance and servicing of the refrigeration equipment.

This technical brief presents key figures illustrating the size and reach of the refrigeration sector and its importance to humankind, as refrigeration is intrinsically linked to the United Nations' Sustainable Development Goals (SDGs). The brief aims to raise policymakers' awareness of the growing importance of refrigeration to further encourage its development in a sustainable manner, particularly in developing countries and emerging economies.

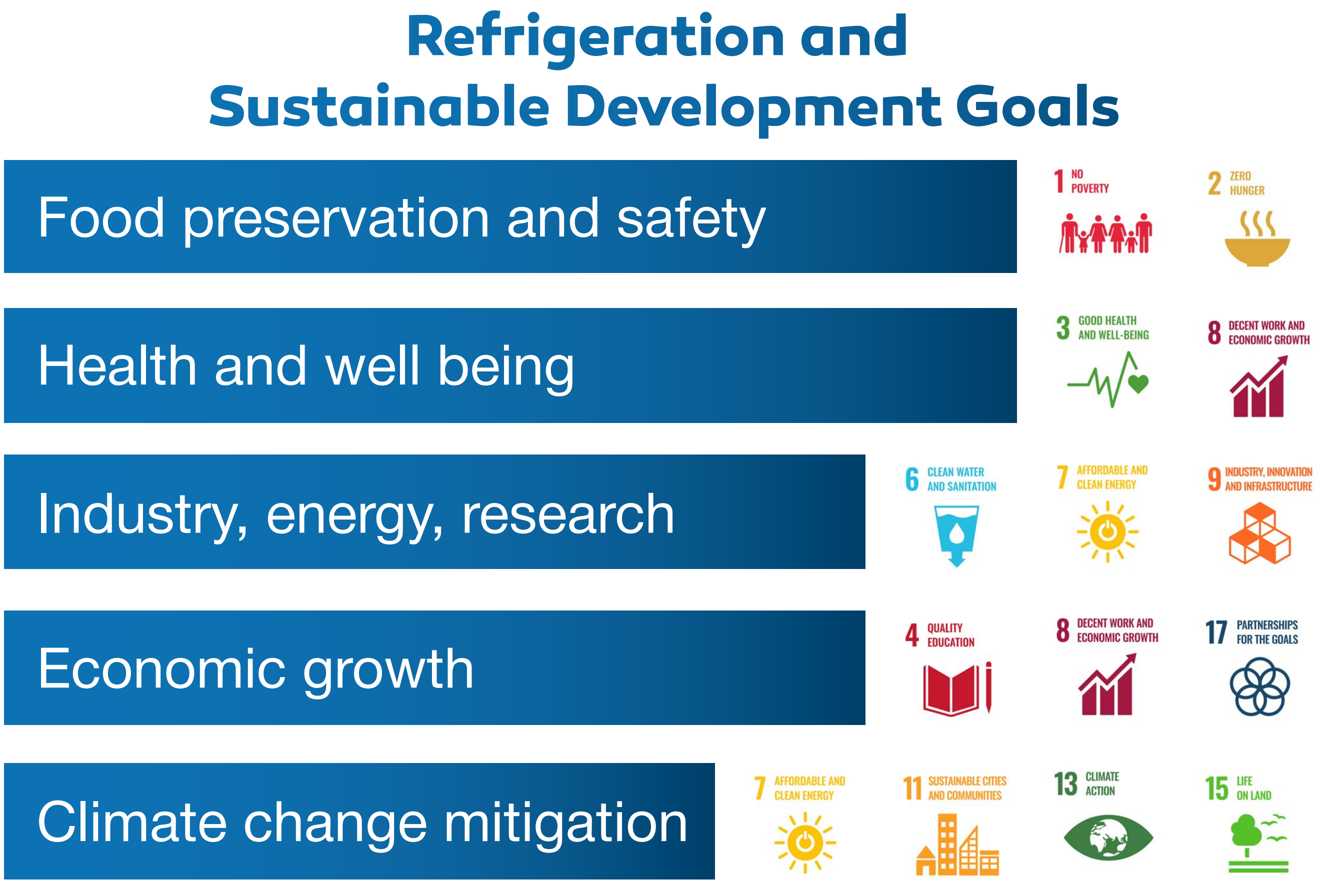

Figure 1. Refrigeration and Sustainable Development Goals (SDGs)

2. REFRIGERATION ECONOMICS

2.1. Refrigeration equipment worldwide: a growing global market

The IIR has assessed the quantity of refrigeration equipment in operation worldwide based on published sources and IIR estimates, as summarised in Figure 2 (see appendix 1 for details on sources).

In 2024, there were approximately 5.4 billion pieces of refrigeration equipment in operation worldwide, including 2.9 billion air-conditioning units — stationary and mobile — and 2.2 billion domestic refrigerators and freezers.

Global annual sales of refrigeration equipment total over USD 300 billion, excluding installation and maintenance costs (based on published sources [3] and IIR estimates).
According to an analysis by the International Finance Corporation (IFC) and the United Nations Environment Programme (UNEP)-led Cool Coalition, in 2023, developing countries accounted for 40% of the global market for stationary and mobile air conditioning, and residential and non-residential refrigeration applications [4]. By 2050, the market for sustainable refrigeration in developing countries is set to more than double. The fastest market growth is expected in Africa, which should see its market increase sevenfold, and South Asia, where the market is projected to quadruple in size [4].

Image. Digital stock market data visualization over a modern cityscape at night. (Source: Shutterstock)

QUANTITY OF REFRIGERATION EQUIPMENT IN OPERATION WORLDWIDE

COLD CHAIN

- **2.2 billion** domestic refrigerators and freezers
- **120 million** commercial refrigeration units
- **5.7 million** refrigerated road vehicles
- **2 million** refrigerated containers (“reefers”)
- **85,000** cold stores

AIR CONDITIONING

- **1.3 billion** residential air conditioning units
- **215 million** commercial air conditioning units (including chillers)
- **1.3 billion** mobile air conditioning units (passenger cars, commercial vehicles and buses)

HEAT PUMPS

200 million residential, commercial and industrial heat pumps

CRYOGENICS

51,500 Magnetic Resonance Imaging machines
138 natural gas liquefaction plants

LEISURE AND SPORTS

19,600 ice rinks

Figure 2: Quantity of refrigeration equipment in operation worldwide

2.2. Refrigeration and employment: worker shortage in a growing industry

About 12 million people are employed worldwide in the manufacturing, installation, maintenance and servicing of refrigeration equipment. The IIR calculated the number of workers in the refrigeration industry based on national country reports when available, which were then extrapolated to the global level. This estimate does not include indirect jobs or jobs in related sectors depending on refrigeration, such as the frozen food industry or Liquefied Natural Gas (LNG) industry. For example, in the U.S., LNG exports directly employ over 25,000 people but indirectly contribute to a total of about 222,000 jobs [5].

When considering the labour force, the **IIR estimates that about 4 out of every 1,000 workers worldwide are employed in the refrigeration industry**. This global average rate hides significant regional disparities (see Appendix 2 for more detail). Australia leads the way with a notable ratio of 26 workers per 1,000 employed in the refrigeration industry [6].

In the U.S., just under 5 out of 1,000 workers are employed in the manufacturing, installation, maintenance, or servicing of refrigeration equipment [7]. As the world leader in heat pump and air conditioning manufacturing [8, 9], China has the largest refrigeration workforce, with 1,605,000 workers [10]. Yet China's refrigeration workforce represents only 2 out of 1,000 workers in the country's total workforce.

The global energy transition offers huge potential for employment growth. In the U.S. for instance, employment of mechanics and installers in heating, refrigeration, and air conditioning is projected to grow by 9% from 2023 to 2033 [11].

However, the global refrigeration sector is grappling with an aging workforce and the pressure to replace retiring workers with skilled talent [12–14]. Europe faces a severe shortage of technicians and installers [15], worsened by a recent decrease in heat pump sales recorded in 2023 and 2024, which has resulted in the loss of 4,000 jobs [16]. The European Heat Pump Association (EHPA) has projected that 500,000 skilled workers will be needed to meet the EU's heat pump deployment goals by 2030. This estimate is based on the EU's ambitious targets for heat pump installation as part of its broader climate and energy objectives, including the REPowerEU plan, which aims to reduce reliance on fossil fuels and accelerate the green transition [17].

To ensure the sector can deliver on its potential, urgent measures must be implemented to attract and train the next generation of skilled workers. This includes not only addressing the immediate need of installers and technicians but also fostering a talent pipeline with expertise in advanced manufacturing, engineering, and digital technologies — skills that will be essential for the future of the refrigeration sector.

Image. HVAC technician installing or servicing an outdoor air conditioning unit on a residential building. (Source: Shutterstock)

Making the refrigeration sector more attractive to young people and career changers is essential. This can be achieved through a combination of targeted initiatives, such as:

- Expanding vocational training and apprenticeship programmes specifically focused on refrigeration and heat pump technologies to equip workers with the necessary skills.
- Highlighting the sector's critical role in combating climate change and advancing sustainability, which can inspire young generations to pursue meaningful careers in refrigerationcover the entire celestial sphere.
- Partnering with schools, colleges, and universities to integrate refrigeration-related skills and knowledge into curricula, ensuring a steady pipeline of talent.

Without these efforts, the growing workforce shortage could become a major bottleneck, delaying the production, installation, and maintenance of refrigeration and heat pump systems. This would jeopardise the global ability to meet climate goals and energy efficiency targets. Tackling this challenge now is not just about supporting economic growth — it is a vital step towards building a sustainable, resilient, and climate-friendly future for the entire refrigeration sector.

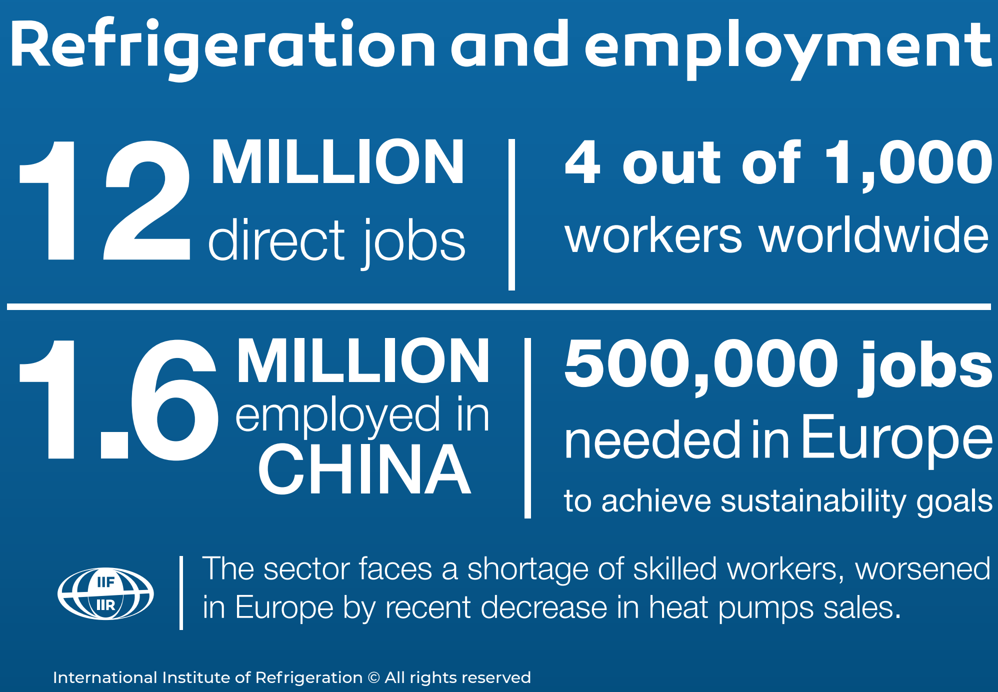

Figure 3. Refrigeration and employment

3. ROLE AND APPLICATIONS OF REFRIGERATION

3.1. Refrigeration and food systems

Refrigeration is crucial for maintaining food quality and safety at every step of the food cold chain, including food processing, cold storage, refrigerated transport, distribution, and end consumption.

The growing demand for perishable goods is driving the expansion of the global cold chain. The world's refrigerated warehouse capacity has increased significantly in recent years, reaching about 85,000 cold stores, mostly in China [18], India [19], and North America [20]. However, many developing countries still require substantial additional capacity to meet their cold chain needs. For example, Brazil is one of the world's top five producers of food products and a leading exporter [21]. Although the refrigerated storage capacity has expanded significantly, the country still lacks around 30% of the estimated cold chain capacity required [20, 22].

The refrigerated transport market is expected to thrive (+20% over this decade) in emerging markets such as India and China [23, 24], while maintaining a steady growth (+4%) in other regions such as North America [25]. Based on these trends, the IIR estimates that there are approximately 5.7 million refrigerated vehicles in service worldwide, including vans, trucks, semi-trailers or trailers [26].

Refrigeration is also widely used in food retail stores (supermarkets, grocery stores, etc.) and food service outlets (restaurants, cafes, hotels, etc.). It enables the storage and display of food and beverages at various temperatures.

Temperature abuse — i.e. storing food at incorrect temperatures — is one of the most important parameters in reducing the quality of perishable food and increasing economic losses. While most food waste is generated at the consumer level, a significant amount of food loss occurs during transport, storage, and retail, amounting to approximately USD 210 billion in economic losses [27].

Maintaining consistent, optimum temperatures throughout an expanding and efficient food cold chain is therefore of economic importance globally [28]. According to the Food and Agriculture Organization of the United Nations (FAO), farms smaller than 2 hectares produce around one third (35%) of the world's food [29]. Reliable and sustainable cold chains help prevent postharvest loss and increase income for financially vulnerable farmers, upon whom the global food system heavily depends.

At the consumer level, household refrigerator ownership can be viewed as an indicator of economic development, since refrigerator ownership increases with income or per capita expenditure [30, 31]. In several middle- to high-income countries, nearly all households own at least one refrigerator, such as in the U.K., the U.S., Chile, and Brazil. In Colombia, ownership averages around 87%, ranging from 27% in one of the poorest regions to 100% in the wealthiest [32]. Overall, there about 2.2 billion domestic refrigerators and freezers in service worldwide (see Figure 2).

Given the highly perishable nature of the harvests, the global fisheries and aquaculture sector relies heavily on refrigeration.

2 ZERO HUNGER

The IIR estimated that 19% produced for human consumption in 2017 was lost due to lack of refrigeration, particularly in Africa (47%) and Latin America (38%) [33] . FAO reports that freezing is the primary method of preserving fishery and aquaculture products for food purposes. 62% of the 93 million tonnes of processed aquatic animal production for human consumption in 2022 were frozen [34]. Frozen food is a method of preserving products that offers a convenient and affordable way to consume safe and nutrient-rich fruit and vegetables. For example, vegetables are usually frozen shortly after harvest, mini and seafood produced for human consumption in 2017 was lost due to lack of refrigeration, particularly in Africa (47%) and Latin America (38%) [33] .

1 NO POVERTY

Overall, the IIR estimated that in 2017, 12% of the food produced globally was lost due to an insufficient cold chain [33]. Expanding cold chains worldwide could save over 475 million tonnes of food, potentially feeding 950 million people annually [33]. Considering that hunger currently affects approximately 735 million people globally [37], **refrigeration can play a critical role in enhancing food security**.

Reducing food waste also means reducing the resources used in farming, particularly water, which is becoming an increasingly threatened vital resource due to climate change.In Europe for example, the amount of final energy used for air conditioning in residential buildings tripled between 2010 and 2019 [40]. Household ownership of ACs is about 36% worldwide [41], with great disparities across countries and regions — from around 8% in India [23] and 20% in Europe [40], to 90% in the United States [42] and 100% in some Middle Eastern countries.

Estimated at 1.5 billion units in 2024, the global stock of stationary air conditioners could more than double by 2050, reaching over 3.5 billion units, according to the IIR **(see Figure 4)**. In India, where the World Meteorological Organization (WMO) estimates that climate change has made heatwaves 30 times more likely to occur [43], the IIR projects that the stock of stationary air conditioners could increase fivefold by 2050. In China, the world's largest air conditioning market, the stock is expected to double, as it is in Latin America and Europe.Overall, the IIR estimated that in 2017, 12% of the food produced globally was lost due to an insufficient cold chain [33]. Expanding cold chains worldwide could save over 475 million tonnes of food, potentially feeding 950 million people annually [33]. Considering that hunger currently affects approximately 735 million people globally [37], **refrigeration can play a critical role in enhancing food security**.

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Image. Freshly caught fish stored in blue crates filled with ice at a seafood market. (Source: Shutterstock

3.2. Air conditioning

As global temperatures rise due to climate change, adaptation through air conditioning is becoming a vital necessity to maintain labour productivity and safeguard human health.

Several studies have shown that **extreme heat impairs work efficiency and causes economic losses globally.** Workers in hot conditions are more prone to mistakes and reduced decision-making capacity, which increases the risk of work injuries or even death [38]. The International Labour Organization estimates that temperature increases due to global warming will result in a productivity loss equivalent to 80 million jobs by 2030 [38]. Economic losses due to heat stress are projected to reach USD 2,400 billion in 2030 [38].

Air conditioning is expanding dramatically in warmer climates, even though only 15% of the 3.5 billion people currently living in the warmest parts of the world own air conditioners [39]. With rising global temperatures, the air conditioning demand is also increasing in the Northern Hemisphere.

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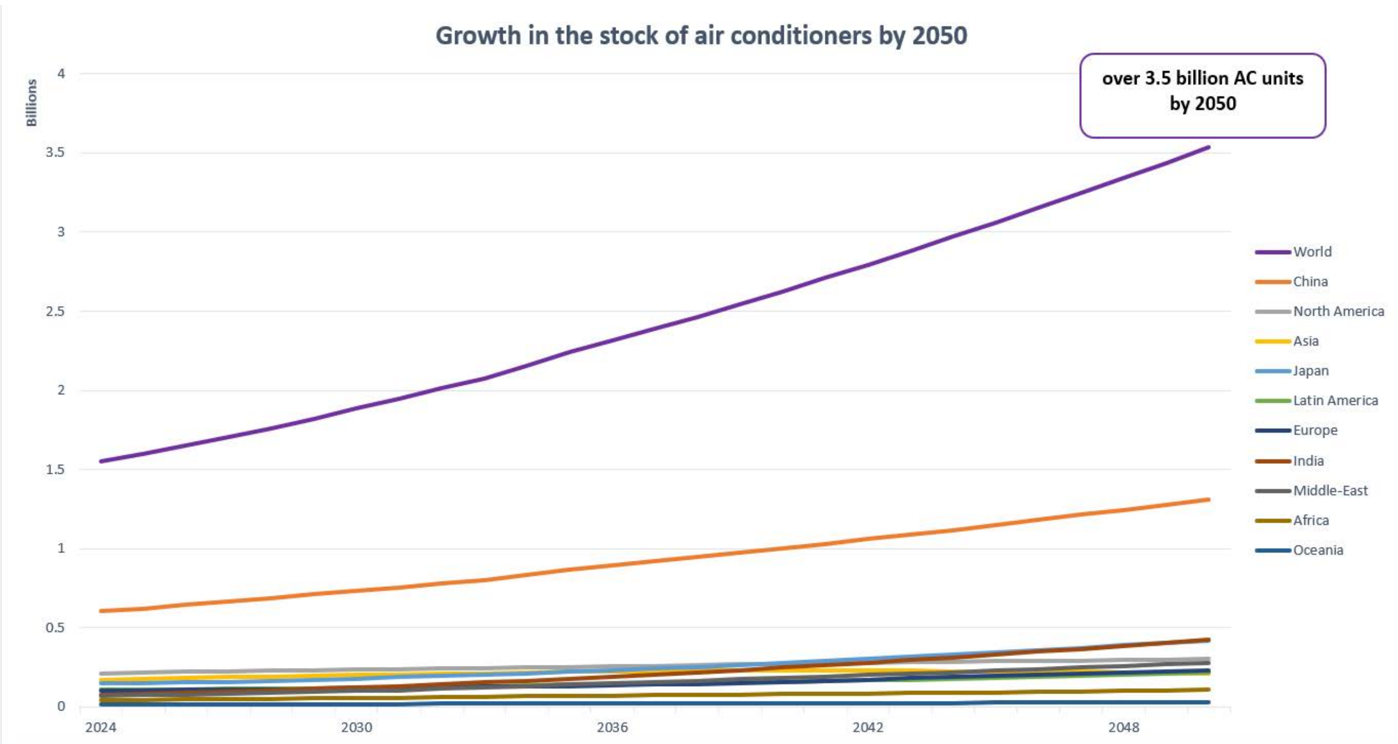

Figure 4. Global stock of stationary air conditioners between 2024 and 2050, according to IIR estimates (excluding mobile air conditioning).

As demand for air conditioning continues to rise, passive cooling strategies are becoming essential to help reduce the overall reliance on these systems. The integration of design measures for heat prevention (i.e. shading, glazing, ventilation) and for heat modulation (i.e. building materials and insulation), enables buildings to maintain thermal comfort without relying on energy-intensive air conditioning. This approach can help decrease the environmental and economic costs associated with air conditioning.

There are currently about 1.3 billion mobile air-conditioning units in cars and buses worldwide. Mobile air conditioning provides increased comfort and safety to the occupants. It is a standard feature in high-income countries. In emerging countries, around 60% to 100% of new vehicles are equipped with mobile air conditioning [44]. In electric vehicles, which represent a fifth of the global car fleet [45], the air conditioning system also controls the temperature of the battery pack to ensure the efficiency and safety of the battery during operation [46].

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3.3. District cooling

District cooling is an energy-efficient alternative to stand-alone air conditioning units in both residential and non-resi dential buildings.

11 SUSTAINABLE CITIES AND COMMUNITIES

District energy networks typically consist of a central production unit that supplies thermal energy through a network of pipes, using renewable sources such as free cooling from nearby sea/lake water, and heat from waste heat sources . In coastal regions, seawater air conditioning (SWAC) is a district cooling technology that utilises deep cold seawater, offering about 80% lower electricity consumption and costs compared with chillers used in conventional AC systems [47]. The penetration rate of district cooling is the highest in the Middle East, particularly in the U.A.E., Qatar, and Saudi Arabia, representing 15% to 25% of the region's total installed cooling capacity. In Qatar, for instance, district cooling accounts for 19% of the country's cooling capacity [48].

The overall amount of cold energy delivered has been estimated at about 83 TWh or 300 PJ per year, based on the largest district cooling systems in operation worldwide — around 200 PJ in the Middle East, 80 PJ in the U.S., 14 PJ in Japan, and 10 PJ in Europe [49]. The technology is expanding in other regions such as Latin America, with Colombia leading the way [50].

Image. A district cooling plant in Egypt's New Administrative Capital, near Cairo City.

3.4. Heat pumps

Heat pumps are energy-efficient devices that use the refrigeration cycle for both heating and cooling. In heating mode, heat pumps extract heat from an outside source and then transfer it indoors at a higher temperature. In cooling mode, heat pumps transfer heat from indoors to the outside.

Heat pumps represent a promising solution for improving energy efficiency and reducing environmental impact in both residential and industrial applications. They provide around 10% of the world's space heating needs [51]. Reversible heat pumps also meet both heating and cooling needs of electric vehicles [52]. For industrial applications, high-temperature heat pumps can be used to recover waste heat, a by-product of industrial processes in sectors such as agrifood, beverage, chemical, paper, and textile industries [53].

By utilising the refrigeration cycle to provide both heating and cooling, heat pumps offer substantial energy savings, particularly in systems like ground-source heat pumps, which can cut energy demand by up to 50% in cooling mode and up to 40% in heating mode [54]. When powered by low-emission electricity, they contribute significantly to reducing CO_2 emissions, supporting a sustainable energy future. Although economic factors such as the lower cost of natural gas can hinder their widespread adoption by households, financial incentives and subsidies could help accelerate the transition.

In the past decade, the heat pump market has expanded rapidly, driven by decreased costs and policy incentives. After two consecutive years of double-digit-growth (+15% in 2021 and +11% in 2022), global heat pump sales have slowed down [55]. Nevertheless, the IEA estimates that heat pumps have the potential to reduce global CO_2 emissions by at least 500 million tonnes by 2030 — equivalent to the current annual CO_2 emissions of all cars in Europe [8].

3.5. Refrigeration and health

Refrigeration benefits human health by preserving food and pharmaceuticals, as well as through low-temperature therapeutic techniques.

Refrigeration inhibits the development of bacteria and toxic pathogens, therefore preventing foodborne diseases. By improving food preservation, the cold chain is crucial in eliminating the H. pylori bacteria, associated with most cases of stomach cancer [56]. A steady decline in the incidence and mortality rates of stomach cancers has been observed consistently across all regions for more than five decades, according to the IARC/WHO World Cancer Report [56]. Additionally, by improving food storage, refrigeration has been associated with increased consumption of fresh fruit and vegetables, further contributing to cancer prevention [57] and overall well-being.

Cryosurgery, or cryoablation, is used as a clinical treatment in certain forms of skin cancer, prostate cancer, bone cancer, and others. Cryogenic liquid such as liquid nitrogen is used to freeze and destroy cancer cells and abnormal tissues [58]. The technique is proven to have a 99% success rate in treating cases of skin cancer [59,60] and low-risk breast cancer [61,62].

Refrigeration also plays a pivotal role in vaccines, a particularly striking example being the eradication of poliomyelitis. The polio vaccine, which is highly heat-sensitive and must be kept frozen for long-term storage, has contributed to a 99% reduction in polio cases since 1988 [63]. Recently, some vaccines have been developed that require ultra-low storage temperatures (below –60 °C). It is especially the case for viral vector vaccines, such as the Ebola vaccine, and vaccines that use genetic and nucleic acid techniques with fragments of the virus's DNA or RNA, such as the COVID-19 vaccine [64].

The global market of heat-sensitive health products, stored at controlled temperatures, have expanded tremendously in the past decade [65] and is expected to continue growing. Valued at an estimated USD 17.8 billion in 2023, the healthcare cold chain market is projected to expand at a compound annual growth rate (CAGR) of 9.0% through 2033 [66].

Superconductivity — a phenomenon enabled by cryogenic technologies — is central to Magnetic Resonance Imaging (MRI) scanners, helping provide high-definition images of patients vital organs or physiological processes within the human body. It is estimated that there are approximately 51,500 MRI machines worldwide processes within the human body. It is estimated that there are approximately 51,500 MRI machines worldwide [67]. MRI scanners use superconducting magnets, which are cooled to 4 K (–269 °C) using liquid helium. Helium recovery and liquefaction are also cryogenic processes.

Finally, air conditioning provides significant health benefits. In July 2024, the Secretary-General of the United Nations called for global action on extreme heat in response to the increasing frequency and duration of heatwaves. This underscores the crucial role of refrigeration in mitigating the effects of extreme temperatures, addressing vital human needs, and ensuring both access to safe food and public health during such events. According to the 2022 Lancet Countdown report on health and climate change, around 195,000 heat-related deaths were averted in 2019 thanks to air conditioning access among people aged 65 and older [39]. Heatwaves have been reported to be the deadliest natural disasters for older adults, with those suffering from cardiovascular disease, living in poverty, or residing in isolated, low-cost housing at the highest risk [68].

Image. A collection of vaccines stored in a fridge.

3.6. Refrigeration in industry, transport and energy sectors

Cryogenics — the science and technology of extremely low temperatures — has numerous applications across sectors such as the food and beverage industry, electronics, transport, transport, medicine, space science, and energy [69].

Air separation by cryogenic distillation is a mature technology for the mass production of air products like oxygen and nitrogen, which are used in a broad range of industrial applications. For instance, the consumption of high-purity oxygen by steel, medical, and chemical industries amounts to about 500 million tonnes per year [70], while liquid nitrogen is widely used in the food and beverage industry,from food processing to refrigerated transport in cryogenically cooled trucks.

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

In the energy sector, refrigeration plays a key role in gas liquefaction, which consists in cooling a gas below its boiling point so that it can be stored and transported in liquid phase. Natural gas accounts for a quarter of global electricity generation. Liquefying natural gas, a cooling process achieved through several refrigeration cycles, considerably reduces the volume to be transported, by a ratio of 1/600. Between 2019 and 2023, LNG demand grew around eight times the rate of overall natural gas consumption. In 2023, LNG accounted for half of inter-regional natural gas trade [71,72].

7 AFFORDABLE AND CLEAN ENERGY

Hydrogen has recently gained increased attention for its potential as a low-carbon energy source for applications in road transport , chemicals, iron and steel industries.

Over the last 20 years, commercial hydrogen liquefaction plants have been constructed in the U.S., Japan, Germany, Australia and South Korea [73]. In rocket propulsion, hydrogen is the fuel of choice [69]. Low-carbon hydrogen can be produced using renewable energy ("green hydrogen") or fossil fuels with carbon capture ("blue hydrogen"). Refrigeration can also be used for cryogenic carbon capture, which is based on the partial condensation of impurities in the off-gas generated during hydrogen production at low temperatures [74]. However, to date, production of low-emissions hydrogen with high levels of CO_2 capture is still limited [41].

The information and communication technology (ICT) sector relies heavily on refrigeration as well. For instance, 30% to 55% of energy consumption in data centres is used for cooling IT equipment [75]. Data centres were responsible for about 1.5% of global power consumption in 2022, with an annual growth rate of 20% to 40% [76]. Emerging cooling technologies, such as liquid cooling, could potentially halve the sector's energy consumption [77]. In addition, liquid-cooled data centres offer a higher potential for waste heat recovery due to their higher temperatures of waste heat [78]. Reusing waste heat from data centres presents a promising opportunity to reduce costs and increase efficiency.

Image. Air Liquide liquid hydrogen production facility. (Source: Mediakit)

3.7. Refrigeration in science and research

Refrigeration is central to major strategic scientific projects, serving as a foundational technology that enables breakthroughs across diverse fields. These projects not only push the boundaries of refrigeration technology but also spur innovation in energy efficiency, materials science, and thermal management, highlighting refrigeration's pivotal role in bridging scientific discovery and real-world applications. As global regulations rapidly evolve to address climate change and sustainability, industries must innovate to remain compliant and competitive. Science provides the knowledge and tools necessary for these advancements, enabling industries to develop cutting-edge refrigeration solutions that meet stringent regulatory demands. This interplay between science and innovation underscores the need for continuous research and adaptation, ensuring that industries can effectively navigate the fast-changing regulatory landscape while driving progress in both technology and sustainability.

Refrigeration for innovation in freshwater solutions

Ensuring universal access to safe drinking water by 2030 is one of the Sustainable Development defined by the United Nations (SDG 6), as water scarcity affects over 40% of the global population due to climate change [79]. Desalination is the most mature and commercially available solution for freshwater production, with the Middle East accounting for half of the world's desalination capacity [80]. Refrigeration is at the heart of recent innovative water solutions, such as atmospheric water harvesting, where water is extracted from the air, cooled to induce condensation, and then collected [81]. Another technique, known as freeze desalination, involves freezing seawater on a cold surface, separating the saline brine, and then melting the ice crystals to obtain freshwater [82].

Refrigeration for innovation in computing technology

Quantum computers can solve problems that are too complex for classical computers thanks in part to a phenomenon called superposition. While the building blocks of a classical computer — bits — can take a value of either 0 or 1, the most common building blocks in quantum computers — qubits — can have a value of 0 and 1 simultaneously. This superposition enables quantum computers to perform parallel computations. Refrigeration is essential to this technology, for qubits must be cooled to cryogenic temperatures, just a fraction of a Kelvin above absolute zero, to perform without errors for long periods of time.

Refrigeration for biomedical research

Cryopreservation and cold storage are essential for preserving biological samples, vaccines, and organs for transplantation, driving advancements in medicine, biotechnology, and public health. By cooling materials to ultra-low temperatures, often using liquid nitrogen at –196 °C, metabolic processes are halted, preventing degradation and extending viability. This technology supports critical applications such as storing cell lines for research, preserving reproductive materials for fertility treatments, and maintaining the efficacy of temperature-sensitive vaccines through robust cold chain systems. However, challenges such as ice crystal formation, cryoprotectant toxicity, and the complexity of whole-organ preservation remain areas of active research. Innovations in vitrification, nanotechnology, and sustainable refrigeration are paving the way for more efficient and scalable solutions, ensuring these technologies continue to meet the demands of modern science and healthcare.

Refrigeration for innovation in physics

Particle accelerators offer a wide range of research applications in industry, nuclear physics, and even medicine, including medical imaging or tumour radiation treatments. To date, CERN's Large Hadron Collider (LHC) remains the world's largest and most powerful particle accelerator. It consists of a 27-kilometre ring of superconducting magnets, maintained at –271.3 °C using superfluid helium, enabling the high energies needed to test fundamental particle physics theories. In 2021, Stanford University proposed a concept for a more energy-efficient particle accelerator at a lower operating cost. The proposed Cool Copper Collider (C3) uses a cryogenically cooled — using liquid nitrogen —, normal-conducting linear accelerating structure [83].

Launched in 2021, the James Webb Space Telescope (JWST) is considered as the flagship astrophysics project for 2020-2040. Built in collaboration between the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Canadian Space Agency (CSA), the JWST is the premier observatory to explore galaxies, observe planets orbiting other stars than the Sun, and study our own solar system. The JWST Mid-Infrared Instrument (MIRI) carries detectors that need to be cryogenically cooled at a temperature below 7 Kelvin to operate properly. The Webb MIRI cryocooler is an innovative system which reuses its own liquid helium as a cooling source [84].

In Europe, stakeholders from scientific institutions, businesses and governments from the Netherlands, Belgium, and Germany are collaborating to build the Einstein Telescope (ET), a third generation gravitational-wave detector [85]. The goal is to develop a large-scale research infrastructure for advancing scientific exploration of the cosmos. While second generation detectors operate at room temperature, the ET will feature a low-frequency interferometer operating at cryogenic temperatures between 10 K and 20 K. This equipment will allow the study of celestial objects in finer detail than even the largest telescopes, opening a new window to precision astronomy.
ing the efficacy of temperature-sensitive vaccines through robust cold chain systems. However, challenges such as ice crystal formation, cryoprotectant toxicity, and the complexity of whole-organ preservation remain areas of active research. Innovations in vitrification, nanotechnology, and sustainable refrigeration are paving the way for more efficient and scalable solutions, ensuring these technologies continue to meet the demands of modern science and healthcare.

3.8. Leisure and sports

In the context of global warming, ski resorts and Winter Olympic Games rely increasingly on technological adaptations such as snowmaking and refrigeration systems. Worldwide, snowmaking coverage ranges from about 40% of ski resorts in France to about 90% in Italy, the U.S. or China [86–89]. **The IIR estimates that snowmaking represents close to USD 2 billion in annual investment costs for ski resorts globally**.

Furthermore, the production of artificial snow is energy intensive. In Canada, snowmaking uses about 478,000 megawatt-hours of electricity annually — with 130,095 tonnes of associated CO_2 emissions — which is equivalent to the annual consumption of 43,000 Canadian homes [90].
New and recently retrofitted snowmaking systems are significantly more efficient, incorporating heat recovery for district heating and optimised refrigerating systems using environmentally friendly refrigerants [91]. Similarly, in ice rinks, heat recovery from the refrigeration system is used to meet the facility's heating demands, offsetting the fact that the refrigeration system is the largest energy user (40% to 65%) [92].

4. REFRIGERATION AND CLIMATE

4.1. Refrigeration and energy consumption

In today's global economy, the expansion of the cold chain accompanies economic development, electrification, and population growth. As a result, global electricity consumption is affected by the growing number of units of refrigeration equipment installed (see Figure 2 for the rising number of air conditioners).

The IIR estimates that the refrigeration sector — excluding heat pumps — consumes approximately 20% of the overall electricity used worldwide. Air conditioning alone accounts for around 12% of global electricity consumption [93]. Given the increase in refrigeration equipment installed worldwide, the global electricity demand for refrigeration could more than double by 2050, in a scenario similar to the IEA Stated Policies Scenario, based on policies currently in place (see IIR modelling scenarios in Dupont and Oudart (2024) [93]).

It should be noted that air conditioners currently available on the market are over 40% more efficient than models sold 20 years ago [41]. The energy demand and CO_2 emissions associated with air conditioning can be curbed through the widespread adoption of stringent minimum energy performance standards (MEPS). The IEA states that air conditioners sold in emerging and developing economies in 2030 may be 50% more efficient than today's models in a Net Zero Scenario, combining energy efficiency policies and technological improvement across all regions [41].

Numerous technological strategies are also being investigated to reduce energy consumption. For instance, with their ability to provide both heating and cooling, heat pumps offer substantial energy savings. Regarding other air conditioning systems, researchers have explored applying non-uniform indoor environment to optimise thermal comfort for occupants and reduce energy consumption. This concept enables designers to avoid serving vacant areas using complex modelling and temperature and CO_2 sensors to detect occupancy. This research on non-uniform indoor environment can be applied in workspaces, shopping centres, airports or even data centres [94].
In food retail, refrigeration equipment accounts for 30% to 60% of electric energy consumption in supermarkets [95]. The energy efficiency of this equipment is even more critical, as it operates year-round. In moderate and cold climate regions, recovering heat from refrigeration systems for heating purposes in the colder season is a regular practice and can result in significant energy savings, specifically when applying CO_2 as a natural refrigerant [95].

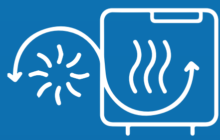
Passive cooling strategies provide another way to promote more sustainable cooling. For air conditioning, measures such as insulation, natural shading and ventilation, or reflective surfaces can effectively lower cooling demands. Passive cooling strategies have been shown to reduce the cooling load of residential buildings by 25%, even in tropical climates [96, 97].

Image. Industrial area emitting large amounts of smoke and air pollution into the atmosphere during sunset. (Source: Shutterstock)

ENERGY-EFFICIENT REFRIGERATION: KEY TECHNOLOGIES AND REGULATIONS

HEAT PUMPS

Ground-source heat pumps can cut energy demand by up to 50% in cooling mode and up to 40% in heating mode



DISTRICT COOLING

District cooling using deep cold seawater can cut electricity consumption and costs by 80% compared to conventional AC systems

BUILDING PASSIVE COOLING

Passive cooling measures in residential buildings can cut cooling load by 25%, even in tropical climates

REGULATIONS

The adoption of MEPS can cut energy use by up to 50% by 2030 in developing countries

Figure 5. Key energy-efficient technologies and regulations

4.2. Refrigeration carbon emissions

Refrigeration technologies contribute to advancing environmental aspects of sustainable development goals, for instance through the cryopreservation of plant and animal genetic resources to protect biodiversity, in line with SDG 15.

15 LIFE ON LAND

In addition, refrigeration technologies can serve to capture CO_2 from industrial plants through cryogenic carbon capture, a technology still in its early stages of development.

However, the refrigeration sector also has significant environmental impacts. According to IIR estimates, emissions from the refrigeration sector account for approximately 7.5% of global CO_2 emissions in 2023 [97]. This represents about 10% of global energy-related emissions, which totalled 37.4 $GtCO_2e$ in 2023.

Around 30% of refrigeration's global-warming impact is due to direct emissions from the leakage of fluorinated refrigerants into the atmosphere (CFCs, HCFCs, and HFCs). The remaining 70% comes from indirect emissions originating from the electricity production required to power refrigeration systems [98]. It should be noted that indirect emissions have decreased in recent years, due to grid decarbonisation in some regions.

13 CLIMATE ACTION

The refrigeration sector accounts for 7.5% of global CO_2 emissions

To combat global warming, stakeholders in the refrigeration sector are implementing actions with a two-fold objective:

- Reduction of direct refrigerant emissions:

  Direct emissions of refrigerants are being addressed through the enhancement of refrigerant containment, minimisation of refrigerant charge, improvement of end-of-life recovery processes, and the adoption of alternative refrigerants with low global warming potential. Additionally, training and certification programs for technicians are being expanded to ensure proper handling and disposal.

- Reduction of primary energy consumption:

  Reducing primary energy use by increasing the efficiency of refrigeration systems, thereby reducing indirect emissions associated with energy production.

Carbon emissions from the refrigeration sector

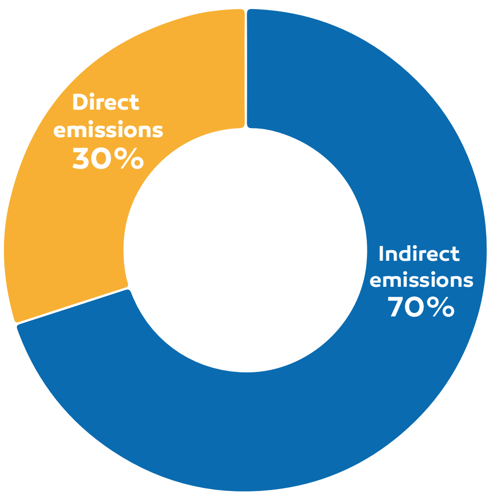


Figure 6. Carbon emissions from the refrigeration sector, according to IIR estimates using global emissions data from IEA

Adopted in 2016, the implementation of the Kigali Amendment to the Montreal Protocol contributes to reducing direct GHG emissions by gradually phasing out the global production and consumption of HFCs. In Europe, the EU has made significant strides in the phase-down of HFCs thanks to its regulation on Fluorinated Greenhouse Gases Regulation (hereafter EU F-Gas Regulation) initially implemented in 2006. In February 2024, a revised version of the regulation (2024/573) was adopted, which includes a total HFC phase-out by 2050 and accelerates the transition to natural refrigerant-based alternative technologies. Similarly, in the U.S., the American Innovation and Manufacturing (AIM) Act of 2020 set an ambitious goal to reduce HFC production and consumption by 85% by 2036.

The global phase-down of HFCs could help prevent a 0.1 °C–0.3 °C increase in average global temperatures by 2100 [99]. Addressing emissions from refrigeration is indeed a key component of the global effort to meet the Paris Agreement's goals of limiting the global average temperature rise to well below 2 °C above pre-industrial levels, and pursuing efforts to keep it under 1.5 °C.

The Paris Agreement mandates its 196 signatory countries to establish and regularly update Nationally Determined Contributions (NDCs). Integrating the refrigeration sector into NDCs — through specific targets and actions related to energy efficiency and refrigerants — allows governments to develop targeted, effective strategies for resource mobilisation and secure access to international climate financing needed to achieve mitigation goals [100]. As of November 2024, half of the countries that developed and updated NDCs had either provided information on the refrigeration sector (21% of countries) or at least covered HFCs within the scope of the targeted greenhouse gases [101].

Image. Forest with CO_2 icon in the foreground. (Source: Shutterstock)

IIR RECOMMENDATIONS

Refrigeration, as defined by the IIR, encompasses the cold chain for food and health products, air conditioning, cryogenics and heat pumps. It is a cross-cutting sector that influences vital aspects of economic and social growth. Integral to economic development, food safety, healthcare and energy systems, refrigeration must be prioritised when addressing global energy and environmental challenges. To fully harness its potential, the sector needs to be structured to maximise synergies and benefits across these interconnected areas.

Establishing a national governance model, such as national committees, should be promoted as a key action to structure the sector and ensure that its cross-cutting nature is addressed effectively. These committees — comprising representatives from government, industry, academia, and civil society — can serve as platforms for better collaboration, policy development and integration, and capacity building. They can help align national refrigeration strategies with global sustainability goals, such as the Paris Agreement and the Kigali Amendment to the Montreal Protocol, while supporting the implementation of national action plans. National committees can also facilitate the integration of refrigeration into broader economic, energy, and climate policies, ensuring that the sector contributes to national and international targets.

Governments and national stakeholders are encouraged to incorporate refrigeration into their Paris Agreement NDCs and to develop national cooling and heating action plans. These documents provide a framework for coordinating efforts to advance sustainable refrigeration across all sectors. Actions plans help define the pathways for market transformation towards energy-efficient, climate-friendly, and more affordable refrigeration solutions through programmes such as Minimum Energy Performance Standards (MEPS) and labelling, awareness campaigns, and rebate schemes for energy-efficient refrigeration systems using low Global Warming Potential (GWP) refrigerants.

Assistance should be provided to developing countries to reach the refrigeration capacities required to reduce food loss, ensure food safety, and safeguard human health. Investments should be directed toward developing or strengthening the appropriate refrigeration infrastructure, particularly in regions where food loss and limited access to refrigeration technologies pose significant challenges. **Financial mechanisms — such as international climate funds, green financing, and public-private partnerships — should be leveraged to support these investments**. These mechanisms can help mobilise the necessary resources to bridge the gap in refrigeration capacities, enabling developing countries to adopt sustainable and energy-efficient solutions. Additionally, targeted grants, concessional loans, and technology transfer programmes can facilitate the deployment of refrigeration technologies tailored to local needs and conditions.

Industries should integrate scientific advancements into refrigeration innovation to meet fast-changing regulations and sustainability goals. Investing in energy efficiency, materials science, and thermal management will ensure regulatory compliance, reduce environmental impact, and maintain competitiveness. Collaboration between science and industry is key to developing cutting-edge solutions that address regulatory demands while driving progress.

The energy efficiency of refrigeration plants — large-scale systems used for industrial cooling, cold storage, and district cooling — should be improved to limit refrigeration's impact on global energy consumption and enhance energy security. This requires further research and development to integrate renewable energy sources (such as solar, wind, geothermal, and biogas) into innovative, energy-efficient refrigeration technologies. This also involves policy measures to encourage consumers to adopt increasingly efficient refrigeration equipment.

Both governments and the refrigeration industry must commit to complying with global agreements aimed at reducing emissions from high-GWP refrigerants used in refrigeration systems. This includes measures such as leakage control, refrigerant charge reduction, and end-of-life recovery. The use of natural refrigerants offers a sustainable alternative to traditional, synthetic refrigerants, with lower environmental impact. However, these systems require appropriate design and well-trained workforce.

The refrigeration and heat pump sector is facing a labour shortage, which must be addressed by advancing workforce training and qualification. The adoption of more energy-efficient, climate-friendly refrigeration systems offers a unique opportunity to attract young professionals to promising refrigeration-related careers, combining technological innovation with positive environmental impact.

Refrigeration-related research and development must be actively supported by national and international authorities, funding agencies, and public and private industry stakeholders in order to achieve sustainable economic development and improve health and well-being, food safety, energy efficiency, and environmental sustainability worldwide.

APPENDIX

6.1. Estimating the quantity of refrigeration equipment worldwide

The IIR has assessed the number of refrigeration equipment units in operation worldwide based on published sources and previous IIR estimates. See references listed in Table A1.

Sector	Equipment	Number of units in operation in 2024	References	Method
Domestic refrigeration	Refrigerators and freezers	2.2 billion	33	IIR estimates
Commercial refrigeration	Commercial refrigeration equipment (including condensing units, stand-alone equipment, and supermarket systems)	120 million	75	
Refrigerated transport	Refrigerated vehicles (vans, trucks, semi-trailers or trailers)	5.7 million	26	Reference + IIR estimates
	Refrigerated containers (“reefers”)	2 million	102	Reference + IIR estimates
Refrigerated storage	Cold stores	85,000	18–20, 103	Reference + IIR estimates
Stationary air conditioning	Residential air-conditioning units	1.3 billion	93	IIR estimates
	Commercial air-conditioning units (including chillers)	215 million	93	IIR estimates
Mobile air conditioning	Air-conditioned vehicles (passenger cars, commercial Vehicles, and buses)	1.3 billion	44	
Medicine	Magnetic Resonance Imaging (MRI) machines	51,500	67	
Liquefied Natural Gas (LNG)	LNG liquefaction plants	138	104	
Heat pumps	Heat pumps (residential, commercial and industrial equipment, including reversible air-to-air air conditioners)	200 million	105, 106	
Leisure and sports	Ice rinks	19,600	107	Reference + IIR estimates

Table A1. Published data and IIR estimates on refrigeration equipment in operation worldwide

6.2. Estimating the global refrigeration workforce

The International Standard Industrial Classification of All Economic Activities (ISIC) does not clearly distinguish the refrigeration industry, as employment in refrigeration, air conditioning and heat pumps spans multiple sectoral classifications of workers and activities. For example, using the ISIC classification, data from the International Labour Organization (ILO) shows that over 194 million people were employed in the "electricity, gas, steam, and air conditioning supply" sector in 2023 [108], which is too broad a category for the scope of our analysis. Similarly, the International Energy Agency (IEA) includes HVAC (heating, ventilation, and air-conditioning) and heat pump jobs under "key energy end uses" in its World Energy Employment report, but this category also covers vehicle manufacturing and energy efficiency in buildings and industry [13].

Regarding employment, the aim in this technical brief was to assess employment in the global refrigeration industry, encompassing the manufacturing, installation, maintenance, and servicing of all types of refrigeration equipment. The estimated number of workers in the refrigeration industry was derived from available national country reports and extrapolated at the global scale.

Employment data was collected from national labour surveys, National Cooling Action Plans, and national refrigeration associations (see references listed in Table A2), and the proportion of refrigeration workers relative to the total labour force in each country was then calculated. These ratios were applied to the global labour force, differentiating between income groups according to the World Bank's country classifications [109]. A distinction was made between middle-income and high-income countries, considering that high-income countries — particularly Australia and in North America — have the highest energy-related workforce per capita in the world [13].

Countries with available data	Direct jobs in refrigeration, including manufacturing and wholesale trade of equipment when available	References	World Bank country classifications by income level
Australia	378.000	6	High income
United States	801,517	7,11	High income
Canada	108,751	110–112	High income
Brazil	250,000	113	Upper middle income
China	1,605,000	Chinese Association of Refrigeration (CAR)	Upper middle income
Colombia	21,525	ACAIRE	Upper middle income
Mexico	129,100	114,115	Upper middle income
Bangladesh	50,000	National cooling action plan	Lower middle income
Ghana	5,000	116	Lower middle income
India	200,000	23	Lower middle income

Table A2. Available national data on the number of direct jobs in refrigeration.

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