


Mapping Existing Solutions and Best Practices on Sustainable Cooling

Scoping review


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Abbreviations and acronyms

AC	Air Conditioner
CaaS	Cooling as a Service
CAQDAS	Computer-assisted Qualitative Data Analysis Software
CFC	Chlorofluorocarbon
CO2	Carbon Dioxide
DX	Direct Expansion
EE	Energy Efficiency
GHG	Green House Gases
GIZ	German Corporation for International Cooperation
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
IEEE	Institute of Electrical and Electronics Engineers
KCEP	Kigali Cooling Efficiency Program
MAC	Mobile Air Conditioning
MCP	Multi-country Publications
MEPs	Minimum Energy Performance Standard
NCAP	National Action Plans
NDC	Nationally Determined Contributions
PICOS	Population, Intervention, Comparison and Outcomes
PRISMA	Preferred Reporting Items for Systematic Review
PROSPERO	International Prospective Register of Systematic Reviews
PV	Photovoltaics
RAC	Refrigeration and Air Conditioning
RACHP	efrigeration, Air Conditioning and Heat Pumps
RE	Renewable Energy
SCP	Single Country Publications
SDG	Sustainable Development Goals
TR	Ton of Refrigeration
UN	United Nations
WHO	World Health Organization

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Executive summary

The review in brief

Worldwide, cooling energy demand has increased sharply in the last few decades, which has raised concerns over depletion of energy resources and the contribution to global warming. As the world transitions to clean energy, becomes more urbanised, and is subject to increasing temperatures due to climate change the issue of cooling comes into greater focus. The COVID-19 pandemic and the new mRNA vaccines, with their low temperature transport requirements, have further highlighted the need for reliable vaccine cold chains. The total globally pledged COVID-19 economic stimulus package funding, currently in the order of US$14 trillion, provides an opportunity to accelerate the development and implementation of sustainable cooling solutions. Given the urgency and magnitude of this challenge and the need for multi-disciplinary delivery mechanisms to tackle these issues there is an urgent need to understand the issues of access, technologies, policies, and available best practices for cooling around the world. Although there are reviews available that discuss cooling solutions none of these aims to understand the status of cooling sectors and the available technology that might help policies development for sustainable cooling and tracking of impacts and progresses.

What is this review about?

This scoping review is intended to map the issues and best practices related to cooling technologies for space cooling in buildings, cold chain (healthcare and food), mobile air-conditioning (only transport) and access to cooling. It identifies the most recurrent problems, barriers and solutions for sustainable cooling in different sectors involving cooling and access to cooling. The review summarises findings from 192 peer reviewed papers, reports, and unpublished documents of which, 11% mentioned access to cooling, 21% cold chain-healthcare, 18% cold chain-food, 8% mobile cooling, and 78% space cooling (some of these documents mentioned more than one sector).

The review includes studies using experimental, simulated or quasi-experimental designs to provide an understanding for each cooling sector and its current status. Included studies were the range of cooling technologies and policies available in different cooling sectors, issues related to cooling technologies, emissions from cooling technologies, and best practices in cooling technologies and policies. This study examined similar reviews that provide guidance for developing best practice recommendations for the implementation of sustainable cooling strategies.

Search methods

A primary search for the review began on 1 February 2021 and was updated in April 2021. The Scopus, Web of Science, IEEE, and Google Scholar bibliographic citation databases were included in the primary search. Snowballing methods[1] were also employed to identify relevant studies which were not covered in the primary search.

Data collection and analysis

A minimum of two independent review authors assisted in determining the review's inclusion and exclusion criteria. The inclusion and exclusion process focused on the screening of document titles and abstracts, as well as examining full text reports. The review authors independently extracted the data for all eligible studies. The findings were presented using a narrative synthesis across all the studies.

What are the main results in this review?

Access to cooling

Access to cooling is a critical element in achieving most Sustainable Development Goals (SDGs). However, if not managed sustainably an increase in cooling load will create a feedback loop by increasing the demand for electricity and associated emissions, leading to increased global warming. The solutions of highly efficient and low Global Warming Potential (GWP) technologies already exist, but they require urgent policy actions

1 Snowballing refers to using the reference list of a paper or the citations to the paper to identify additional papers. Claes Wohlin (2014) Guidelines for Snowballing in Systematic Literature Studies and a Replication in Software Engineering, EASE '14, May 13 - 14 2014, London, England, BC, United Kingdom Copyright 2014 ACM 978-1-4503-2476-2/14/05

to enable uptake by consumers. In addition, there is a need for research to make these technologies available and affordable to low-income countries. Lack of awareness and knowledge of the cooling sector as well as the benefits of cooling access among manufacturers, governments, users and investors are mentioned across all publications surveyed. The right policy and financing environments are essential for the growth of access to cooling.

Cold Chain - Healthcare and Food

The cold chain plays a major role in both the health care and food sectors. Maintaining the cold chain is important to ensure that effective and potent vaccines are administered to patients. Vaccines exposed to temperatures that are too high or too low can lose their effectiveness and even be deadly to the vulnerable populations they are intended to protect. Most recently, cold chains are playing an important role in the delivery of COVID-19 vaccines to enable populations to reach herd immunity. Amongst the most common barriers faced in low income countries failure of cooling equipment (15.25 per cent), lack of training (10.17 per cent), human errors (6.78 per cent) and lack of standards for cooling equipment (5.08 per cent) are the main ones. Some solutions identified in the literature include solar cooling, phase change materials, drones as a transport option, equipment reliability, electricity supply and reliability, reliable monitoring and maintenance programs, access to finance and research and development of new cooling technologies. Equipment failure, and lack of spare parts or maintenance, and lack of appropriate training are also considered to be critical risks for the use of vaccine cold storage in remote locations.

The role of the cold chain in the supply of food is expanding and can reduce waste in the supply chain. While efficient refrigeration equipment is important for cold chain management, other aspects such as trained personnel, effective and efficient management practices also play a crucial role in efficient management of the healthcare and food cold chains. Phasing out HFCs and increasing overall energy efficiency in the Refrigeration and Air conditioning (RAC) sector is needed to reach the Paris Agreement greenhouse gas (GHG) reduction targets supported through Montreal Protocol's Kigali Amendment. Poorly designed systems and outworn or badly maintained equipment are the typical challenges in RAC sector found in many developing countries. These issues reduce the energy performance of the equipment. Refrigeration systems rely heavily on refrigerants which releases significant amounts of HFCs into the atmosphere due to leaking during operation and servicing.

With the rising temperatures due to climate change, cooling demand for cooling food is also expected to increase and thereby presents an additional challenge. The energy demand of food cold chains is influenced by a range of factors beyond the principle choice of a cooling technology and cooling unit size, such as climatic conditions (humidity, temperature), type of crop or value-added yield and storage design. Some solutions for the cold chain - food sector found in the documents reviewed are solar cooling, community cooling hubs, insulated refrigeration systems, enforcing standards in cold chain management, Cooling as a Service and access to finance for research and development.

Space Cooling (Residential and Commercial Buildings)

The building sector is responsible for consumption of around one-third of the total primary energy resources in the world and releasing 30 per cent of global CO_2 emissions. A summary of the documents reviewed in this area concludes that space air conditioning is responsible for approximately 40 per cent of the total energy consumption in residential and commercial buildings globally. Space cooling, typically using an electric-powered fan or air conditioning (AC) system, currently contributes substantially to global energy demand. Furthermore, energy demand for cooling buildings is projected to increase by about 80 per cent by 2050 compared to 2010 baseline.

Energy consumption in the building sector to provide cooling is the most significant issue that authors cite when developing strategies to reduce cooling impact. The amount of energy to satisfy cooling needs becomes an issue because energy generation is still highly carbon intensive and cooling becomes an indirect greenhouse gas emitter. The rapid increase in air conditioning systems as the first choice for cooling, unsustainable building design that requires increased cooling, increased frequency of heatwaves as a result of climate change are some of the drivers for increased energy consumption. Improving building energy performance can substantially reduce the building cooling load. The amount of active cooling needed can be reduced by introducing passive design, and therefore it is important to consider the thermal performance of the building, when including opportunities for passive cooling. This also equally applies whether buildings are built new or renovated. Building codes have been proven to play a major role in driving better practices in the use of materials for building envelope, heating, cooling, ventilation, and lighting to reduce energy consumption. Cooling as a Service and district cooling are examples of other ways of providing a more efficient cooling services.

Mobile Cooling

Mobile cooling from both air conditioning and refrigeration of goods is energy intensive and represents as much as 20 per cent of vehicle energy consumption. The mobile air conditioning (MAC) and refrigeration rely on the use of refrigerants. These systems use power to remove heat and moisture from the air inside the vehicle and transfer it outside. Reefers[2] are estimated to consume up to 19 per cent of the energy used to move refrigerated food stuffs large distances and most rely on external electrical power from the port while ashore. Due to the expected increase in passenger transport by 2030, improving efficiency and using more renewable energy will not be sufficient as a 70 per cent reduction in energy consumption from this sector is needed to meet the growing cooling demand. Transport sector is a significant contributor to global greenhouse gas emissions of which almost 80 per cent comes from road transport.

Several technologies to address this such as seat ventilation, cabin ventilation, solar glazing of windows, or climate control seating were discussed as potential solutions in the documents reviewed. Other technological solutions include different vapour compression systems, thermal storage, vacuum cooling, and absorption chilling. Renewable energy (RE) was suggested as a cleaner and more efficient mode of supplying cooling energy in this sector. Despite the low share of RE in transport it has recently attracted policy makers' attention in many countries. Decarbonizing transport, fuel tax, standards such as fuel and emissions standards, regulations (e.g. EU F-gases, phase down of Hydroflurocarbons (HFCs)), research and development and shifting to low GWP refrigerants were also mentioned as solutions.

Process Cooling

Process cooling systems, sometimes referred to as industrial cooling, are used in various industries, including data centers, petrochemical, pharmaceutical, food and beverage, plastics, and healthcare. It is a critical requirement for equipment cooling, refrigeration, heat extraction, and maintaining the required temperature during manufacturing or other processes. Only a few documents (less than 3%) were found to mention process cooling during the literature search. Due to the limited availability of literature highlighting details of process cooling, a thorough analysis of issues, challenges, and opportunities has not been possible. Barriers for process cooling mentioned in these documents were limited to refrigeration (for storing food and medicine) and air-condition (for space cooling). These include lack of supportive regulatory framework, lack of qualification and certification programs, high upfront and transaction costs, limited access to finance for market and research, and lack of knowledge of economic benefits.

2 Reefers are Refrigeration containers [1] J. H. R. van Duin, H. Geerlings, A. Verbraeck, and T. Nafde, "Cooling down: A simulation approach to reduce energy peaks of reefers at terminals," Journal of Cleaner Production, vol. 193, pp. 72-86, 2018/08/20/ 2018, doi: https://doi.org/10.1016/j.jclepro.2018.04.258.

Summary of findings

Evidence from the review found that 'access to cooling' is a critical element in achieving most SDGs, however, if not managed sustainably, an increase in cooling load will create a feedback loop by increasing electricity demand and associated emissions leading to increased global warming. Solutions for higher efficiency and lower GWP technologies already exist, but they require urgent policy actions to enable uptake by consumers. In addition, there is a need for research to make these technologies more available and affordable to low-income countries.

Despite the political, financial, and human dimensions of vaccines supply (such as COVID-19 vaccines) and food cold chain issues, thus far the overall decision-making challenges in technology-supported cold chain management have received very little attention in the published research. While efficient and reliable equipment is important for cold chain management other aspects such as trained personnel and effective and efficient management and maintenance practices also play a crucial role in the healthcare and food cold chains.

This scoping review found that in almost all cases unsustainable building design contributes to high cooling requirements so improving building energy performance can substantially reduce the building cooling load. The amount of active cooling needed can be reduced by introducing passive design approaches, and therefore it is important to consider the thermal performance of the building including opportunities for passive cooling. Building codes have been proven to play a major role in driving the use of more sustainable heating, cooling, ventilation, and lighting.

Based on the qualitative analysis of the literature many programmes that use Mandatory Energy Performance Standards (MEPS) have proven it to be the single most effective policy measure for boosting the efficiency of cooling appliances and equipment, including air conditioners (ACs) and refrigerators. In setting and applying MEPs policymakers need to consider the actual energy efficiency of ACs available in the market and use accurate energy performance measurement standards, protocols and testing procedures. Some other key policies and approaches include introducing policies on accelerating the transition to low-GWP and high-efficiency cooling, strengthening building codes and appliance labelling policies, developing national databases and improving data collection on cooling technologies and improving information access.

The review found that the volume of publications focusing on sustainable cooling has increased substantially following the ratification of the Kigali Amendment of the Montreal Protocol in 2019 – about 38 per cent in just two years compared to 62 per cent between 2007 and 2018. The cluster analysis of keywords, titles, and abstracts in the sustainable cooling articles studies were found to have highlighted the following key terms: building thermal comfort and air conditioning; cooling systems efficiency and performance; and energy use simulation and modelling. This study used these terms to identify technological best practices and enabling policy measures in each sector.

What do the findings in this review mean?

Because of the limited evidence base, the effects of cooling technologies on energy consumption could not be determined with any confidence. While this scoping review suggests several potential benefits of sustainable cooling technologies and policies, it also points to the need for practical, action-based quantitative research on sustainable cooling technologies and policies and understanding existing baselines, practice and barriers especially in developing countries.

Key Lessons and Policy Recommendations

Based on the findings of this bibliometric and qualitative analysis, the authors have identified the following policy recommendations:

- This review shows that providing 'Cooling for All' will provide a substantial challenge to national energy budgets, CO2 targets, and climate goals in the future which demands an immediate change to more sustainable and high energy efficient cooling technologies.
- Most of the articles reviewed demonstrate simulated results on cooling technologies and management but failed to provide real world, action-based, quantitative research results on practical implementation. Therefore, there is a need for more country specific empirical research.
- Policies should be aimed at reducing cooling needs through demand management and shifting to low emissions cooling which include low GWP refrigerants, district cooling and renewable powered cooling.
- There is a need to understand cooling from a demand perspective and how solutions and end-user choices change with what they can afford to access.
- There is also a need for policy to improve the efficiency and manage the waste from incumbent cooling technologies.
- Targeted support and localised solutions are needed to provide affordable access to more sustainable cooling, especially in developing countries.
- Fundamental research is needed on Refrigeration and Air conditioner (RAC) technologies, minimum standards for equipment and infrastructure, transport cooling technologies, and low-cost cooling technologies for all cooling sectors.
- Skills development and education are needed to support the research to enable the effective and efficient deployment and maintenance of cooling technologies in developing countries. This is also critical to ensuring that sustainable cooling solutions are run in climate friendly and energy efficient manner and after installation maintenance is important.
- Innovation is required in the energy supply system, thermal energy storage, including transport, and novel business models (e.g., district cooling or cooling as a service) as the transition to the use of renewable energy continues.
- "Fit-for-market" business and financial models are the key to successful intervention as they will enable access, affordability and return on investment.

Authors' conclusions

Cooling is a complex problem that requires a holistic system-based approach in order to provide suitable solutions to the issues identified. Carrying out a scoping review that includes all sectors is complex because each sector represents a different problem with different datasets. Establishing a comparison across this data is impractical, and in some cases, insufficient data is available.

Each country has different existing practices and needs across different cooling sectors, which require specific strategies and approaches. Therefore, a deep dive into country- and-city level data is needed to understand current cooling access, practices and issues and to develop evidence-based, tailored strategies and solutions for sustainable cooling.

01

Chapter 01

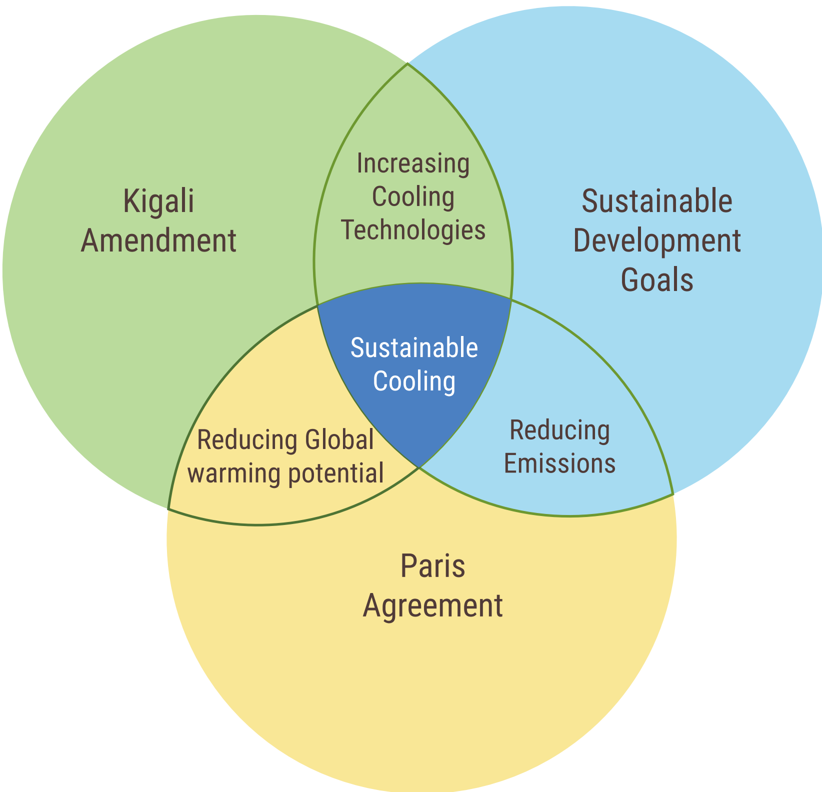
Background

The year 2019 has been a record-breaking year for global temperatures [2]. As a result, significant populations are at increasing risk from a lack of access to sustainable cooling. Such events threaten our ability to achieve the Sustainable Development Goals (SDGs), particularly goals in the areas of energy and health. About 1.05 billion people in rural and urban areas do not have access to cooling, including adequate refrigeration[3]. To operate a fan or air conditioner, energy access is needed. According to SEforALL (2018), air conditioning, refrigeration, and mobile cooling accounted for 3.4 per cent of the world's total final energy demand in 2018 [4].

In a warming world, access to sustainable cooling is not a luxury, but is somewhat of a basic need. It is an issue of equity and must be considered as an essential service to achieve the SDGs. 'Cooling for all' is not only providing an air conditioner or a refrigerator in every home but is a much broader issue [5-7]. Sustainable cooling is also needed to provide affordable access to nutritious food, safe medicines, and protection from heat [8, 9]. In addition, sustainable cooling is necessary to address the cooling needs of the vulnerable as the world transitions to clean energy and an increasingly warmer world [10].

There is a requirement to develop enabling strategies focusing on renewable and sustainable cooling solutions in all countries to achieve emissions reduction commitments under the 2015 Paris Agreement. The transition from existing cooling practices to more sustainable solutions provides an opportunity to reduce energy consumption, avoid carbon emissions and create more jobs [11-13]. However, despite the positive publicity from improved practice and technology benefits enough attention has not been paid to the policies required to ensure such a transition [14].

Figure 1: Linkage between SDGs, Paris Agreement and Kigali Amendment

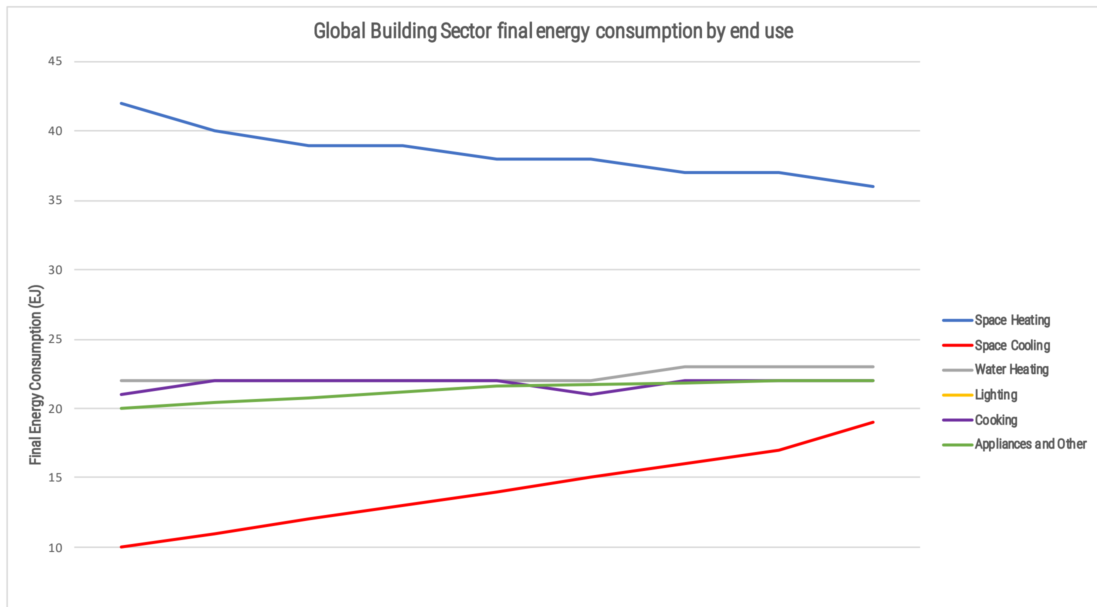


Meeting cooling demand with emerging efficient solutions creates a direct intersection between three internationally agreed agendas and goals for the first time (Figure 1): the Paris Agreement, the Sustainable Development Goals, and the Montreal Protocol's Kigali Amendment [4]. These global goals and agreements call for a significant reduction in the production and use of high-GWP hydrofluorocarbons (HFCs), potent greenhouse gases widely used in air conditioners and refrigerators [10].

Sustainable cooling solutions will also deliver significant benefits across the global economy to nations, corporations, businesses, and populations. In addition, achieving sustainable cooling will go a long way to providing the basic needs for cooling [15].

The global demand for cooling is rapidly increasing and has tripled since 1990 [3]. As a result, it has become the fastest-growing service by end-use within the building sector. Figure 2 depicts the trend of cooling demand in terms of energy consumption.

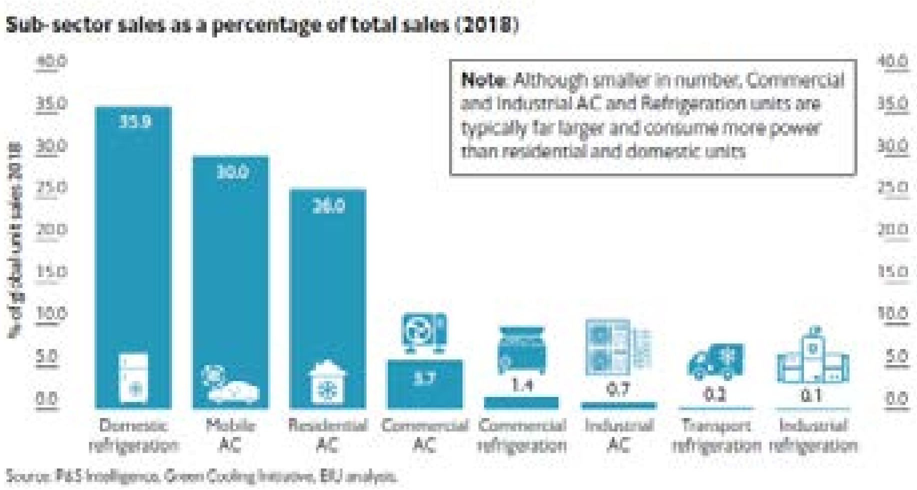
Figure 2 Global Building Sector Final energy consumption by end-use (Adopted from IEA, 2018)



Globally, space cooling accounted for 8.5 per cent of the electricity demand in 2019, and without action to address energy efficiency, energy demand for space cooling is expected to triple by 2050 [5]. Moreover, demand is especially multiplying in developing countries with 80 per cent of the refrigerator and air conditioner (RAC) market estimated to be located in developing countries [16]. In addition, there is a massive growth in electricity demand due to the growing demand for cooling equipment, challenging energy supply infrastructure arrangements [17].

A lot of research is being undertaken to develop efficient cooling technologies. Despite this, the overall energy consumption of the cooling sector is estimated to increase by 90 per cent by 2050 compared to the 2018 level [18]. Higher demand for air conditioning is directly related to higher electricity demand and increased pollution. Hydroflurocarbons (HFCs) have been found to have a significant impact on global warming, and the Kyoto protocol regarded HFCs as the second primary source of global warming after CO_2 emissions. Approximately 2.5 per cent of the 37.1 Gtons of Carbon Dioxide (CO_2) equivalence were emitted from refrigeration systems worldwide in 2018 [19]. Figure 3 shows the number of refrigeration and air conditioning units sold as a percentage of total sales.

Figure 3 : Subsector sales as a percentage of total sales Source: [20]



Carbon emissions are expected to increase in the absence of renewable power generation and the means and policies for sustainable cooling technologies. This increase in emissions poses a challenge to meeting the Sustainable Development Goals and the goals of the Paris agreement [6]. Furthermore, the current technology pathways will not be sufficient to deliver universal access to cooling, let alone meet the UN SDGs 2030 targets [21].

Given the urgency and magnitude of this challenge and the need for multi-disciplinary delivery mechanisms to tackle the above issues there is an urgent need to understand the current access to cooling, cooling technologies, cooling policies, and available cooling best practices. Although there are reviews available that discuss cooling solutions, none aim to understand the status of sectoral cooling and the technologies available that might help develop policies that enable sustainable cooling and then tracking of its impact and progress.

The purpose of this review is to synthesize existing evidence regarding technologies, policies, and best practices in the following cooling activities:

- Space cooling in buildings.
- Cold chain (healthcare and food).
- Mobile cooling (only transport) and,
- Access to cooling.

By mapping the literature, this study identifies the current status in terms of lack of cooling at the global and country-level, geographical distribution of studies in the literature and the technologies and policies applied in general. Evidence-based research is needed to deliver sustainable cooling for all to ensure meeting the Paris Agreement, Kigali amendment to the Montreal Protocol, and the UN Sustainable Development Goals (SDGs). Therefore, this study adds information into the landscape of the previous body of work in the literature on cooling technologies and policies and systematically uses it for a scoping review.

Why is it important to do this review?

The authors of this review have not identified any existing scoping reviews focusing on cooling access, strategies, policies or regulatory issues, and technological best practice. However non-systematic reviews have been identified on related topics. For instance, there is peer-reviewed literature focusing on reviewing sustainable cooling technologies in buildings [22], district heating and cooling systems [23], phase change materials for passive cooling [24], solar cooling [25] and evaporative cooling [26] etc. In addition, many reports were published on sustainable cooling. For example, a report published on clean cooling by van Eck and Waltman [10] provides an introduction to sustainable cooling and its challenges. The authors of this publication engaged with industry, government, finance, NGO, and academic experts across 12 countries. They identified the importance of understanding the cooling demand, cooling demand management, and technology and commercial cooling systems evaluation.

Demand for cooling is on a rapid growth curve. Over the past 40 years, the energy consumption in buildings has also increased drastically [27]. Despite being a significant issue, which already causes an enormous threat to the environment and human health, sustainable cooling is still significantly challenging [28]. The growth in demand for cooling solutions causes a spike in energy use and emissions. Even with strong efficiency requirements in place, the absolute increase in energy use could be significant as more households purchase refrigerators, air conditioning units, and other cooling equipment. [29]. Meeting current and future cooling demand sustainably will require innovative approaches [30]. The industry is conservative about cooling, and the dominant technologies used for providing cooling have hardly changed in decades [10] . Moreover, most governments are reluctant to initiate policies regarding sustainable cooling solutions which is still a primary issue [15]. As a result, sustainable cooling has received very little, to no, attention from policymakers to date, unlike other issues such as electricity, transport, and heat [15]. Many countries acknowledged the financing need for access to cooling after initiating the Kigali Cooling Efficiency Program (K-CEP) but it still remains limited as financing needs continue to be poorly defined and tracked globally [31], requiring further investigation.

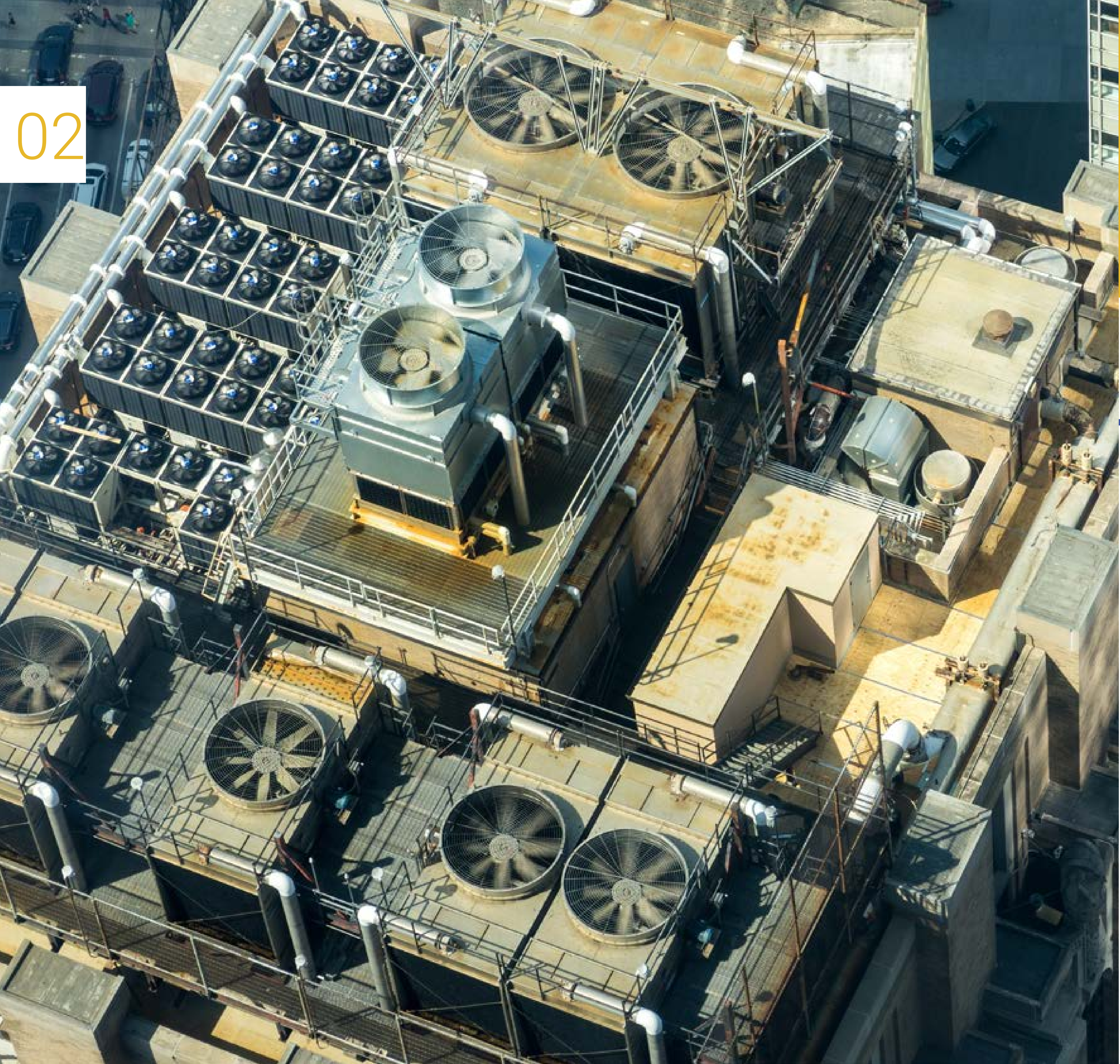
None of the identified previous studies or reviews has provided a comprehensive, systematic picture of existing technologies and policies for all sectors of cooling because:

1. the scope of the reviews was limited, and evidence presented in these reviews may have been only a partial representation of relevant studies.
2. they did not use systematic inclusion or exclusion criteria; and
3. they did not critically appraise studies included in the studies or reviews, so little is known about the quality of the evidence.

This study has focused on identifying the technologies and policies for the cold chain, space cooling, and mobile cooling. It also examines the issues and barriers related to access to cooling.

The objective of this scoping review is to develop a summary of the information available in the literature on issues, challenges, technologies, policies and best practices in sustainable cooling sectors.

A secondary objective of this review is to examine the effectiveness of various interventions and identify specific mechanisms that are used as best practice examples to counteract the current trend of electrically driven cooling technologies to provide a more sustainable pathway for the future in the cooling sector.



02

Chapter 02

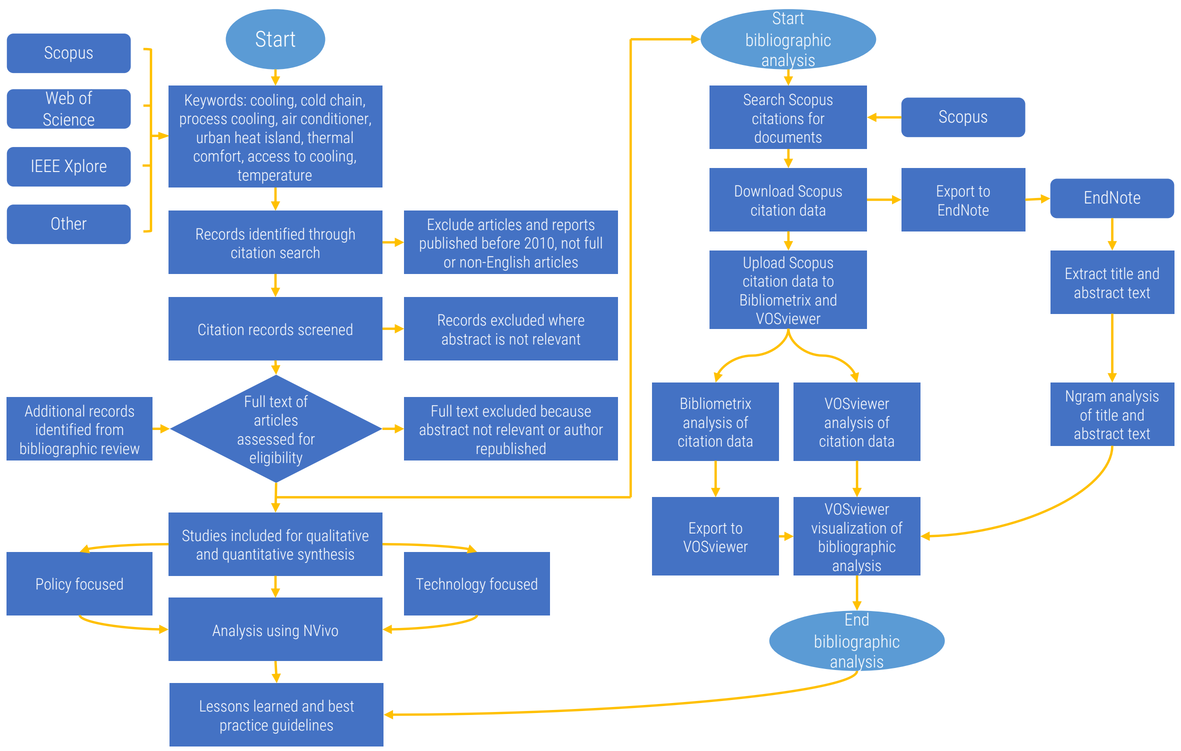
Methodology

A scoping review is like a systematic review as it requires a comprehensive and structured search of the literature to maximize the capture of relevant information, provide reproducible results, and decrease potential bias from flawed implementations to answer a clearly defined topic or question. Scoping reviews include findings from a range of different study designs and methods. It often focuses on the content identified, and quantitative assessment is usually limited to the number of sources reporting an issue or recommendation. This type of review approach is advantageous when the information on a topic has not been comprehensively reviewed or is complex and diverse [32]. A scoping review also helps to identify the knowledge gaps and clarifying key concepts [33].

The methodology used in this review is based on the framework outlined by [34, 35]. The methodology summarised the evidence available on a topic in order to convey the breadth and depth of that topic. The review was conducted in the following five key steps: (i) identifying the research question, (ii) identifying relevant studies, (iii) study selection, (iv) charting the data, and (v) collating, summarising and reporting the results using bibliometric analysis [36] and NVivo [1] [37].

The scoping review systematically maps the literature, identifies key concepts in the research, types and sources of evidence to inform policymaking and researchers [38]. A PRISMA[2] checklist was used in this research (Annex I), but the protocol used in this study was not registered as PROSPERO[3] currently does not accept systematic scoping review protocols and reviews that are not health related. The flowchart of the method is shown in Figure 4.

Figure 4 : Methodology Flowchart



1 NVivo is a software produced by QSR International. It is a tool for organising and managing data in order to assign attributes to similar groups of information for comparative purposes.
2 The PRISMA 2020 statement comprises a 27-item checklist addressing the introduction, methods, results and discussion sections of a systematic review report.
3 PROSPERO is an international database of prospectively registered systematic reviews in health and social care. See https://www.crd.york.ac.uk/prospero

2.1. Research Questions

The guiding research question aims to identify links between interventions and outcomes of policies and technologies with positive environment benefits such as energy savings, cooling load savings or emission reduction strategies. The review is guided by the following question:
'What are the issues, challenges, and solutions of existing policy, regulatory and technological best practices on sustainable, accessible and affordable cooling?'

2.2. Identification of relevant studies

The literature search aimed to systematically identify peer-reviewed literature on the evidence about sustainable cooling technologies and policies. The search is guided by the research question mentioned above. The literature were searched using electronic search within databases, hand searches and internet search using specific keywords.

Electronic Search

As the literature describes this topic in a very heterogeneous manner, the electronic search engine process using databases was iterative to ensure that a balance was achieved between recall and precision. Input was gained from librarians to develop the search strategy (Annex II). Documents were excluded on the basis of language and publication date.

Hand Search

In order to identify grey (non-peer reviewed) literature, recent reports, and other studies which were not published in traditional journals were collected using hand searches in various data bases and "snowball searches". All hand searches were completed on the 10th April, 2021. Hand searches to capture the literature were conducted in Google, Google Scholar, and donor organization websites.

Assessment of reporting biases

It is recognized that reporting bias can occur via many routes (such as biases associated with publication and non-publication, rapid or delayed publication, multiple publications, the ease of access of publications, the citation or non-citation of research findings depending on their nature and direction, and the selective reporting of outcomes) and can lead to the overly optimistic estimates of intervention effects. The search strategy was sufficiently comprehensive to increase opportunities to identify all studies that met the inclusion criteria and to identify where multiple publications from single research exist. Both published and unpublished data were included in the review.

Searching other resources

To locate additional studies not identified through the procedures described above an Internet search was carried out using key words and prominent author searches. Five pages of hits for each key word or author search in Google were reviewed.

The first search was implemented on 1st February 2021, in three electronic databases: IEEE (includes records from 2000 to March 2021), Scopus (includes records from 2000 to date) and Web of Science (records from

2000 to date). The databases were selected to cover a broad range of disciplines to cover all cooling sectors. The search query consists of terms considered by the authors to be relevant words related to sustainable cooling, cooling demand, access to cooling, energy efficient cooling, cold chain, cooling strategies and policy. Searches were limited to English language articles published between January 2000 and March 2021.

The final search approach adopted a 'snowball' technique in which citations within articles were manually searched if they appeared relevant to the review and included in this review [40]. All citations were imported into the Endnote[1] reference management software which was used to manage bibliographies and references used in this review.

2.3. Study Selection Process

Inclusion Criteria

The inclusion criteria adopted for the PICOS framework (which stands for population/problem, intervention, comparator, outcome) are summarized in Table 1. Included studies had the following study design: cost-benefit analysis; empirical research; longitudinal studies; qualitative studies; or quantitative research. This research develops a comprehensive review of sustainable cooling interventions to counteract problems associated with an increasing demand for cooling or lack of access to cooling. It only includes studies with explicit policy or technological interventions focused on sustainable cooling that provide evidence on the associated changes. Studies of policy intervention were included if the outcomes represented a valid comparison between "a state of no intervention" versus "a state with intervention".

1 Endnote: Reference Managing system [41] EndNote. "EndNote Home." https://endnote.com/ (accessed April, 2021).

Table 1: PICO Framework

Problem	The lack of access to sustainable cooling places vulnerable communities and communities in high-density tropical areas at high risk. Frequency of heatwaves is greater than before, with a higher likelihood of warmer conditions. Cooling demand has already tripled globally since 1990. To be consistent with the SDGs, Paris Agreement, and Kigali Amendment, cooling provision needs to aim to have a low Global Warming Potential (GWP) and be affordable, accessible, and energy efficient.
Intervention	Sustainable Cooling, Low-energy demand Cooling, Energy-efficient Cooling, Zero Carbon Strategies for Cooling (Cooling based on renewable sources). District cooling, vaccine, cold chain, new cooling strategies. Passive Cooling; building envelope, active building façade, natural ventilation, night purging, passive radiative cooling, passive design (windows, roof, ceiling, walls). Active Cooling; Solar Cooling, Heat Pump cooling, forced ventilation, evaporative cooling. Energy-efficient systems; air conditioning efficiency improvement, HVAC efficiency improvement, evaporative cooling, desiccant cooling, absorption cooling, adsorption cooling and any subsidy programmes focused on efficient cooling and/or technologies.
Comparator	Policy Interventions versus no policy intervention. Sustainable Cooling Technology vs Non-sustainable cooling technology.
Outcome(s)	Addressing cooling issues: • Reduction of CO_2 emissions. • Energy demand reduction. • Energy consumption reduction. Access to cooling: • Increase in different sectors. • Sustainable technologies available for different sectors. Cooling demand reduction. Impact of cooling solutions: • Energy savings cooling load reduction. • Cooling demand reduction; and • Productivity increase.
Study design	Empirical Research, longitudinal studies, qualitative studies, quantitative research.

Inclusion Criteria
Articles published in English.
Selected period 01/01/2000–31/03/2021.
Research focused on interventions mentioned in Table 1.
Studies published in peer-review journals and report published by reputable organizations.
Type of studies: original articles, reviews, scoping reviews, narrative reviews, reports.
Exclusion Criteria
Articles without access to the full text.
Articles not in English and beyond the selected period.
Articles that mentioned heating only.
Articles that mentioned unspecified information.
Articles that do NOT include relevant information on cooling sectors.
Articles focusing on air quality control from cooling rather than temperature control.

This study aims to collect recent information considering only studies carried out during the last 20 years. Likewise, this study only collects results from documents written or translated in the English language to prevent misinterpretation.

2.4. Data collection and analysis

Screening Process

An Excel Spreadsheet was designed to ease the screening and selection of eligible studies found from Scopus. All titles and abstracts found within the search strategy were documented on the spreadsheet using a unique identification number. Each number represented a different study. A team of 4 analysts double-screened all titles and abstracts from the Scopus search. A set of three pilot stages was run to establish consistency amongst all analysts. Each pilot set had 100 studies to be reviewed. Although consistency was evident during the first trial run, second and third trials were conducted to double-check whether consistency could be an issue during the study. A similar process was completed for more technical databases (IEEE and Web of Science). Two analysts double-screened the sets of studies from these sources and no trial run was conducted during this stage.

After completing the three trial sets from the Scopus results, the same four analysts reviewed the studies as per the trial. In cases where there was disagreement the team conducted online meetings to discuss consensus on those studies. The criteria outlined in Table 1 establishes the PICOS framework used as the base for the analysts to include/exclude studies. Since the criteria are not always evident within the title and abstracts of studies, to avoid biased considerations, analysts include studies for full-text reading when the consensus was not easy to reach during meeting sessions. For studies attained through manual inclusion using snowball techniques, an initial analyst identified sources of interest, and a second analyst reviewed the selection to verify the inclusion criteria.

All the studies that met the inclusion criteria based on title and abstract screening then underwent a full-text screening. The full-text screening included PDF documents from all the databases. This stage required the analysts to run the same process with the same criteria from the PICOS framework as in the titles and abstracts stage, focusing on the studies' intervention and outcomes. Studies that met the inclusion criteria based on the full-text screening went onto the data collection.

Data Extraction

Once the screening process was completed, a mapping table was developed to record qualitative information of authors, study locations, citation, results, and solutions. The qualitative information from studies included were used to identify issues, challenges, solutions and best practices. In addition, the quality (risk of bias) of studies were independently assessed by the authors. Throughout the screening process, the reviewers met regularly to resolve conflicts and discuss any issues related to the articles selected for this review.

Data Analysis

Data analysis were carried out to identify important research themes, active research areas, issues, solutions and best practice in the sustainable cooling area.

Bibliometric Analysis

Bibliometric analysis was carried out to review and identify the impact of sustainable cooling in the scientific field. The use of a bibliometric analysis is a suitable methodology to identify the volume and growth pattern of literature focusing on a particular topic. It helps to spot important research themes, active researchers and prominent research institutions. The results of such an analysis can be useful for future research planning. The bibliographic analysis undertaken here was carried out using the Bibliometrix R library [36] in conjunction with R Studio environment [42] and the biblioshiny [43] web interface [44]. Additional analysis was conducted using Python v3 and related Python libraries[1] . The citation data available from Scopus and other citations database includes the article's keywords, title and abstract text but can also include the articles abstract full text. It should be noted that keywords are structured contextual text derived from a fixed vocabulary and do not have semantic structure. Title and abstracts, however, are unstructured free text.

The analysis methods available for text data range from word or term counts i.e., their frequency, to counts of the co-occurrence [45] and collocations of terms [44] i.e., bigrams, trigrams etc., both at the document and at the corpus level, bags of words models using a term and document frequency [46], decomposition of term frequencies or collocations to reveal latent structures [47] and advanced word and document embedding techniques using artificial neural network deep learning can also be utilised to reveal embedding of both term usage and semantic structure within a corpus of documents [48].

Qualitative analysis using NVivo

The NVivo software was used for qualitative analysis of issues, solutions, and best practices. Once the full-text article was finalized, all articles were exported to NVivo for qualitative analysis. NVivo, developed by QSR International (Melbourne, Australia), the world's largest qualitative research software developer, is a computer-assisted data analysis software (CAQDAS) package used for qualitative data analysis. It allows qualitative inquiry beyond coding, sorting and retrieval of data. It was also designed to integrate coding with qualitative linking, shaping, and modelling. The following sections discuss the fundamentals of the NVivo software (version 2.0) and illustrate the primary tools in NVivo which assist qualitative researchers in managing their data. In NVivo, the researcher can create and explore documents and nodes, when the data is browsed, linked and coded. Both document and node browsers have an attribute feature, which helps researchers refer to the data characteristics [37]. It also provides a modeler designated for visual exploration and explanation of relationships between various nodes and documents. Using this, the researcher can create, label, and connect ideas or concepts.

Collating, summering and reporting of results

Based on the findings the studies produced individual results on sustainable cooling technologies and policies. Results include cooling sectors as mentioned in the objectives. Results are summarised as issues and solutions for all cooling sectors identified in the reviewed documents and strengths and limitations of the scoping review.

2.5. Assessment of risk of bias in included studies

During the review there was a particular awareness of limitations associated with:

- lack of allocation concealment.
- selective outcome reporting; and
- the use of non-validated outcome measures.

Since none of the studies matches with the outlines in the Cochrane Handbook for Systematic Reviews of Interventions [49], the 'Cochrane risk-of-bias tool for randomized trials' tool could not be used. Therefore, the authors assessed the risk-of-bias independently to check the quality of each study for high, unclear, or low risk-of-bias.

Subgroup analysis and investigation of heterogeneity

As stated in the protocol, it was planned to analyse the issues, solutions, and best practices, where available, according to cooling sectors. Given the small number of identified studies, however, any such subgroup analyses could not be conducted.

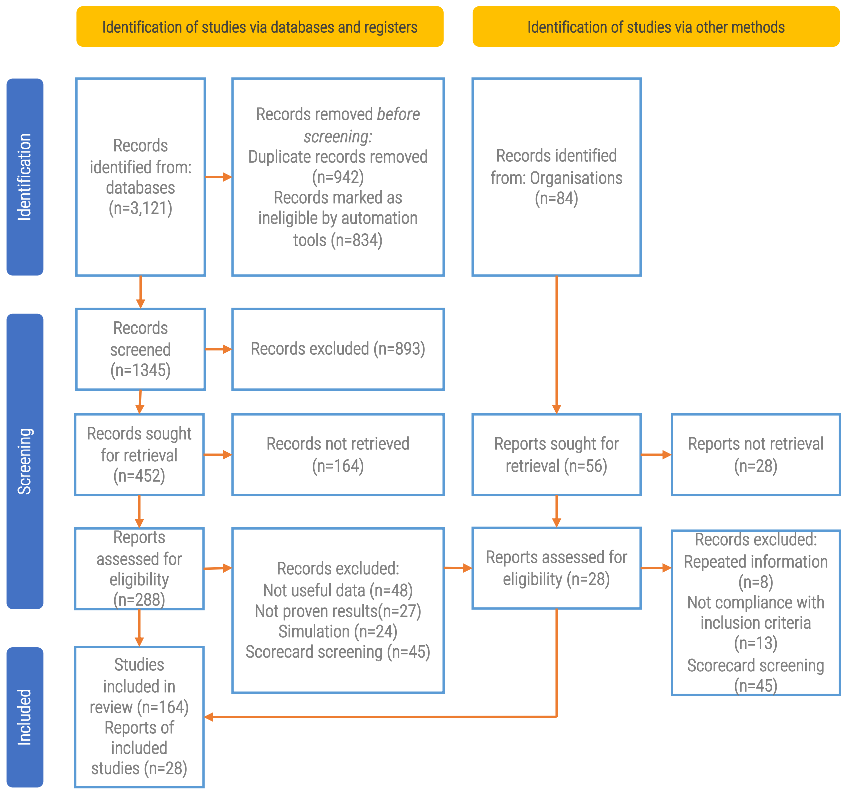
1 Python libraries used for analysis included NumPy, Pandas, re, unicode, and nltk.

Chapter 03

Results

The PRISMA flow diagram [50] for this study is shown in Figure 5. The search string shown in Table 1 was applied to Scopus, IEEE and Web of Science databases which returned 1,345, 297 and 1,479 articles, respectively. The literature search was extended to Google search engine and Google Scholar to identify peer-review articles from journals that might not be indexed in the two databases. Another 84 records were identified from a hand search using the snowball technique and personal communications. The literature search generated a total of 3,205 articles which was reduced to 2,197 after the removal of duplicates. While screening the titles and abstracts, 1,765 studies were excluded, and studies were included for eligibility assessment. The included studies were screened, and 1,294 studies were further excluded, including literature reviews, out-of-scope studies, and articles with no documents available After the eligibility screening, 192 studies were included for qualitative synthesis, out of which 164 studies were used for the bibliometric analysis and the rest used for qualitative analysis. The approach identified another 11 studies used along with 72 articles for qualitative analysis to identify the pattern of cooling demand and energy technologies and policies.

Figure 5: PRISMA Flowchart



3.1. Charting the Data

The documents which were analysed consist of two types. There are 164 documents which have citation records in the Scopus database and there are 28 policy documents without citation records. A text search was carried out considering all selected articles and reports to identify the main words used in these publications and its frequency of occurring.

Figure 6 : Word Frequency Among Screened Articles

3.2. Description of studies

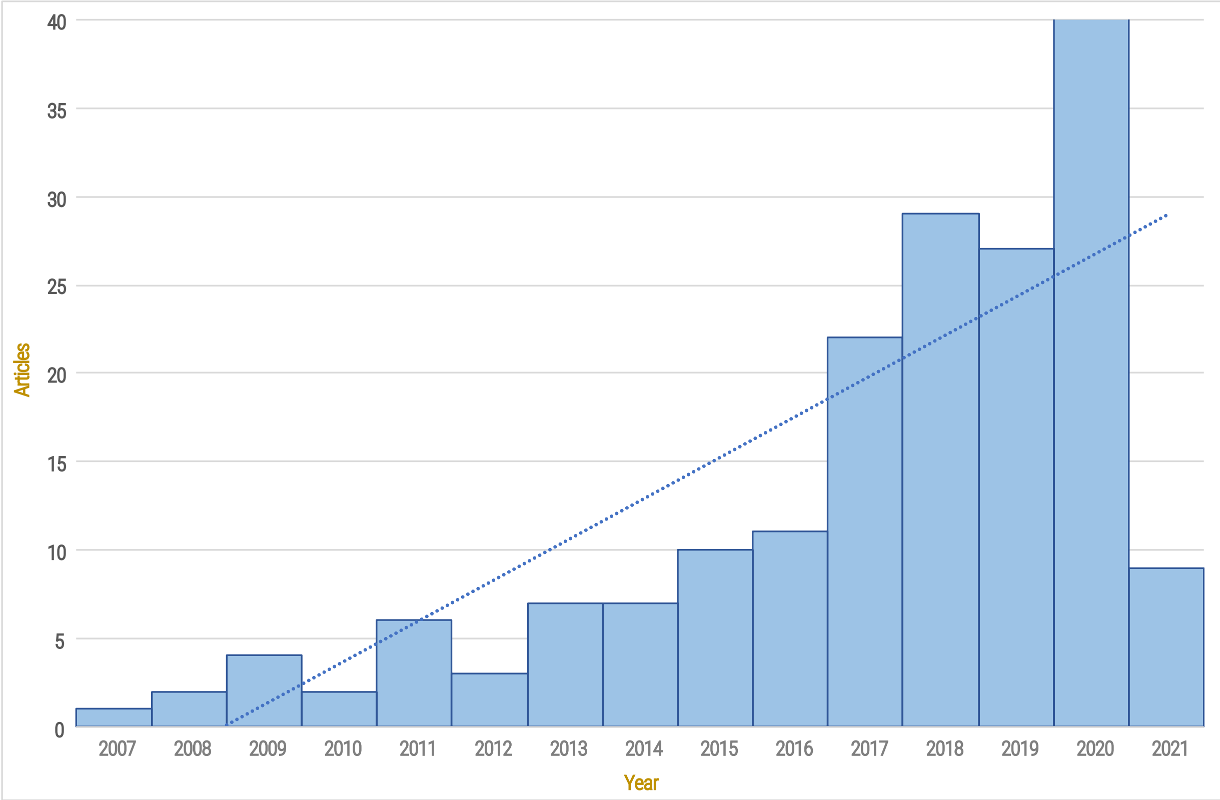
Summary information for the 164 downloaded (with citation records) sustainable cooling documents was analysed by Bibliometrix and is shown in Table 1. The document citations analysed span a time period of 14 years from 2007 to 2021. Note that only the first few months of 2021 was included as the documents were sourced in March 2021. The documents (164) were a mix of journal articles (104), book chapters (1), conference papers (47), and review articles (12). The per year production of these documents is broken down in Table 2. The annual percentage growth rate of the publication production over the 2007-2021 period was 17 per cent, with a larger proportion of the documents (67 per cent) being published after 2016 (Table 2). This increase in the rate of publication can be explained by the implementation of Kigali amendment of Montreal Protocol [51] and also Paris Agreement [52].

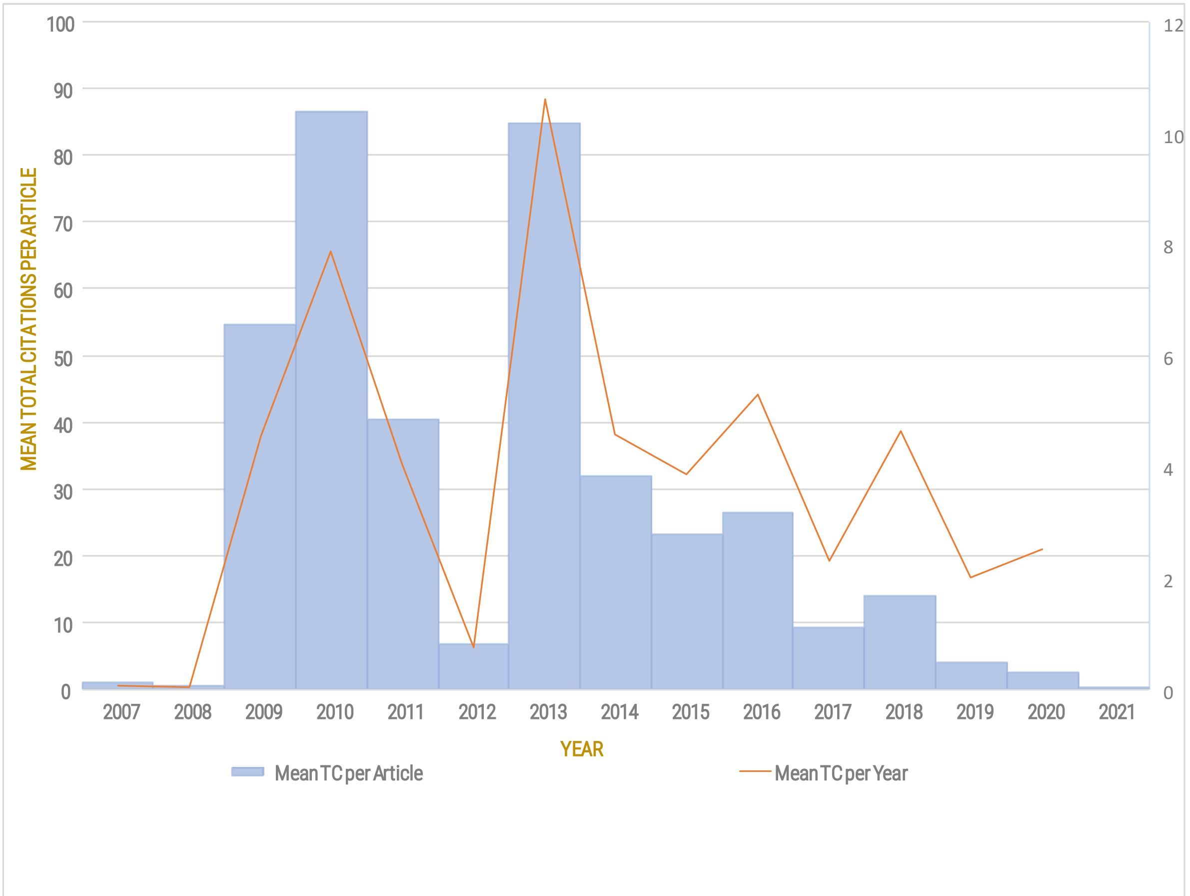
Table 2: Summary of information of reviewed documents

Timespan	**2007 – 2021**
Sources (Journals, Books, etc)	92
Documents	164
Mean years from publication to citation	3.92
Mean citations per documents	16.24
Mean citations per year per document	2.576
References	6552
Articles	104
Book Chapters	1
Conference Papers	47
Review Papers	12
Keywords Plus	1410
Author's Keywords	572
Authors	537
Author Appearances	606
Authors of single-authored documents	9
Authors of multi-authored documents	528
Single-authored documents	9
Documents per Author	0.305
Authors per Document	3.27
Co-Authors per Documents	3.7
Collaboration Index	3.41

Table 2 shows that the 164 documents had 3.92 mean years from publication until citation with mean citations per document of 16.24. The mean citations per year per document was 2.576. The annual number of publications found in the documents is shown in Figure 7 . The positive publication growth rate can be observed in Figure 7 with noticeable increases in the total number of publications in 2017 and again in 2020 as previously mentioned.

Figure 7: Annual scientific production for the sustainable cooling documents, mean total citations per article and mean total yearly citations.





The mean total citations per article and the mean total citations per year are graphed alongside each other in Figure 7. The citations per article started to increase since 2013 onward as heat loads increases due to global climate change [13]. In 2016 the Kigali Amendment to Montreal Protocol was agreed by 170 countries which enhances research in this area to work towards to achieving reduction in HFC consumption [51]. After the Amendment entered into force in 2019, there was a sudden peak in the research publications focused on sustainable cooling issues and solutions.

Out of 192 literature reviewed, 21 mentioned access to cooling, 40 mentioned cold chain-healthcare, 34 mentioned cold chain-food, 15 mentioned mobile cooling, and 151 mentioned space cooling. Please note that the sum of these numbers is not equal to 192, as some literature may have mentioned more than one sector. The best practice examples for sustainable cooling were found in 18 literature. Bibliometric Analysis

A total of 52 countries were found to have authors represented in the publication of the sustainable cooling documents. The top 20 contributing countries all had published more than 5 times during the 2007 to 2021 period. The remaining 32 contributing counties published 5 or less times, with 14 countries having contributors who have a single publication.

Figure 8: Scientific production by country for sustainable cooling documents

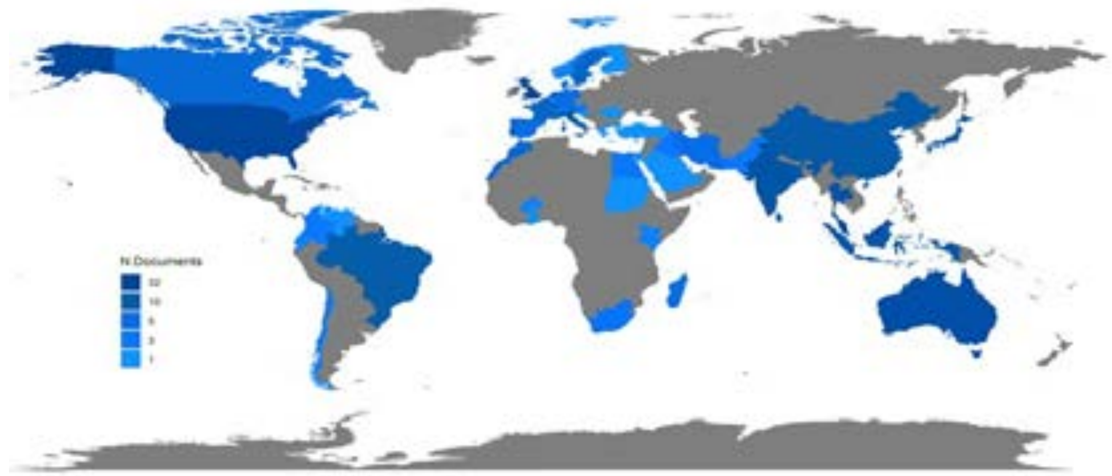


Figure 9: Network of authors published documents in sustainable cooling

Figure 8 depicts a world map providing a visualisation of the country's author contributions and country collaboration map[1] and a visualisation of the collaboration network within countries. As reflected in the visualisation of Figure 8, the top 20 countries account for approximately 80 per cent of the contributing authors. Figure 9 shows the network of authors contribution in sustainable cooling. The Bibliometrix analysis also provided a listing of the top countries as represented by the corresponding author's county.

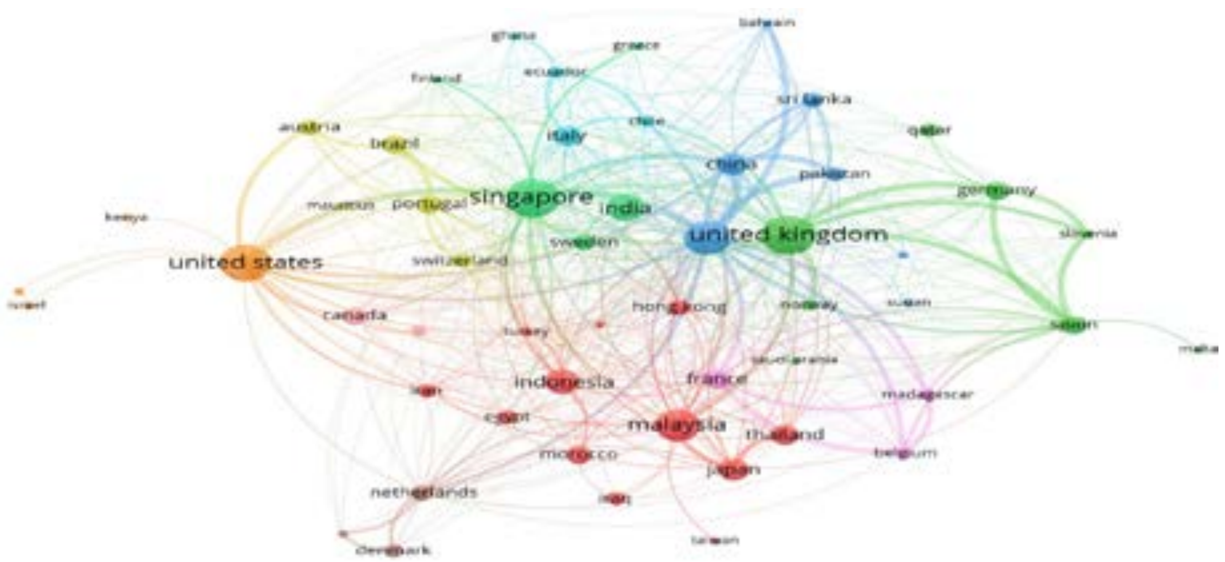
Figure 9: Network of authors published documents in sustainable cooling

The network of Figure 10 produced by VOSviewer [53] shows the high modularity within clusters[2] and the high level of author collaboration within the clusters.

1 The country collaboration map was produced by Bibliometrix.

2 The unified mapping and modularity-based cluster method used in VOSviewer is similar to that found in multi-dimensional scaling (MDS)[53] L. Waltman, "A review of the literature on citation impact indicators," (in English), Journal of Informetrics, Review vol. 10, no. 2, pp. 365-391, 2016, doi: 10.1016/j.joi.2016.02.007.

Figure 10: Country collaboration network for the sustainable cooling documents



	Cluster	Items	Country collaboration network title and abstract word bigram collocations ranked by PMI
	Cluster 1	12	adaptive envelopes; coconut oil; colored coating; external shading; phase change; wall thickness;
	Cluster 2	8	double skin; night time; fuel poverty; phase change; water filled; low income; filled glass;
	Cluster 3	7	sri lanka; night time; phase change; hot humid; cold storage; green infrastructure; high rise;
	Cluster 4	5	base scenario; air conditioning; solar powered; global warming; tropical climates; climate change;
	Cluster 5	5	ethlyene glycol; kw ton; colored coating; naturally ventilated; hot humid; double glazing; clear glass;
	Cluster 6	4	green roofs;
	Cluster 7	4	vapor compression; naturally ventilated; multilayer optical; variable insulation; mirror films;
	Cluster 8	3	hot humid;
	Cluster 9	3	phase change; passive strategies; cold chain; vaccine cold; change materials; air conditioning;
	Cluster 10	2	naturally ventilated; variable insulation; low income; green roof; thermal comfort; radiant cooling;

3.2.1. Keyword, title, and abstract text analysis

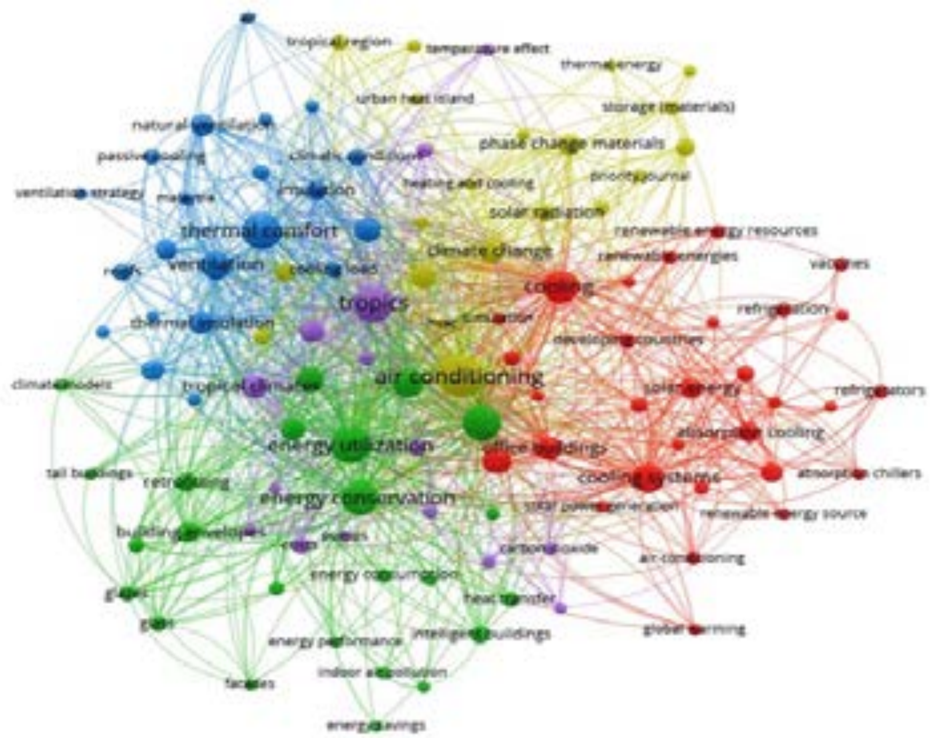
The citation records for the sustainable cooling documents use a total of 3,342 keywords. The number of unique keywords is 1,740. The number of keywords used ranges from 1 to 46 with a mean of 20.4 keywords per citation record, having a standard deviation of 8.6 keywords. Keywords are categorical variables in a co-occurrence analysis.

Table 3 shows the 30 most frequent keywords found in the 164 sustainable cooling articles citation records. The keywords air conditioning, Thermal comfort, cooling systems, energy efficiency and cooling are the top 5 keywords found in the citation records. These keywords appeared in approximately 25 per cent or more of the article's citations Table 3.

Table 3 : Most frequent keywords presented across cluster

	Cluster	Items	Bibliographic document coupling most frequent keywords
	Cluster 1	14	roofs(6), thermal comfort(5), green roof(5), urban heat island(4), tropics(4), energy utilisation(3)
	Cluster 2	14	cooling(7), cooling systems(6), air conditioning(5), absorption cooling(4), energy efficiency(4)
	Cluster 3	12	air conditioning(6), phase change material(6), cooling(5), energy conservation(5), buildings(4)
	Cluster 4	11	thermal comfort(8), thermal insulation(5), heating(5), tropics(5), energy efficiency(4), ventilation(4)
	Cluster 5	11	thermal comfort(7), air conditioning(7), energy efficiency(6), tropics(4), energy conservation(4)
	Cluster 6	10	thermal comfort(8), tropics(6), housing(4), ventilation(4), natural ventilation(3)
	Cluster 7	9	energy utilization(7), buildings(5), air conditioning(4), energy conservation(4), retrofitting(4)
	Cluster 8	8	air conditioning(6), pumps(5), tropics(5), geothermal heat pumps(4), air source heat pumps(3)
	Cluster 9	7	tropics(4), air conditioning(3), vernacular architecture(3), houses(3), tropical climates(3)
	Cluster 10	3	double skin(2), double skin façade(2), tropical climate(2), design(2), mixed mode ventilations(2)
	Cluster 11	2	glass(2), building sustainability(2), building envelopes(2), transparency(2), glazes(2)

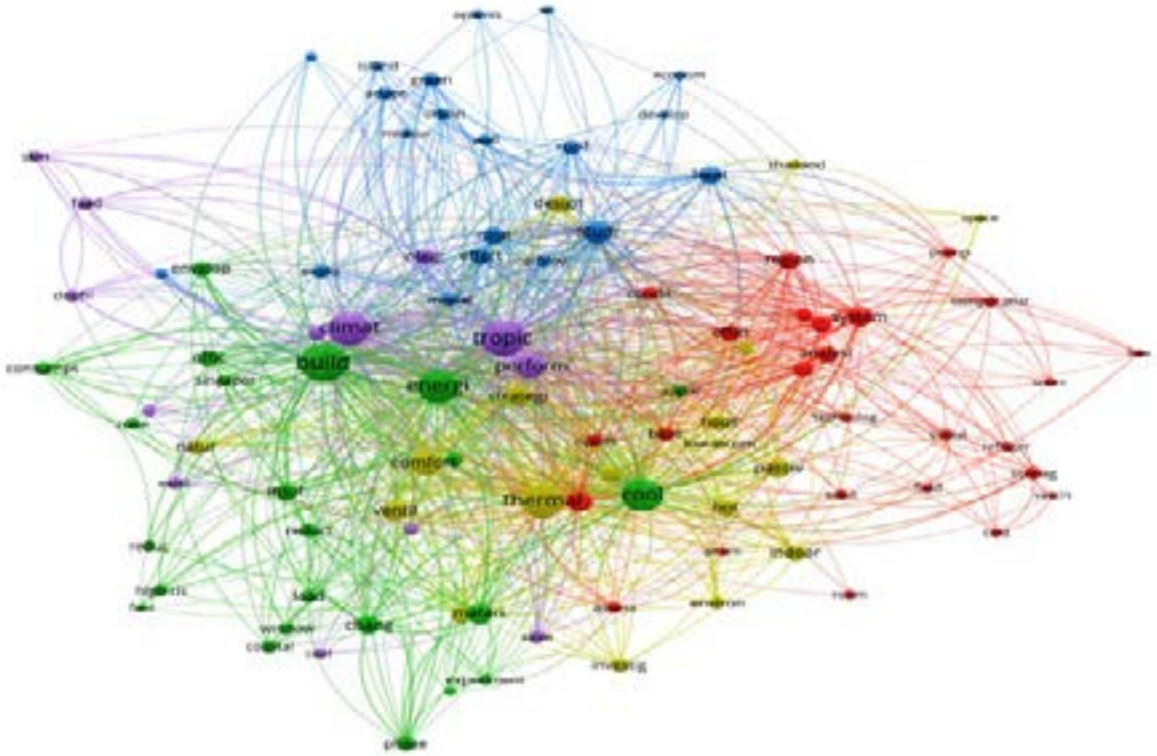
Figure 11: Co-occurrence network for 50 most frequent keywords



	Cluster	Items	Co-occurrence network for 50 most frequent keywords
	Cluster 1	30	cooling, cooling systems, sustainable development, office buildings, solar energy, thermoelectric equipment
	Cluster 2	24	energy utilization, energy efficiency, energy conservation, buildings, housing, architectural design
	Cluster 3	21	thermal comfort, ventilation, heating, thermal insulation, natural ventilation, insulation, climatic conditions
	Cluster 4	20	air conditioning, building, climate change, phase change materials, solar radiation, walls
	Cluster 5	15	tropics, tropical climates, tropical environments, costs, cost effectiveness, performance assessment

Figure 11 shows a network graph of the results of this co-occurrence analysis which found 5 clusters of keywords from the 110 most frequent keywords. The 5 clusters represent those keywords which co-occur in the same bibliographic citation record. Cluster 1 can be contrasted with Cluster 2 which has a high co-occurrence of the following 6 top ranked keywords.

Figure 12: Co-occurance network for title words



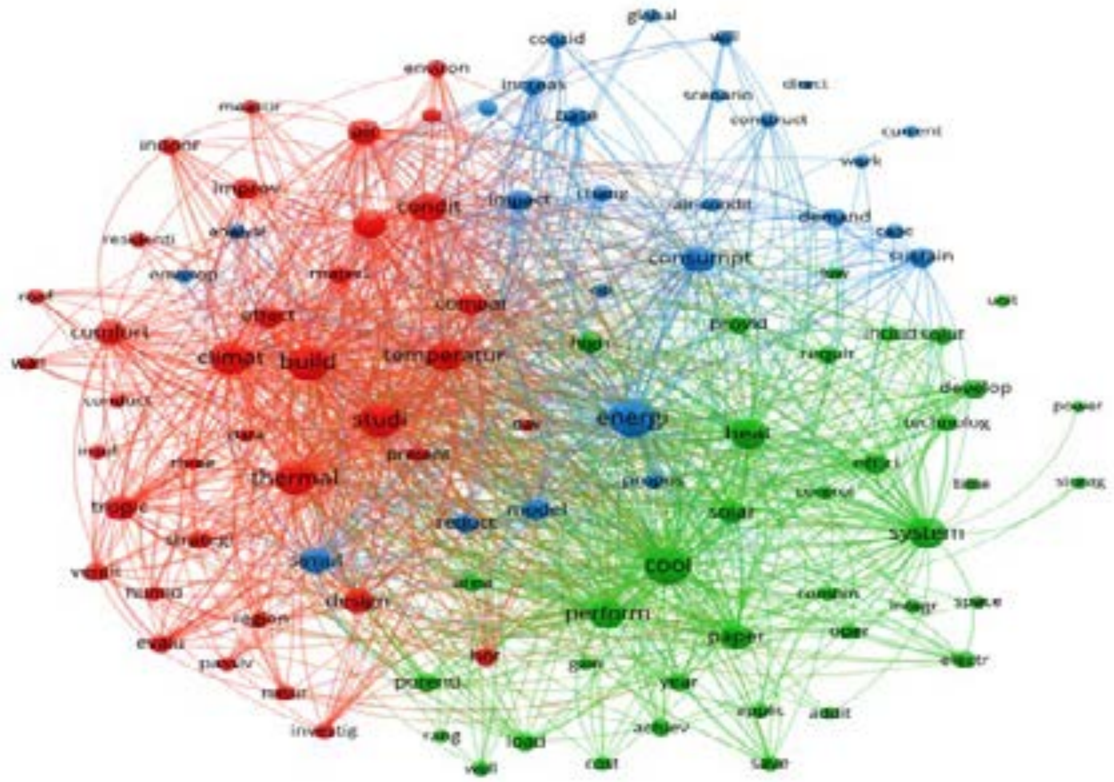
	Cluster	Items	Co-occurrence network for 100 most frequent title words
	Cluster 1	26	residential, system, region, analysis, solar, air , efficiency, base, condition, sustainable, storage
	Cluster 2	23	build, cool, energy, material, change, insulation, office, envelope, phase, reduction, improve
	Cluster 3	20	study, heat, case, effect, roof, evaluation, green, model, adapt, urban, wall, achieve, impact, island
	Cluster 4	18	thermal, comfort, strategy, ventilation, passive, design, house, potential, hot, indoor, natural, humid
	Cluster 5	13	tropic, climate, performance, intergrate, retrofit, save, glaze, exist, double, orient, skin, coat

A term co-occurrence matrix is created and utilised to cluster and create the network graphs shown in Figure 12 for the title text and Figure 13 for the abstract text.

Figure 12 shows that 5 clusters were found in the title words. When compared with the clusters found for the citation keywords there is a similarity. The most similar clusters are the keywords in Cluster 3 and the titles in Cluster 4, and keywords in Cluster 5 and the titles in Cluster 5 which are associated with thermal performance and cooling in tropical climates, respectively. The keyword in Cluster 2 and the titles in Cluster 1 are both related to energy efficiency in buildings, while the keywords in Cluster 1 and the titles in Cluster 2 are related to cooling systems, however, do not have as high a degree of similarity as the previously described similar clusters. The keywords in Cluster 4 are related to titles in Cluster 2 and 3.

The network graph clusters for the abstract words produced three strong and distinct clusters (Figure 13). These clusters are not dissimilar to those identified with both the keywords and title words network graphs. The three abstract words clusters align very closely with the themes of cooling, energy efficiency and technology in cooling which were identified in the qualitative analysis.

Figure 13:Co-occurrence network for 100 most frequent words in Abstracts



	Cluster	Items	Co-occurrence network for 100 most frequent abstract words
	Cluster 1	37	build, study, climate, thermal, temperature, conditioning, reduce, air, tropic, comfort, design, effect
	Cluster 2	37	cool, heat, system, perform, paper, efficiency, solar, high, develop, potential, load, area, provide
	Cluster 3	26	energy, consumption, simulation, model, impact, sustainable, reduce, base, increase, demand

3.2.2. Thematic analysis of the co-occurrence of keywords

Thematic analysis is an approach most often associated with qualitative methods and is used to identify themes or patterns of meanings within a data set [54]. This analysis was used to closely examine the data to identify common themes ideas and patterns of meaning that come up repeatedly. Figure 14 shows the thematic evaluation of the key words used in the documents reviewed. It shows that the air conditioning research study continued at the same pace from 2007-2015. After 2015, research with the key word 'air conditioner', increases dramatically as an identified theme. This change is associated with the implementation of the Kigali Agreement and the Paris Accord during this period. The research themes of outdoor air temperature, ventilation, tropics, refrigeration, energy efficiency in 2016-2018 were subsumed into the theme of air conditioning in 2019-2020. While air conditioning was the major identified theme in 2019-2020 the themes found for the articles published in early 2021 suggest that the focus has shifted to broader research topics again, although air conditioning was still a well-researched topic.

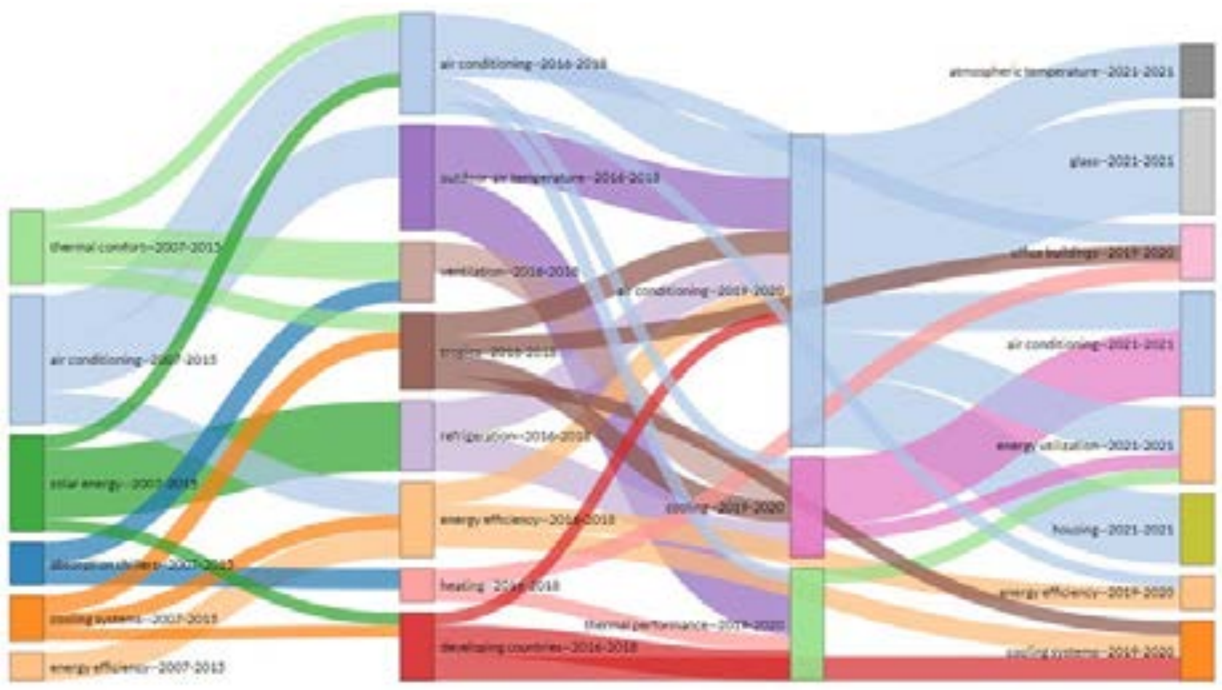


Figure 14: Thematic evolution of document keywords for the period 2007 to 2021

3.3. Access to Sustainable Cooling

Cooling is essential for achieving many of the Sustainable Development Goals [18] [4]. Access to sustainable cooling means providing affordable and sustainable solutions to address the needs of the vulnerable, such as access to nutritious food, safe medicines, and protection from heat [55]. Access to cooling is essential for safe living and working condition, nutritious and healthy food supply, effective vaccines and medicine care. According to SE4All report [6],

"Sustainable cooling is an issue of equity that underpins the ability of millions to realize the Sustainable Development Goals (SDGs)."

However, delivering comprehensive, efficient and sustainably cooling access within climate change, natural resource and clean air targets is still challenging [9]. As the need for cooling grows, delivering it sustainably to meet the Paris Agreement on Climate Change is a challenge [16]. The demand for cooling in both the developed and developing world is growing dramatically. Despite the high number of installed appliances forecast in the Clean Cooling Assessment Report [14] approximately one-third of the global need for cooling will still be unmet. Total emissions from the global cooling sector as of 2018 are shown in Figure 15. Sixty two percent of these are in Asia [56]. Most cooling technologies use Hydrofluorocarbon (HFC). The consumption of HFC is 45 per cent in air conditioning and 73 per cent in commercial refrigeration, which shows the importance of reducing HFC in room air conditioners and self-contained commercial refrigerators while providing access to cooling for all [56].

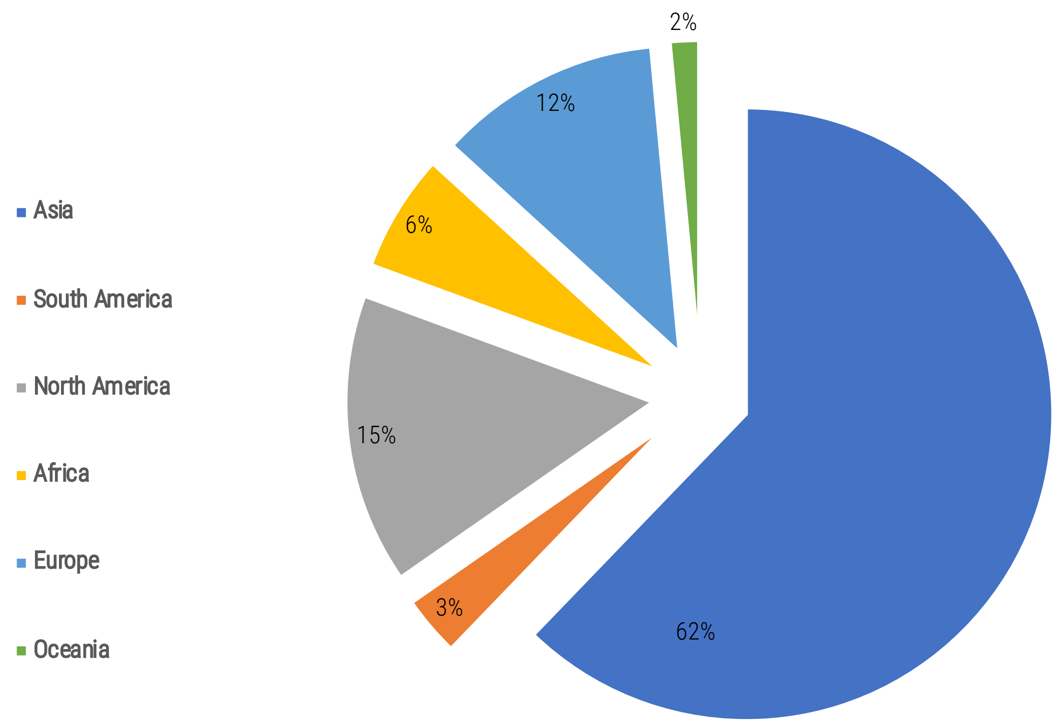


Figure 15: Emissions (MtCO2eq) from the cooling sector in 2018 by region.

About 11 per cent (21 out of 192) of articles mention access to cooling and its importance. According to SE4All (2018) [4], the importance of providing access to cooling issues is beginning to be understood by governments and other stakeholders, but the rate of progress is still slow. Sustainable cooling must be affordable, financially sustainable, and accessible to all to deliver the societal, economic and health goals.

All reviewed documents highlighted issues, challenges, and possible solutions to increase access to sustainable cooling. Figure 16 below shows the categories of issues/barriers and solutions to these for access to sustainable cooling mentioned in all the reviewed documents. The width of the slices is proportional to the number of occurrences within the reviewed documents (including multiple occurrences within a single document and across multiple documents).

Figure 16: Most frequent barriers and solutions occurred in the reviewed documents

3.3.1. Issues Identified

About fourteen barriers to increased access to sustainable cooling were mentioned in the reviewed literature, as shown in Figure 16. Cooling technologies are heavily reliant on electricity access but only 87 per cent of the world has access to electricity [14, 28]. The electricity access rate varies around the world with many developing nations severely lacking universal access, which prevents access to cooling in many developing and emerging economies [57, 58].

Lack of awareness on the benefits of efficient cooling needs among users was mentioned as a reason for poor sustainable cooling access [17]. Cooling presents a blind spot when it comes to energy and climate change mitigation. Only 42 per cent countries mentioned the refrigeration and cooling (RAC) sector in their Nationally Determined Contributions (NDCs) [52] where a few (e.g. Ghana, Jordan and Vietnam) have explicit commitments. But these countries have their own limitations in addressing their socioeconomic challenges, and therefore access to cooling is not a priority for them [14]. The same source mentioned a lack of policy incentives such as tax incentives. There is a general lack of conducive policies to effectively remove barriers to investments in cooling energy efficiency at the national and sectoral levels [59, 60]. For example, supporting the RAC sector with government subsidy schemes will help increasing access to cooling in different sectors specially reducing losses from the food chain sector as well as increase comfort cooling [9]. Lack of skills for the operation or maintenance of cooling technologies and appliances are mentioned as significant barriers to deployment of cooling technologies, which slows down the access to cooling [10].

The documents reviewed have identified the barriers to cooling equipment uptake related to awareness, affordability, financing, culture/consumer attitudes, market dynamics, policy priorities, electricity availability, technical capability and skills, national interest, lack of innovation and an inadequate evidence base information. These barriers are slowing down the progress towards access to cooling [10, 14, 29, 61].

Evidence suggests [14] that there is a lack of awareness and knowledge of the cooling sector specially in the area of the investment which is hindering the socioeconomic and environmental benefits of cooling access and therefore has failed to attract such investors [57]. Cooling equipment is too expensive for the people who need it urgently to use for reducing food spoilage in the agricultural sector [62]. The same is also true for domestic refrigeration and space cooling.

Lack of funding for cooling research increases the challenges for access to cooling [4]. For example, the EU provided less than 0.22 per cent of its annual research budget towards sustainable cooling research compared to other comparable sectors [9, 18]. Strong growth in access to sustainable cooling is possible as policies for more efficient buildings, transport, refrigerators and other cooling appliances are available to keep the cooling energy demand low [63]. Currently awareness amongst policy makers and customers on the role of cooling in both economic development and climate change mitigation is lacking [21]. The key issues for access to cooling are:

- Lack of energy access
- Lack of awareness and knowledge of cooling sector and benefits of cooling access among manufacturers, government, users and investors which leads to a failure to attract private sector investment.
- High cost of efficient cooling appliances
- Lack of skill in using and maintaining appliances, which reduces the deployment of cooling technologies.
- Lack of incentives to innovate due to slow regulatory changes, and
- Lack of research findings on the topic of access to cooling and financial incentives.

3.3.2. Solutions to accelerate Access to cooling

It is crucial to understand cooling need and demand, however this understanding is not evident among stakeholders such as investors, customers, policy makers, academia, industries, including the supply chain, as the need for cooling is universal but cooling means very different things for different stakeholders [3, 14]. An assessment of cooling need considering socio-economic-technical issues will be helpful to increase awareness among stakeholders. Figure 17 summerizes the solutions for increasing access to sustainable cooling derived from the analysis of the reviewed documents.

Lower GWP refrigerants to replace HCFCs are widely available in higher energy efficiency (EE) equipment and increasingly accessible. Therefore, it is possible and beneficial to leapfrog from HCFCs directly to lower GWP refrigerants and higher EE in some regions and sectors [64, 65].

Appropriately designed cooling systems that are not oversized can reduce the operating cost, making it more affordable for the user and, therefore, will increase access to cooling [3, 9, 28, 66-69]. To address the issues of access to sustainable cooling, a needs-driven, system-level approach to mitigate demand is needed. According to the Birmingham Energy Institute (2018) it is also important to understand multiple cooling needs, energy use , resources and efficient technologies to integrate the resources along with service needs [21]. A study in China [70] shows that despite efficient technologies to promote energy efficiency, due to demand for a more comfortable lifestyle, the cooling technologies are used longer and resulted in an increase in energy consumption. The study found a rebound effect in space air conditioner energy consumption due to longer daily usage periods in the household as air conditioner efficiency levels improved [70]. There is a need for policy to support development and implementation of sustainable solutions for cooling [59]. According to the Climate Policy Initiative report the keys to successful intervention of cooling access are [29]:

- "fit-for-market" business and financial models that enable access, affordability and return on investment.
- effective policy interventions; and
- developing the skills and workforce to design, install and maintain the volume of appliances [29].

Cooling as a Service (CaaS)[1] is mentioned as a novel business models to address cooling access [14]. This service involves building and business owners paying for cooling services instead of investing in cooling infrastructure. As a result, users benefit from high-quality cooling at better prices and do not need to distract any budget towards acquiring the system [31]. This enhances access to sustainable cooling.

Finance is one of the challenges for access to cooling [72]. Access to funding for supporting early adopter deployments and funding capital deployment help scale up technologies, as well as increase cooling access [9, 14]. Investment to increase thermal comfort and decreasing the demand for cooling such as passive cooling, cool roofs, building codes, etc. accelerate cooling access. An example of this is "Pay As you Save[2] service [72], which helps reduce the upfront cost for consumers for purchasing cooling equipment.

Skills and training are required across all cooling sectors. Identifying skills gaps for each country and customizing training to fulfil that gap in the delivery of cooling solutions is important [63]. According to [74], the key focus areas needed skill developments are:

- Capacity building on designing and implementing passive cooling measures in buildings and infrastructure.
- Planning and design for investors and regulatory policy makers.
- Appropriate sizing and maintenance of super-efficient equipment and appliances for effective operation; and
- Upskilling around health and safety for safe handling of ultra-low GWP refrigerants.

1 A service-based model for cooling making affordable, efficient and high-tech cool air accessible to everyone. [71] CAAS. "Cooling as a Service." (https://www.caas-initiative.org/) (accessed May 20, 2021).

2 A financial mechanism that allows service providers to pay for the upfront cost for an energy solution and recover its cost on a monthly bill with a charge that is less than the estimated savings. [73] C. E. Works. "What is Pay as you Save." https://www.cleanenergyworks.org/ (accessed May 15, 2021).

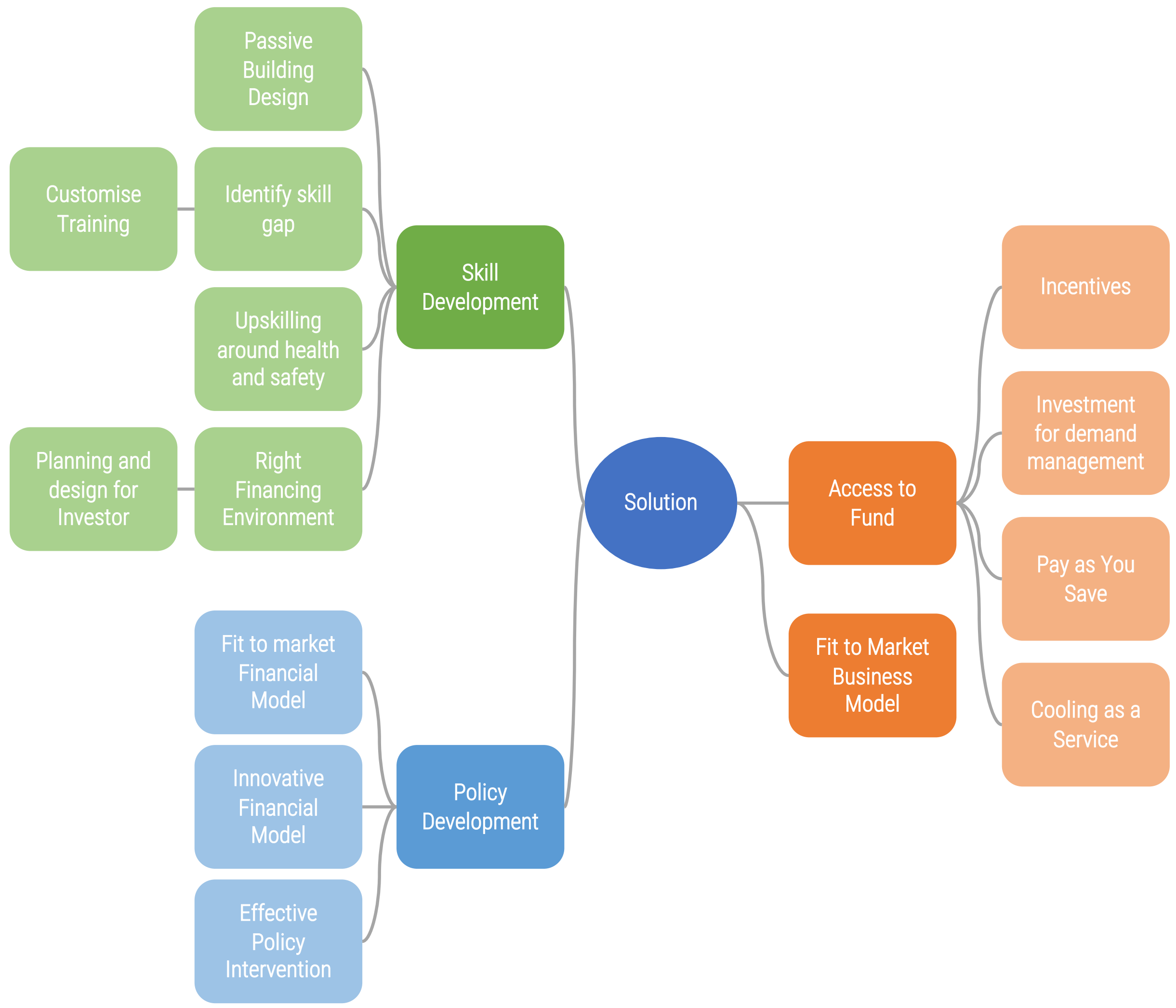


Figure 17 : Solutions for Access to Cooling derived from the analysis

3.4. Cold Chain - Healthcare

The cold chain-healthcare is the system of transporting and storing vaccines within the temperature range of +2°C to +8°C from the place of manufacture to the point of administration and also play a major role for storing critical medicine (eye drops inhalers, insulin), blood and organs. The World Health Organization estimates that 1.5 million people die each year from vaccine-preventable diseases [75]. That same study indicates that about 50 per cent of freeze-dried vaccines and 25 per cent of liquid vaccines are wasted each year [16]. Recent pandemics prove the importance of the cold chain in healthcare. Cold chains are playing a significant role in the delivery of COVID-19 vaccine.

The first generation of COVID vaccine needs ultra-cold chain technology [76]. Cold-chain supply or other complex supply chain systems present added challenges for developing herd immunity against COVID-19 for countries without adequate existing infrastructure [77]. According to Rebecca et. al. [77], around 20 per cent of the world's poorest countries do not have adequate cold chain capacity, and while some countries do have equipment, in many instances, it is old or broken and unable to keep vaccines cool. The total globally pledged COVID-19 economic stimulus package funding, which is currently in the order of US$14 trillion, provides an opportunity to accelerate the development and implementation of sustainable cooling solutions.

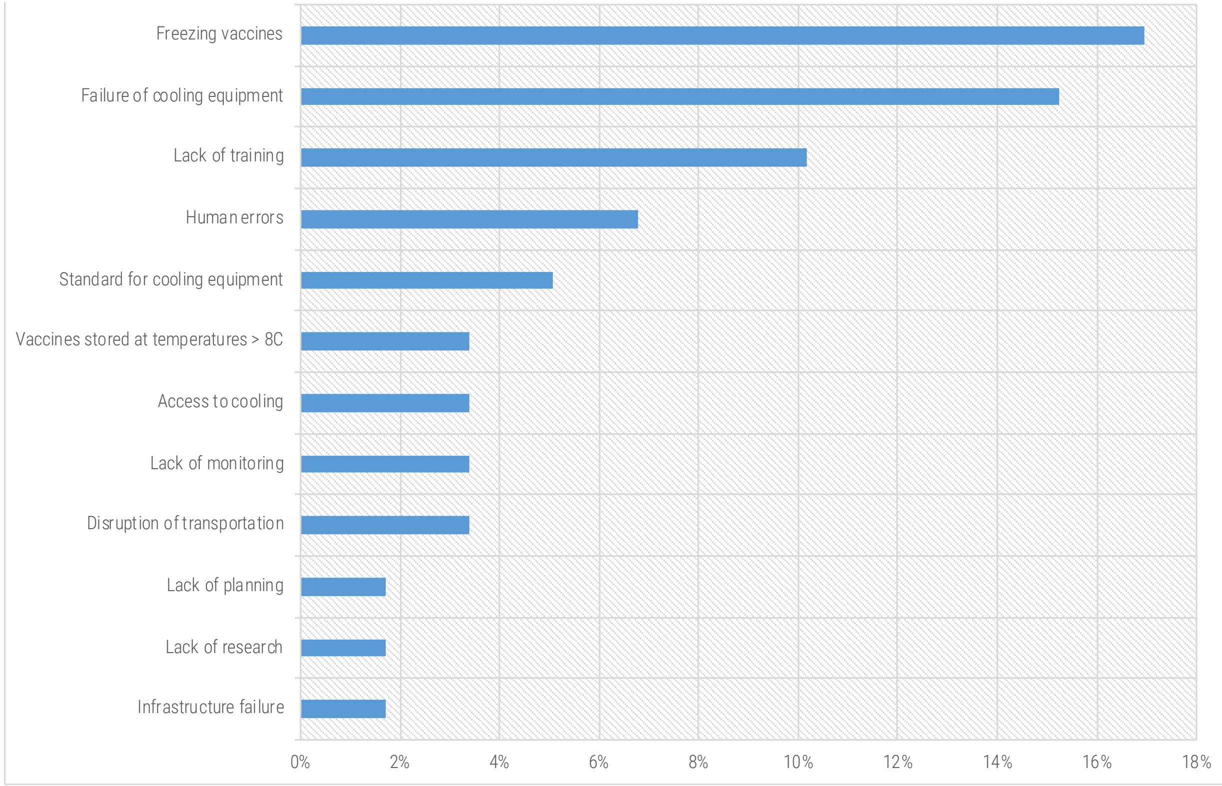
Vaccines can perform optimally only when kept in a specific temperature range. Temperature excursion, where the storage temperature exceeds the optimal limits for the vaccine, was identified as one of the most important factors for vaccine degradation. About 90 per cent of vaccines are designed so that their effectiveness depends on a rigorously controlled cold chain (a temperature range of 2-8° C). Therefore, maintaining the cold chain is important to ensure that effective and potent vaccines are administered to patients. Vaccines exposed to temperatures that are too high or too low can lose their effectiveness and be deadly to the vulnerable populations they are intended to protect [78].

Despite the political, financial, and human implications of vaccine cold chains, thus far the overall decision-making challenges in technology-supported cold chain management have received very little attention in humanitarian logistics research [21]. In fact, only 8 per cent of the studies included after the third stage of screening for this research mention the topic "cold chain in the healthcare sector" (17 papers) and hence manual addition was required in order to include a more comprehensive list of sources.

3.4.1. Issues identified for Healthcare Cold Chain

Figure 18 outlines a visual representation of the summary in terms of the percentage certain problems were mention by different authors within the Cold Chain – Healthcare sector. Out of 59 authors who referred to this topic, 17 per cent agreed that freezing is the biggest issue for this sector. In addition, about 15.25 per cent mentioned the failure of cooling equipment, 10.17 per cent mentioned lack of training, 6.78 per cent mentioned human errors and 5.08 per cent mentioned lack of standards for cooling equipment are issues that hinder the effectiveness of healthcare cold chains. It is important to highlight that one author can mention and address different issues in the same document therefore, the sum of the total representation of percentages for the issues is not a hundred but the percentage in terms of weight of the issue amongst the batch of papers that are referring to the same topic.

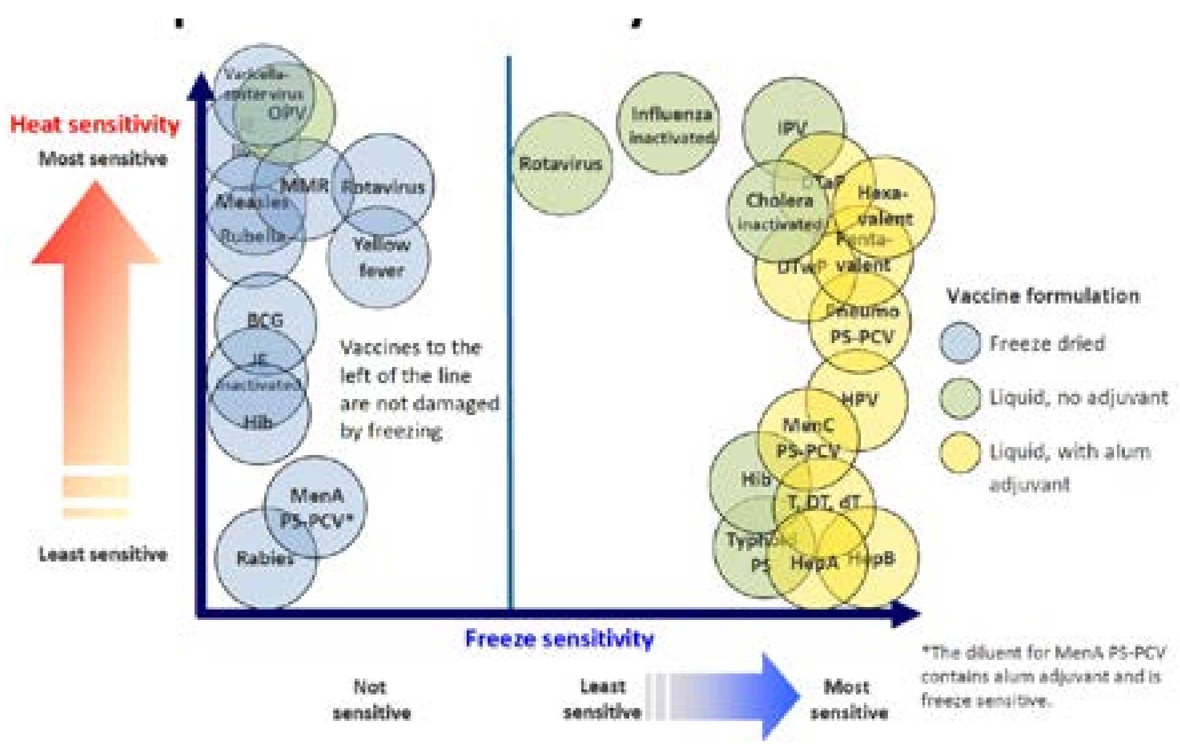
Figure 18: Priorities of Issues identified and their percentage of occurring in the reviewed documents
Source: [8, 9, 75-95]



Freezing sensitivity: Vaccines stored at temperatures < 0C

Vaccines can only save lives if they remain cool. Most vaccines are developed to be stored and transported at the temperature range of 2-8°C and are sensitive to freezing (Figure 19). Each bubble in Figure 19 represents the overall or "representative" heat/freeze sensitivity for that type of vaccine. Although heat exposure is usually the focus, freezing was identified as a problem in an astonishing 75-100 per cent of vaccine chains. Vaccines with active ingredients will spoil automatically if frozen but have generally better heat stability [4, 81, 96]. As much as 37 per cent of vaccines are exposed to temperatures below the recommended range in lower-income countries, making this a critical issue to address [75].

Figure 19 Temperature sensitivity of vaccines



Vaccine freezing is a known problem in many countries [78]. According to Wirkas et. al. (2012), vaccines should not be used if thought to have been frozen [89]. Yet recent studies have found widespread freezing at many levels of the vaccine distribution system. Many vaccines can be damaged by freezing, as often happens if cooling is done with ice packs [79, 96]. For example, in Indonesia, it was found that 75 per cent of hepatitis B vaccine shipments were exposed to freezing temperatures, potentially damaging a significant portion of this expensive vaccine [89]. India, the world's third-largest pharmaceutical producer, is plagued by inadequate cold chain logistics [88]. Nearly 20 per cent of temperature-sensitive healthcare products in India arrive damaged or degraded because of broken or insufficient cold chains, including a quarter of vaccines [4].

Freezing is considered the most critical aspect among the overall issues since this problem is often associated with the other problems of the sector, for example lack of training on cold chain management can cause workers placing vaccines next to ice packs causing freezing [81], failure of cooling equipment causing overcooling also results in freezing issues [97]. Cooling equipment may also require frequent and expensive maintenance or replacement parts posing a high risk of freezing and damaging the vaccines they store when not maintained [98].

Lack of training

Deficiencies in vaccine storage and handling through lack of training is the second biggest issues identified in the reviewed documents. Incorrect vaccine storage or packing procedures, such as placing freeze-sensitive antigens in a freezer or in the wrong compartment of a fridge, are practices evidenced regularly [81]. Such behavioural issues were also noted in different studies in the cold chain sector which were often classified as "careless" in excessively opening the refrigerator, thus increasing stress on the equipment and potentially risking heat exposure [81, 90].

Studies revealed the human behavioural element of the cold chain, namely the incorrect packing of vaccines in vaccine carriers for transport between stores and the field [89]. Limited technician availability further slows deployment, and poor-quality installation can result in early breakdown and reduced cooling equipment lifespan [79]. Refrigerators used for vaccine storage purposes have been used for personal purposes when in rural areas and personnel handling this equipment are not trained appropriately for the use of cooling equipment (e.g., storing food and drinks). Introduction of additional thermal mass (from the food and drinks) affects the internal temperatures of the refrigerator, which may negatively affect the integrity of the vaccines stored [86].

Resilient health supply chain systems require sufficient, empowered and skilled personnel at all levels. However, most national supply chains in countries eligible for support like GAVI[1] i do not have sufficient dedicated personnel to carry out logistics management tasks. These tasks are, instead, taken on by medical staff and technicians as additional responsibilities. These clinical staff, whose capacity is often already stretched, rely on well-functioning logistics processes in order to provide core health services [98].

1 The GAVI Alliance (formerly the Global Alliance for Vaccines and Immunisation) is a global health partnership of public and private sector organizations dedicated to run inclusive "immunisation for all" campaigns.

Failure of cooling equipment

Equipment failure and lack of spare parts or maintenance are mentioned as one of the risks for vaccine cold storage [4, 81]. The tremendous effort expended in reaching any community with immunization services will be lost if vaccines are improperly stored so that they are damaged by the inability to maintain the correct temperature when cooling equipment fails [89]. A study [90] of North West Region, Cameroon found that only 76 per cent of health facilities examined had a functioning thermometer for their vaccine storage unit, and of those, 20 per cent were experiencing abnormal temperatures at the time of data collection due to inefficient maintenance to cooling equipment causing it to fail.

Breakdowns in equipment at any level (transport, storage) poses an even higher risk to vaccines, as vaccines are designed for those systems and highly dependent on them operating without failure [76]. The performance of cold chains has been hampered by large quantities of outdated equipment, which fails to provide the protective benefit of more recent designs. Between 15 per cent and 50 per cent of equipment is older than the recommended 10 years, after which they are more susceptible to breakdown and poor temperature control. [79].

In 1998 an assessment team in Indonesia reviewed data available on the status of 520 solar refrigerators installed in 1991. According to the report, lack of spare parts and technical know-how were the major constraints for running those refrigerators. This shows that even when best practices are in place, failure of equipment poses a high risk to maintaining vaccine temperatures [86]. Solar refrigeration technologies are mature and reliable [99], with the weak component in the system being failure of the storage battery.

Human error

The human behavioural element of the cold chain was mentioned by many references as an important issue in the cold chain sector, which demands for example, skill development in handling the vaccine. In May 2017, 15 children died of "severe sepsis" and "toxicity" from contaminated vaccines in Kapoeta in South Sudan, which was caused by non-compliance with the cold chain protocols, where the vaccines were stored in a building without cooling facilities for four days [81]. Errors by personnel and suboptimal management practices are mentioned as common issues that need to be addressed in order to comply with cooling standards for vaccines [90, 96]. These practices were often the result of personnel using the refrigerators for personal reasons, such as to cool a soda on a hot day [79].

Lack of standards for cooling equipment

Cooling systems are typically not standardized. Without a specific standard for cooling equipment in the healthcare cold chain, and with increasing offerings of different equipment for refrigeration, vaccines are often stored inappropriately [81]. For instance, Tunisia, like many other middle-income countries relies on cheaper and locally assembled domestic refrigerators and cold boxes for storing and transporting vaccines. As discovered by testing the field performance which is not same as it was in a laboratory setting [85], the use of normal domestic fridges for the vaccines cold chain represents a risk for this sector. Household refrigerators are cheaper, widely available and easy to purchase, however, they are not safe for vaccine storage, as they do not reliably maintain the optimal temperature ranges. Despite this, some countries meet 45 per cent of their cold chain need with such fridges [79].

Transport of vaccines, covering the last mile[2]

Since vaccination relies heavily on transport to be effective [4, 21, 101], the condition of roads and access for transport are usually not accounted for when vaccination campaigns are designed and vaccines loose effectiveness if transport lacks back up to provide cold chain standards [14]. For example, road infrastructure and access to reliable electricity is an issue for over 70 per cent of health facilities in Uganda, with limited road networks further complicating access to 'off-grid' solutions absorption type fridges [79]. Inadequate capacity to provide services for cold chain rely on the fact that refrigerated transport requires fuel and energy, and since the condition of roads in the last mile especially in rural or remote areas is a threat, fuel and energy are finite and usually not included when designing vaccination campaigns [81]. Trucks may be stalled due to a lack of fuel causing damage to vaccines, if they are not delivered in time [28].

Lack of Monitoring

Monitoring is mentioned by only two documents. Inadequate monitoring is one of the causes of poor management of the cold chain for vaccines [89]. Without reliable systems to track compliance of cooling standards for vaccines, any efforts made by governments in order to provide proper equipment, training, transport and storage for the cold chain could be lost. This leads to a breakdown in the planning and allocation process of cold chains, which becomes ad-hoc and detached from evidence [79].

2 Last mile delivery is the last step of the supply chain process. It is the journey from a manufacturing company or shipping warehouse to the end customer's destination. As indicated by the name, it's the last step, or last mile, of the process. [100] Á. Halldórsson and J. Wehner, "Last-mile logistics fulfilment: A framework for energy efficiency," Research in Transportation Business & Management, vol. 37, p. 100481, 2020/12/01/ 2020, doi: https://doi.org/10.1016/j.rtbm.2020.100481.

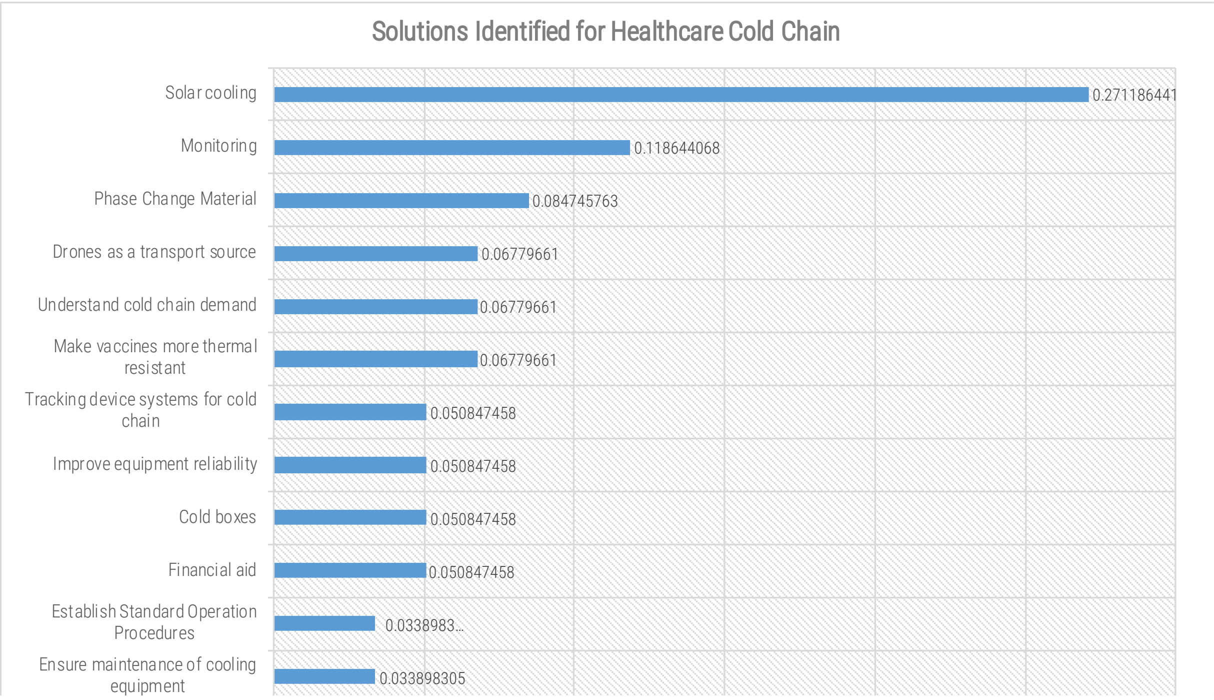
3.4.2. Solutions for Healthcare Cold Chain

Followed by most common problems in this sector, a summary of solutions found in the literature is presented. Figure 20 provides a visual representation in terms of the amount of times certain solutions within the Cold Chain- Healthcare sector was mentioned by different authors. Out of 59 authors who referred to this topic, 27 per cent agreed Solar Cooling is the most recommended strategy to follow when it comes to providing solutions to some of the issues. Monitoring programmes for cooling in the healthcare cold chain (11.86 per cent), phase change materials (8.47 per cent), drones as a source of transport (6.78 per cent), and, understanding the cooling needs in this sector (6.78 per cent) are amongst the most common strategies mentioned as solutions to improve the issues identified in the cold chain- Healthcare sector.

Solar cooling is suggested as one of the solution specially for areas with a lack of electricity access due to its low capital costs, low maintenance requirements, and capacity to operate off-grid [86, 97, 99, 102-106]. Best practice examples are commonly repeated within several papers evaluated in this research. For instance, four solar devices were taken to 4 remote health posts in west Senegal for field testing in 2015 [107]. The test results demonstrated that the devices consistently maintain the vaccine temperature within 3-50C , and a 100W solar panel was sufficient to power the system with ample margin. Testing at New Mexico State University for NASA and SDZR on an early prototype solar cooling with ice storage was successful and led to the development of direct drive vaccine strategies using ice storage [108]. This omits the need for expensive battery storage and replacements [108]. Another potential solution for access to cooling in rural areas is solar refrigeration [4], which works particularly well with solar panels in countries with no access to electricity and is ideal for protecting vaccines in remote rural areas [109].

Providing best technical options is not enough, and, monitoring the safety of vaccines is vital. While it is still a common practice in developing countries that thermometers are put into refrigerators and temperatures are checked at given intervals [6], only fridge tags, min/max thermometers and vaccine vial monitors can reliably provide information whether the safe range was maintained or breached and that strategy must be spread to developing countries as well [81]. A temperature monitoring solution was implemented in Tunisia and successfully demonstrated that the use of electronic continuous temperature monitoring and freeze prevention technologies can help significantly to reduce the incidence of inadvertent freezing of vaccines [78].

Figure 20: Priorities of solution identified for from reviewed documents on Cold Chain -Health Sector



Drones are also mentioned as a part of reducing the demand for storage of the vaccine [28, 81]. Despite the experimental and immature state of the technology, cargo drone strategies are potentially a game-changer for this sector as they can solve the last mile challenge. This technology addresses effectiveness, efficiency, and timeliness in the cold chain challenge with guaranteed delivery in time, irrespective of ground conditions [81]. The use of cargo drones is particularly significant for cold chains, where storage requires important investment, and transportation needs to be quick to ensure that vaccines remain cool [28]. The potential for drones entails savings for local clinic inventories and increases healthcare capacity. It reduces wastage from overstocked expired medicine and ensures minimum inventory levels, leading to cost savings [110]. Therefore, cargo drones promise to make systems responsive rather than predictive.

No academic studies were found in the reviewed documents for technical studies (feasibility and integrity) on drones used in vaccine chains or densely populated urban areas. Hence, there is a need to research the use of drones and their impact on vaccine chains from a managerial, logistics, and operations research perspective [81].

Another technology discussed in many documents is using the Phase Change Materials (PCM) which can serve as a back-up measure for solar direct drive, or for cold box [112]. PCM pack freezer can be included within the system design to support a single-day vaccine immunization campaign [96, 107, 113]. In addition, replacing the standard frozen-water packs with coolant packs filled with PCM is proven to be a best practice for maintaining vaccine temperature within the safe range [78]. The particular properties of this PCM technology mean that it can freeze at a positive temperature of +5 ?C. Packs filled with PCM provide about half of the cooling of a frozen-water pack, but without the risk of freezing [85].

Table 4 : Solutions for Cold chain addressing the healthcare issues identified from the reviewed documents

Solutions/Barriers	Freezing vaccines	Failure of cooling equipment	Lack of training	Human errors	Lack of standard	Vaccines stored at temperatures >8C	Access to cooling	Lack of monitoring	Disruption of transportation
Access to finance			High	Low	Medium		Medium	High	Low
Enforce the use of temperature tracking devices	High	High			Medium			Medium	
Ensure maintenance of cooling equipment	Medium	High	Medium	Low	Medium	High		High	
Establish standard operation protocol	Low	Low				Low		Medium	
Implement monitoring programmes					Medium	High		Medium	
Improve access to cooling through community cold storage					Medium		Low		
Improve equipment reliability and efficiency	High	Low			Medium		Medium		
Use of drones as transport of vaccine supplies			High				Low		Low
Use of Phase Change Material	High						Low		
Introduce solar cooling systems	Low				Medium		Low		
Make vaccines more thermal resistant	High					High			
Understand the cold chain	Low	Low	Low	Low		Low	Low	Low	Low

High priority · Medium priority · Low priority

Anticipating future cooling needs are essential and linked with understanding the cold chain demand as a solution, mainly when procurement and installation of cold chain equipment require planning [79] . Capacity needs also evolve over time with new vaccines introductions, campaigns, and population growth. For example, with the introduction of Inactivate poliovirus, Rotavirus, Tetanus-Diphtheria and Measles-Rubeola in Uganda over the next few years, positive storage volume requirements for all vaccines will increase by 67 per cent [79].

The pandemic that the world is experiencing through COVID-19 will put even more pressure to the storage requirements. Moreover, the strategy will only be successful if it manages to bring together the full range of countries and partners working to improve immunisation cold chains and ensures that their planning supports five fundamental components: data, people, equipment, systems requirement and a continuous improvement strategies. [98]

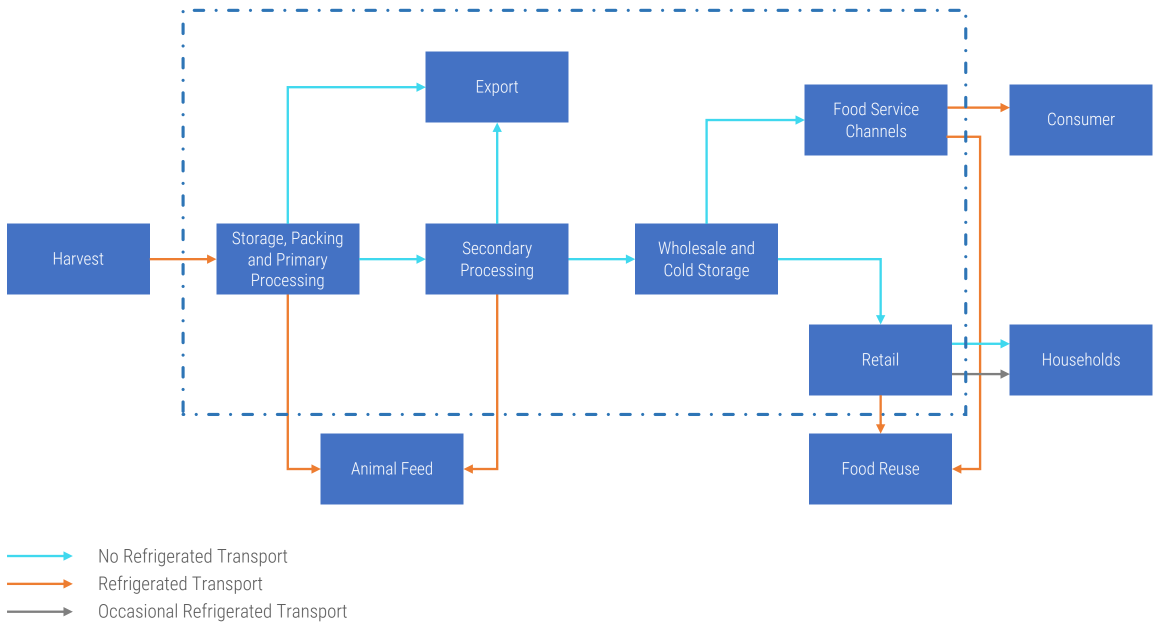
Cooling load can also be reduced by designing vaccines with less cooling requirements (more thermal tolerance) [9, 21, 105]. Although well-performing equipment is important for cold chain management, other aspects also play a key role in ensuring vaccine potency, including trained personnel, effective and efficient and management practices that link trends and priorities in cold chain management with supply chain management and service provision [78, 90].

Table 4 below shows the map that summarises solutions for cold chain healthcare linking with the issues identified previously in this section.

3.5. Cold Chain – Food

The food cold chain is an integrated, seamless and resilient network of refrigerated and temperature-controlled packhouses, distribution hubs, vehicles and processes to maintain the safety, quality and quantity of food, while moving it swiftly from the farm gate to consumption centre [88]. The role of the cold chain in the supply of food is expanding and can reduce waste in the supply chain [114]. Well performing cold chains have the ability to enhance economic wealth, cash flow and security for farmers and improve food quality, safety and value to the customer [16]. Figure 21 is a supply chain map for food that shows the critical role played by refrigerated transport in maintaining the integrity of the cold chain. According to [114], each transport link in the supply chain is a critical control point in the cold chain.

Figure 21: Fruit and Vegetable Sector Supply Chain and Food Waste Boundary Attributed to Commercial Refrigeration



Source: Adapted from [114]

Studies estimated that about 50 per cent of total energy consumption in the food industry is related to cold facilities [8, 91, 115]. The estimated electricity consumption of each equipment category across the cold food chain is shown in Figure 22.

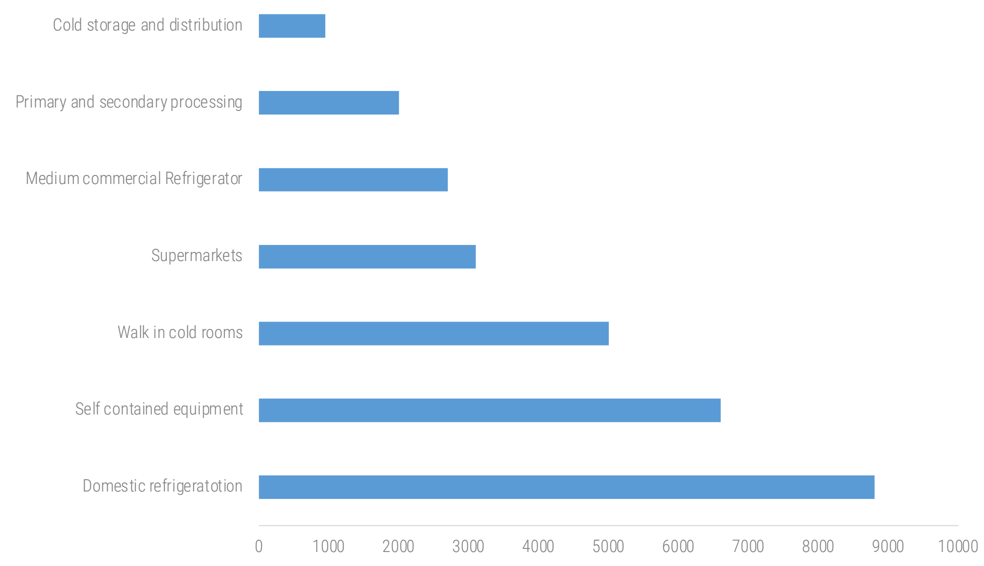


Figure 22: Electricity Consumption (Estimated) of Each Equipment Category Across the Cold Chain Food

Data Source:[116]

Figure 22 shows that self-contained equipment has the highest energy consumption among all equipment across cold food chain as domestic refrigerator is considered to be out of the supply chain and is categorised under process. According to [114], some supermarket chains in Australia are undertaking door retrofit programs on medium temperature meat, dairy and liquor open display cases due to electricity price rises.

With the rising temperatures due to climate change, the demand for cooling food is also expected to rise and thereby presents an additional challenge [117]. The energy demand of food cold chains is influenced by a range of factors beyond the principle choice of a cooling technology and cooling unit size [80]. The most important factors influencing energy demand in cold chain applications include [82]:

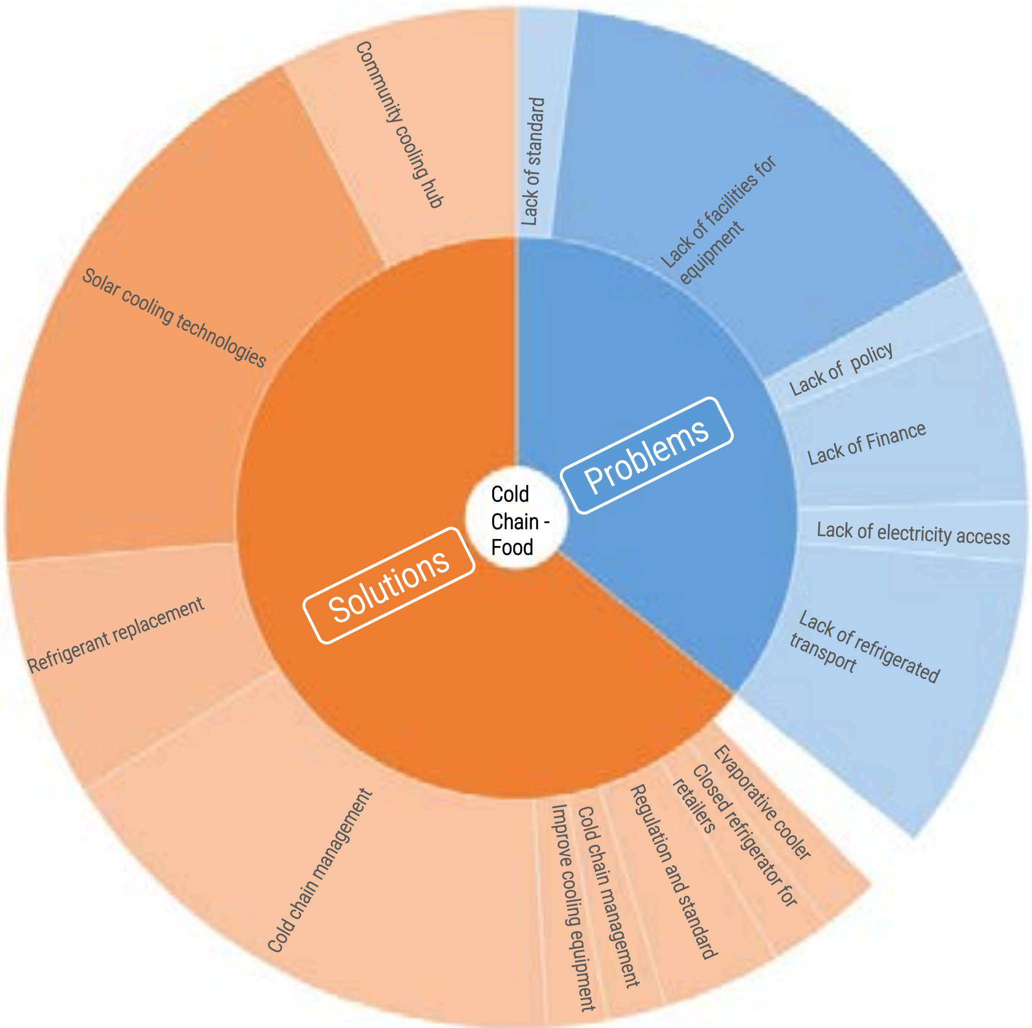
- On-site climatic conditions in terms of temperatures, incident solar radiation, wind speeds and humidity
- Storage design characteristics in terms of insulation quality and
- Basic storage design considerations such as ratio of surface area compared to storage volume, surface albedo, exposure of storage to sun and wind.

Temperature difference between products entering storage and their optimum storage temperature, as well as the actual storage volumes across prolonged periods of time are also mentioned as factors for energy consumption [80].

Current cooling technologies are also highly polluting as they not only leak refrigerant but are also responsible for emitting large amounts of CO2 through energy consumption. Some cooling technologies, such as transport refrigeration units, are powered by inefficient diesel engines that emit grossly disproportionate amounts of nitrogen oxides (NOx) and particulate matter [91]. About 15 per cent (34 out of 226) of the documents reviewed discuss issues associated with Cold Chains- Food.

Research found a strong relationship between access to cooling and the food supply chain. According to [113] the lack of access to cooling in the supply chain (and in households) causes high food wastage in vulnerable areas and communities. The Food and Agriculture Organization (FAO) of the United Nations (UN) [16] suggests that the worldwide food wastage (good quality food that is discarded at retail and consumption stages) and food loss (food that spoils before it reaches the consumer) along the supply chain is approximately one-third of the total food production. It is therefore vital that the refrigeration industry develops clean cold systems and pathways not only to anticipate a dramatic increase in cooling emissions in developing countries, but also allow those

Figure 23 : Most frequent problems and solutions on Cold Chain -Food identified from review



countries to leapfrog to truly sustainable solutions [91].

3.5.1. Issues Identified for Food Cold Chain

Figure 23 presented below illustrates the problems and possible solutions for food cold chain sector within the reviewed documents. The width of the slices is proportional to the number of occurrences within the reviewed documents (includes multiple occurrences within a single document and across multiple documents) occurred within the reviewed documents.

A considerable percentage of the world population inhabits remote areas, where the electricity supply is scarce, deficient or even non-existent [4, 9, 16] – which affects the supply of safe food [102]. An estimated 470 million people in poor rural areas lack access to safe food [118]. Due to the lack or intermittent provision of electricity in remote areas conventional refrigeration equipment for food is not suitable for reducing the for waste [102]. Even when access to electricity is not an issue, cold chains rely on reliable systems working 24 hours a day, seven days a week, so intermittent electricity becomes an issue as well [4, 80].

Lack of cold chain in the first mile[1] is mentioned the most (38 per cent studies) as the main cause for issues in the food cold chain. Food production capacities in rural areas often cannot be utilised, because the food cannot be transported to the bigger towns or cities due to lack of first-mile cold chain storage [4, 113]. According to the Global Food Cold Council (2015) for Near East and North Africa , the lack of sufficient and efficient cold chain infrastructure is a major contributor to food losses and waste, estimated to be 55 per cent of fruits and vegetables, 22 per cent of meats, 30 per cent of fish and seafood, and 20 per cent of dairy [82].

Other studies suggest that about 23 per cent of losses of perishable food can be ascribed to a lack of refrigeration [119, 120]. The lack of adequate cold storage and refrigerated transport causes the loss of around 200 million tonnes of food each year [118]. As suggested by several authors developing countries are affected the most by this trend, indicating that despite the strong growth in the developing giants, cold chains remain rudimentary or non-existent in most developing countries [109, 121]. This means for example that in India just 4 per cent of fresh produce is transported cold, compared to more than 90 per cent in the UK. China meanwhile has an estimated 66,000 refrigerated trucks to serve a population of 1.3 billion, compared to France which has 140,000 to serve 66 million [80]. According to Becker and Kurdziel (2018) poorly designed refrigeration systems and outworn worn out equipment are the typical challenges found in many developing countries, reducing energy performances from this sector [122]. Refrigeration systems rely heavily on refrigerants. Significant amounts of HFCs are released into the atmosphere due to leaking from refrigerants. An example mentioned by Barta et .al (2018) is centralized supermarket refrigeration refrigerant leaks, which are significant (estimated as 10-30 per cent annually) are due to them being field installations [123].

1 First mile delivery is a common term used by professionals in the industry of cold chain to describe the different movements of goods during the supply chain process. Food manufacturers may see a first mile delivery as the transportation of their completed goods from the factory to a distribution centre or warehouse.

Cold chain infrastructure (stationary cold storage and refrigerated transport) remains underdeveloped, even though governments of many developing countries and international funding agencies have identified the development of the cold chain as a means of preventing food loss and waste [28, 62]. Despite some government activity, there is an overall lack of policy support to facilitate first mile processes in the cold chain food the focus remaining further along the value chain, closer to last mile processes [88].

This review has also identified the 'energy intensity' of refrigeration equipment and transport associated with the food supply chain as an issue. Cold chain food development places a burden on the environment since refrigeration is energy intensive and is responsible for emission of greenhouse gases [9, 82, 91]. Keeping products cold throughout the mobile portion of the cold chain (such as trucks, trains and ships) account for 7 per cent of global hydrofluorocarbons (HFC) consumption [74]. This contributes to 4 per cent of the total global warming impact [16]. Furthermore, diesel-powered transportation refrigeration units on trucks consume up to 21 per cent more diesel than a non-refrigerated diesel-truck, which has significant implications for climate change as the development of cold chains becomes more universal in developing countries [88].

This review did not identify many traceability technologies available right now on the market that can provide real-time temperature information along the whole supply chain for food making lack of monitoring an issue [87]. In the same spectrum, the last greatest challenge identified for the food supply chain sector is the lack of a standardized way to collect information and exchange it among systems used between different stakeholders [62]. Different actors in the supply chain can have different technical solutions such as alphanumerical codes, barcodes and radio frequency identification (RFID) tags, leading to compatibility problems. For managers of food supply chains choosing the right traceability technology can therefore be a complicated task as many different solutions are available [87]. This means it is often difficult to track whether the food has been reliably kept within the required temperature range throughout the supply chain.

In summary, the energy demand of food cold chains is influenced by a range of factors beyond the principle choice of a cooling technology and cooling unit size. The most important factors influencing issues to occur within the food cold chain include about seven barriers:

- Lack of awareness and knowledge among manufactures, government, users and investors of the needs in the cold chain sector and the benefits of providing efficient means of cold chain supply for food
- High energy intensity of current practices applied in the cold chain-food sector
- Lack of understanding and data on the energy demand of the supply chain
- Lack of access to electricity for cooling
- The actual lack of a cold chain
- A lack of monitoring of practices within the cold chain and
- A lack of standards to verify the efficiency of the cold chain equipment and the overall supply chain.

3.5.2. Solutions for Food Cold Chain

Authors in several reviewed documents agreed on the importance of understanding the cold chain demand as the first step to be considered when providing practical solutions to the different issues within the sector [16, 28, 80].

Table 5 shows the sector's issues (in orange) and solutions (in green) identified during the literature review. The development of cold chains needs to be understood as an opportunity to close the gap on food loss and waste and carbon emissions especially in the developing world, highlighting the social and environmental benefits of doing so [82]. Ensuring adequate storage and transportation systems for perishable food reduces food loss, price variability of food, and more importantly in the context of climate change, reduces GHG emissions [63]. Supporting cold chains and cold storage that both enable healthier diets and improve agricultural incomes remains a complex challenge and therefore need databases on industry, distributors, retailers and consumers [4, 83]. These technologies are critical for development, but technical solutions are difficult to identify given that low agricultural incomes likely necessitate grants or highly concessional finance to initiate market development and a simple technological solution will not be sufficient to counteract such a massive challenge [6].

Table 5: Solutions mentioned in the reviewed literature on food cold chain

Solutions/Barriers	Access to electricity	Lack of facilities/equipment/ transport	Lack of monitoring	High energy intensity of cold chain transport	Lack of standards to verify compliance	High energy intensity of refrigeration systems
Include solar cooling systems in the generation energy mix	✓					✓
Access to finance		✓				
Implement community cooling hubs	✓	✓				
Introduce evaporative coolers	✓	✓				
Enforce and implement standards for cold chain management			✓	✓	✓	✓
Implement temperature traceability technologies/tracking systems			✓		✓	✓
Enforce and implement training programmes		✓	✓		✓	
Enforce refrigerant replacement				✓		✓
Enforce closed refrigerator regulations for retailers						✓
Improve equipment efficiency						✓

The importance of addressing the issue of providing access to electricity (which will indirectly help with the access to cooling for cold chains) is beneficial since its development would reduce post-harvest food losses, which would raise small farmers' incomes by increasing the proportion of their produce that reaches market. Subsequently, this would increase the food supply, and should also reduce food prices for consumers [9, 105]. Access to cooling would also allow farmers to expand the production of processed as well as raw products, and to sell into more distant and even international markets. This would also boost local economies, generate employment and reduce migration to urban slums [88].

From the policy perspective, there is a need to create a collection and analysis of more granular data about where losses occur across the cold chain to improve the effectiveness of broader policy interventions. Although some countries have information and data regarding food loss and waste, there is a lack of more granular data about the extent of food loss and waste arising in transit. Improved measurement approaches and systems would help the direction of resources into areas/value chains where the maximum benefit could be gained from investment in refrigerated transportation [62, 80].

The widespread development and operation of cold storage infrastructure requires significant financial investments. In order to facilitate these investments, improved access to finance for food producers, wholesalers and retailers, tailored specifically to the economic needs and possibilities of potential entrepreneurs, is necessary [80, 91].

There is a necessity to develop and implement policies, including regulations enforcing the creation of domestic energy labelling schemes and energy efficiency classification system for equipment components and products associated with cold chains [124, 125]. In order to enable a better first-mile cold chain, instead of big cold storages owned by the agricultural companies themselves, smaller cold storages closer to the production where space can be rented may be necessary [6, 113]. The previously discussed challenge in the remote areas in the tropics, namely the unreliable or non-existent electrical infrastructure at the location for food production, complicates the implementation of a functioning cold chain starting from the first mile and then further. However, since the food storage capacity in each location is rather small, standardised containerised solutions (or in other words Community Cooling Hubs) powered by solar devices may be suitable [6, 80, 113].

There is substantial literature on first and last Mile[1] issues with cold chains that offer solar refrigerators in both rural areas and commercial areas as effective solutions [81]. Among successful implementations found in the reviewed literature are:

- Solar-powered adsorption refrigerator in Nigeria [81].
- Solar direct drive technology for commercial cooling demands for the rural milk sector [108, 126].
- Air liquefier driven by solar power that could provide the basis for an economic cold chain in rural Tanzania and other remote locations in developing countries [109].
- Concentrated solar thermal coupled with vapour absorption machines for cool hubs [88].
- Solar as a source of alternative renewable energy generation as part of the mix for energy generation systems [80].

1 First mile delivery is the first leg of the journey that item will make in the individual company's supply chain process and last mile takes place at the customer-end of the supply chain [100] Á. Halldórsson and J. Wehner, "Last-mile logistics fulfilment: A framework for energy efficiency," Research in Transportation Business & Management, vol. 37, p. 100481, 2020/12/01/ 2020, doi: https://doi.org/10.1016/j.rtbm.2020.100481.

3.6. Mobile Cooling

Mobile cooling (or mobile air-conditioning or MAC) or transport sector cooling consumes only 25 per cent of the energy used for all cooling applications [62]. Currently 31 per cent of total GHG emissions of the cooling sector are accounted for transport cooling systems, which is the second largest after space cooling [61, 63]. Therefore, without decarbonizing the transport sector, addressing climate change is not possible [72].

All vehicles are now equipped with mobile cooling units. With more than 100 million units sold in 2018, total stock were 1 billion units. There will be significant growth in mobile cooling in developing countries in the coming years [127]. The demand for mobile cooling can be categorized as follows:

- Passenger car mobile air conditioner
- Bus mobile air conditioner
- Rail mobile air conditioner
- On-highway transport refrigeration units
- Shipping container

Mobile air conditioning (MAC), relies on the use of refrigerants. These air conditioning system systems remove the heat and moisture from the air inside the vehicle using power and transfer it outside. A direct expansion vapour-compression cycle is used in which heat is extracted from the vehicle cabin via an evaporator using a refrigerant, and then transferred to the outdoor air via a condenser. The pressure of the compression cycle causes the refrigerant to condense back to a liquid, lowering the temperature of the refrigerant and beginning the cycle again [128]. Power capacity and leakage rate of some types of vehicles are shown below in Table 6.

Table 6: Power Capacity and Annual Leakage Rate of MAC units for Transport

Types of Vehicle	MAC Size (kW)	Annual Leakage Rate (g/year)
Passenger Cars and Vans	4	30-80
Medium and heavy Freight Truck (typically in the driver cabin)	1.2-4.5	60-100
Bus	25	2400

Source: [128-130]

3.6.1. Issues identified for Mobile Cooling

There is wealth of research articles on air conditioning systems but only a few focussed-on transport cooling. Out of 164 journal articles only two were found with a short discussion on mobile cooling and therefore required manual addition to include a more comprehensive list of sources. Figure 24 shows the issues and solutions identified on mobile cooling from the documents reviewed according to the number of occurrences.

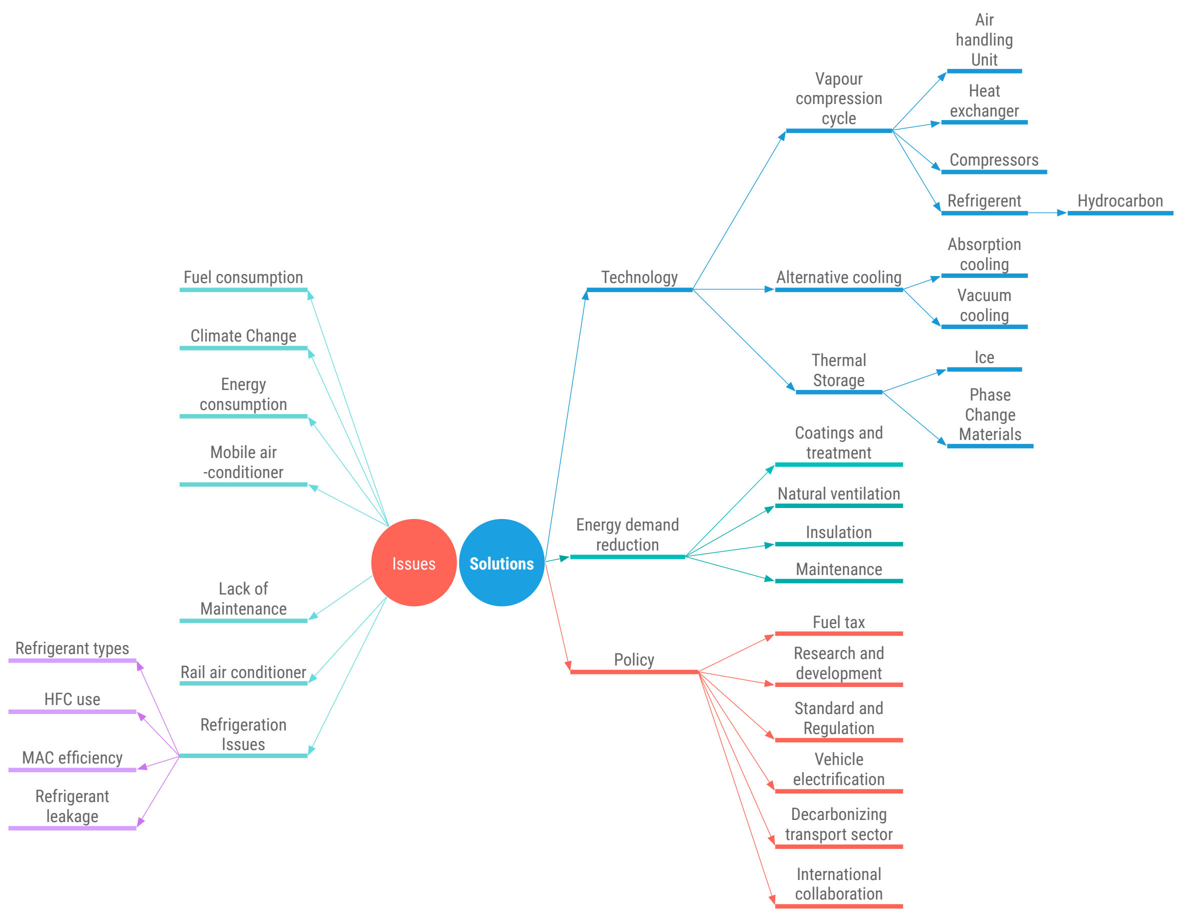


Figure 24: Most frequent barriers and solutions on Mobile Cooling identified from reviewed documents

Making mobile cooling climate friendly is a challenge due to technical constraints related to energy use and refrigerant safety, a situation that will be exacerbated by a shift to battery-powered electric vehicles [118]. It was mentioned by the World Bank, that the projected increase in MAC energy use by both light and heavy road traffic could jeopardize achievement of the decarbonization goals [127].

Transport applications have specific challenges such as shock, vibration, corrosion and extreme operating ambient conditions, which require different designs from other refrigeration applications. Another point raised in the same report is the lack of efficient air-conditioning systems, which reduces the driving range of electric vehicles on a hot and humid day which impedes their uptake [127].

Mobile cooling currently consumes about 1,040 TWh of energy per year across refrigeration and air conditioning applications [131]. A report on cooling assessment mentioned that due to the expected increase in passenger transport by 2030, improving efficiency and using more renewables will not be sufficient, as a 70 per cent reduction in energy consumption in the cooling sector would be needed to meet the growing cooling needs [130]. Reefers[1] are estimated to consume up to 19 per cent of the energy used to move refrigerated food stuffs large distances and most rely on external electrical power from the port while ashore [1], and from the container ship during sea transit [118]. The use of renewable energy is very limited in long-distance road transport, particularly for long haul road freight which accounts for 30 per cent of global transport related energy demand [118].

Transport refrigeration also consumes a large amount of the refrigerated vehicles' fuel [131]. The direct emissions, via leakage of refrigerant (as shown in Table 6) is a significant problem identified in the literature [62, 127]. Emissions impacts from bus MACs are disproportionately large compared to the number of vehicles. Bus MACs represents a comparable fuel consumption challenge compare to car MAC equipment as they operate for a higher proportion of the year than a passenger car. However, while they use more fuel per vehicle, they use less per passenger kilometre. The refrigerant charges for bus MACs equipment are between 16 and 30 times those used in the car segment [131]. This sector is a significant contributor to global greenhouse gas emissions, of which almost 80 per cent comes from road transport [130]. These emissions are intricately linked with climate change through direct emissions from refrigerant leakage (the refrigerant has a significant GWP) and indirect emissions from the energy used to power mobile cooling devices, which is typically from the combustion of gasoline or diesel [15, 130]. There is the potential for reducing the impact of these direct emissions by employing refrigerants with a low GWP. Currently, in most MAC systems HFC-134[2] is used as the primary refrigerant in most MAC systems, although it still has a relatively high GWP of 1,300 times that of CO2 [130]. HFC emissions in 2016[3] accounted for 0.025 W/m2 of radiative forcing. The use of HFCs will be reduced in the coming years following the entry into force of the Kigali Amendment to the Montreal Protocol on 1 January 2019 [10].

1 Reefers are Refrigeration containers. [1] J. H. R. van Duin, H. Geerlings, A. Verbraeck, and T. Nafde, "Cooling down: A simulation approach to reduce energy peaks of reefers at terminals," Journal of Cleaner Production, vol. 193, pp. 72-86, 2018/08/20/ 2018, doi: https://doi.org/10.1016/j.jclepro.2018.04.258.

2 It is used in automotive air conditioning and as a replacement for R12 and R22 in medium and high temperature refrigeration applications

3 Not include HFC-23,

Leakage is one of the biggest problems in mobile cooling due to its direct emission as mentioned in the literature. Refrigerant leakage rates are as high as 125 per cent of their original charge over a ten-year life for a car and 165 per cent for a truck system [127]. The HFC mitigation requirement is substantial in the context of the goal of the Paris Agreement to limit warming no more than 1.5°C [91]. HVAC units for passenger trains rely heavily on HFC-134a or R-407C as working fluids. An attempt to evaluate alternatives such as R-513A and R-449A are under experiment [72].

3.6.2. Solutions for Mobile Cooling

Demand reduction is a common way to limit the emission from any sector. The review showed that the for transport, demand reduction can be applied in the air conditioning system by reducing the task size [3]. Literature suggested via shorter trips or combined trips using carpooling can reduce cooling demand by reducing time of cooling equipment is in use. According to Blumberg et al. (2019), around 18 per cent of the cooling load can be reduced by parking and vehicle design [128]. Other options are using solar reflective glazing films, reflective windshields, reflective paints [132]. Using alternative refrigerants can achieve deep reductions in GWP with equivalent to better overall energy efficiency to the baseline refrigerant R-410a[4] .

Several technologies mentioned to reduce the load and demand on the MAC system and improvement in heat transfer are mentioned in the documents reviewed. Fuel savings could be achieved by seat ventilation, cabin ventilation, solar glazing[5] for glass and climate control seat [135]. Lack of maintenance is mentioned as a contributor to direct emissions through poor refrigerant handling practices and energy performance. For larger cooling equipment, poor maintenance can lead to an increase emissions by up to 30 per cent [127]. Options for demand reduction for mobile cooling are shown in Figure 25.

4 R410A has been the refrigerant of choice in Europe and elsewhere since first introduced in the mid-90s as a replacement for ozone-depleting R22. It is also now being introduced in some of the major world markets and the developing countries as R22 becomes more widely phased out under Montreal Protocol agreements [133] Cooling Post. "What future for R410A." https://www.coolingpost.com/features/what-future-for-r410a/ (accessed June 22, 2021).

5 Solar glazing is a unique combination of solar photovoltaics (PV) and glass where the PV cells are laminated between two panes of specialised glazing. The resulting glass laminate serves the dual function of creating energy and shade at the same time. [134] J. Rugh, L. Chaney, J. Lustbader, and , and J. Meyer, "Reduction in Vehicle Temperatures and Fuel Use from Cabin Ventilation, Solar-Reflective Paint, and a New Solar-Reflective Glazing,," SAE Technical Paper, 2007. Hydrofluoroolefins (HFOs) are unsaturated organic compounds comprising of hydrogen, fluorine and carbon. Unlike traditional hydrofluorocarbons (HFCs) and chlorofluorocarbons (CFCs), which are saturated, HFOs are olefins, otherwise known as alkene [210] X. Wu, C. Dang, S. Xu, and E. Hihara, "State of the art on the flammability of hydrofluoroolefin (HFO) refrigerants," International Journal of Refrigeration, vol. 108, pp. 209-223, 2019/12/01/ 2019, doi: https://doi.org/10.1016/j.ijrefrig.2019.08.025.

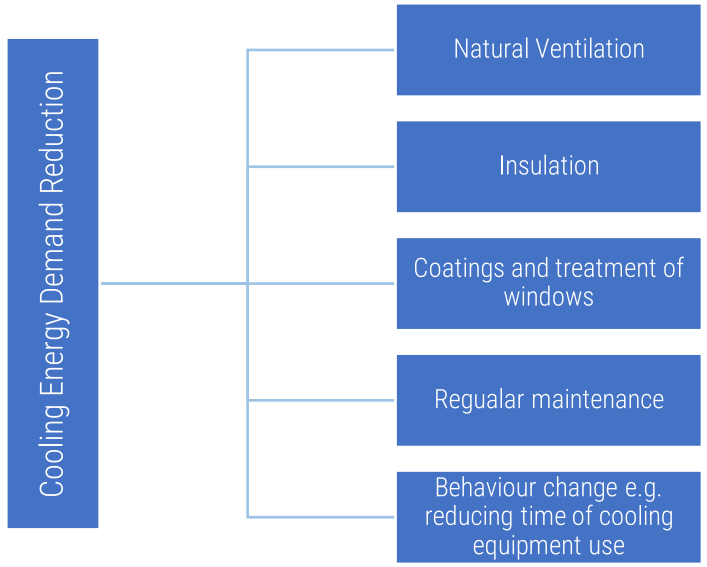


Figure 25: Energy Demand Reduction Solution tree for mobile cooling

Technological options of mobile cooling solutions identified in the review are [136] [128, 137]:

- Vapor compression system optimization: Vapor compression cycle optimization techniques already proven to reduce energy consumption of MAC system by 40-50 per cent. Vapor compression cycle has basically four components evaporator, compressor, condenser, and expansion valve. Another option is to change the refrigerant which is more challenging and has not much success so far.
- Thermal storage: It has an advantage for transport refrigeration. Phase change materials (PCM), ice and cryogenic systems are suggested as thermal storage, but these are not appropriate for all vehicles due to its weight.
- Vacuum cooling: It is a proven technology widely applied in keeping fruits and vegetables fresh. This technology is suitable to use in food transport refrigeration.
- Absorption Chilling: This technology can provide cabin cooling for truck using engine exhaust as heat load. It applies ammonia/water vapour absorption cycle to provide the cooling. The coefficient of performance (COP) of this ammonia/water system varies from 0.3528 to 0.3113.
- Fuel Savings: through technologies such as seat ventilation, cabin ventilation, solar glazing

Figure 26 shows the technological solution tree as discussed above.

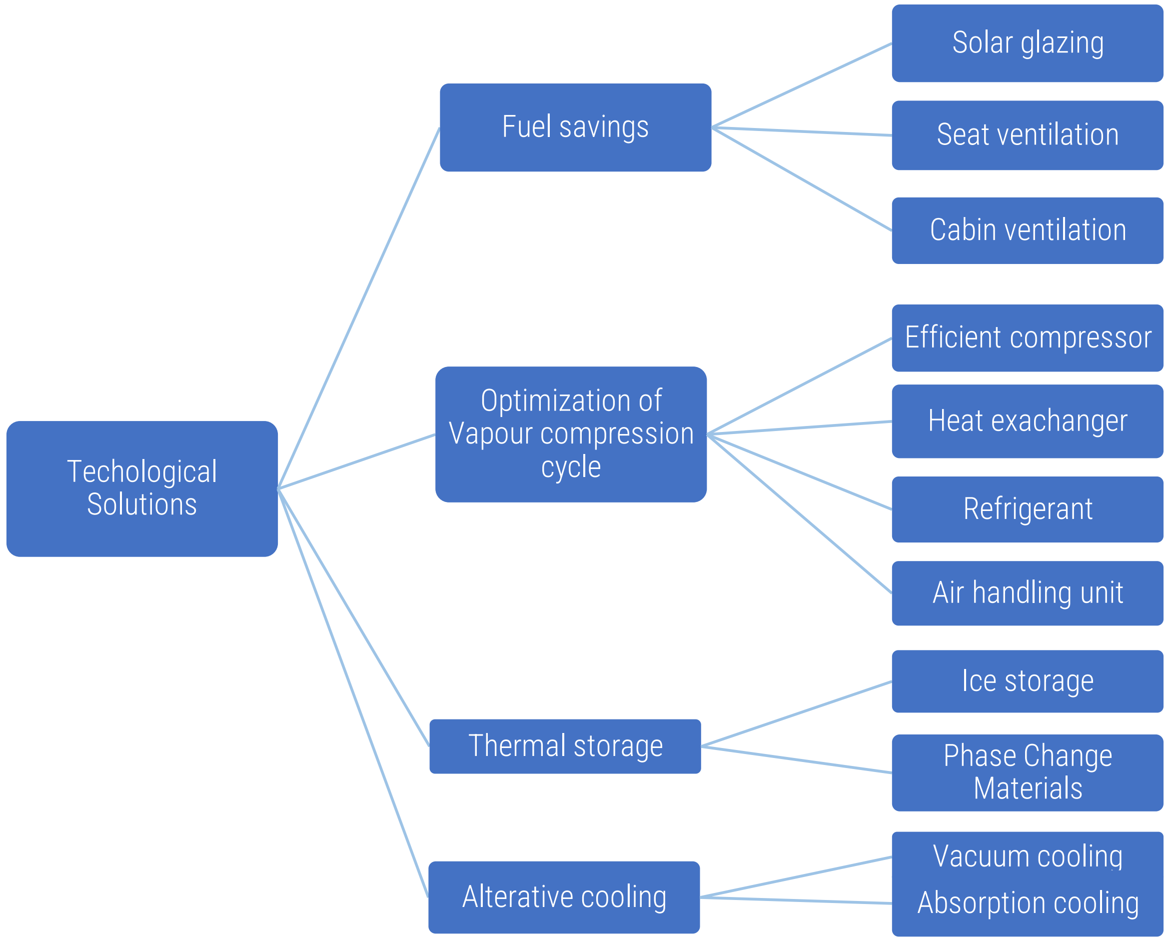


Figure 26 : Technological solution tree for mobile cooling

Using renewable energy for transport is a cleaner and more efficient modes of transport and increasing efficiency and help to reach targets relating to climate change and sustainable development. Despite the current low share of renewable energy (RE) in the transport it has recently attracted the attention of policy makers in many countries [60, 130]. Decarbonizing transport, fuel tax, standard, regulations, research, and development, shifting to low GWP refrigerant policy and vehicle electrification were mentioned as policy solutions in the reviewed documents.

It was mentioned in the literature that there is a lack of policy requirement in limiting the energy consumption of MAC systems for transport in any country. Brazil has a pollutant emission standard which tests the energy consumption of vehicles with any MAC equipment running [130]. There is also a lack of an appropriate international methods to test the energy consumption. In the United States, the fuel standard allows standard targets based on manufacturer data. Except for the European Union, Japan, UK and Canada have successfully introduced regulations to cap the GWP of refrigerants used in new vehicles [130]. Minimum energy performance standards (MEPs) can be implemented in some energy-using components, such as the compressor, fans and heat exchangers [62, 87, 127].

Research and development, demonstration funding, financial de-risking measures, rollout of alternative fuelling or charging infrastructure, low-carbon fuel standards, vehicle emission standards, zero-emission vehicle mandates, obligations and mandates for the share of renewables in fuel, fuel taxes based on the life-cycle of greenhouse gas emissions for fuel or consumption [138] (e.g. greenhouse gas emissions per kilometre), and public procurement of renewable carriers for transport are all mentioned as policy instruments for decarbonizing the transport sector [60, 139]. These more general policies would also drive reduction in the MAC component of emissions Figure 27 shows the policy solution tree. The policy solutions are summarised below [60, 62, 127, 131, 137, 140] :

- Use of renewable energy in the transport sector needs policy attention with integrated planning and policy design are crucial for deploying RE.
- Introducing a price on carbon would be a key tool to stimulate the decarbonisation of the transport sector.
- Fossil fuel subsidies elimination are important measures for decarbonizing the transport sector
- Introducing fuel tax to support biofuel for transport and make it financially competitive
- Provide green finance for promoting new and emerging technologies and
- Research and development for identifying new and efficient technology

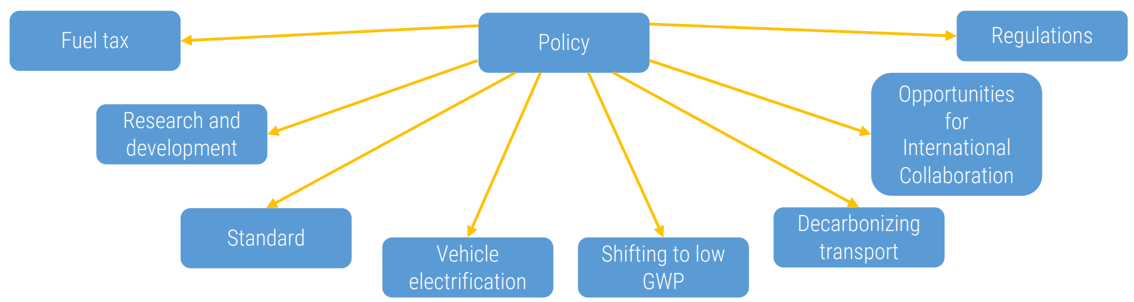


Figure 27: Policy solution tree for mobile cooling

3.7. Space Cooling – Residential and Commercial Buildings

Around the world, the building sector is responsible for consuming around one-third of the total primary energy resources and releasing 30 per cent of global CO2 emissions [141]. Furthermore, energy used by the building sector is increasing over the years due to the broader application of HVAC systems in response to the growing demand for better thermal comfort within the built environment. Over the past 40 years, the energy consumption in buildings has increased drastically to become a significant crisis faced in the 21st Century [4]. As a result, space cooling, typically using an electric-powered fan or air conditioning (AC) system, contributes increasingly to global energy demand. This demand has mainly been caused due to the vast load required to meet the increasing demand for thermal comfort [63].

The cooling demand in commercial buildings is increasing due to higher levels of building insulation (in many cities) and the trend for modern office buildings to have lower thermal mass and larger glazed areas than traditional buildings [66]. In addition, there is also the need to remove the internally generated heat due to the rapid growth in IT and other electronic systems in offices [142].

The Residential Air Conditioning (RAC) sector consumes about 17 per cent of the overall electricity used worldwide, which is expected to grow further [56]. This fact highlights the importance of the RACHP sector energy consumption. Additionally, global warming , from climate change will increase the demand for cooling in buildings, particularly in major cities, where temperatures are expected to grow much more than the global average due to the urban heat island effect [141]. In the countries where energy demands continue to increase fastest, power generation demand is primarily met by burning fossil fuels, which will negatively impact the environment and contribute to climate change [21]. In addition, most of the current systems to provide cooling requirements for buildings consume approximately 40 per cent of the total electricity consumed by the building [143].

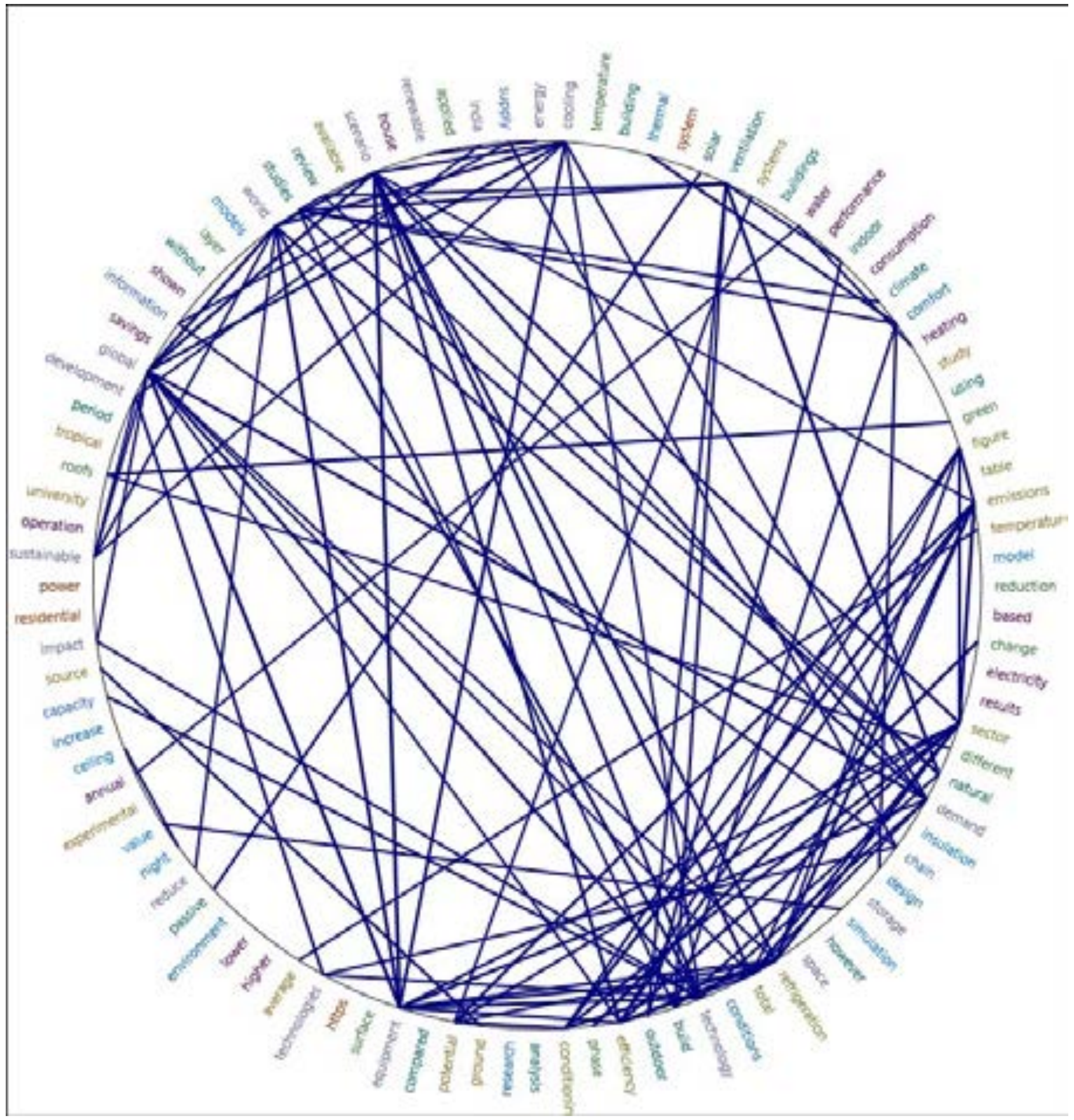


Figure 28: Most frequent words used in reviewed documents for space cooling

This research has identified the problems associated with cooling requirements for the building sector encompassing residential and commercial infrastructure. About 79 per cent (151 of 189 papers) mention either issues or solutions and best practices regarding cooling. Figure 28 shows the most frequent words used in the selected documents, including their connectivity with other words.

3.7.1. Issues Identified for Space Cooling

The barriers identified within the reviewed literature regarding issues associated with cooling in the building sector are [22, 144, 145]

- Amount of energy consumed for cooling due to inefficient building envelope
- Population growth

- Lack of sustainable building design practices
- High cooling loads due to urban heat island effect
- Lack of thermal comfort
- High GWP refrigerant use
- Emissions of HFCs
- Increased frequency of heatwaves.

The amount of energy consumed for cooling purposes is the most significant issue identified within this research, being mentioned in more than 50 per cent of all sources (94 out of 189). A summary of the documents reviewed concludes that space air conditioning is responsible for approximately 40 per cent of the total energy consumption in residential and commercial buildings globally. Furthermore, energy demand for cooling buildings is projected to increase by about 80 per cent by 2050 from a 2010 baseline [4, 18, 146, 147]. The energy consumption from heating, ventilation, and air conditioning systems also contributes enormously to peak electricity demand, which significantly stresses electricity networks [148-151].

The amount of energy to satisfy cooling needs becomes an issue because energy generation is still highly carbon-intensive and, cooling becomes an indirect carbon emitter [9, 143]. Moreover, during the last decades, energy systems worldwide are abundantly dependent upon non-sustainable energy sources (i.e., petroleum, natural gas, and coal) [91, 113, 152]. For example, anthropogenic climate changeincreased GHG emissions as an indirect outcome of occupation in the building sector to provide thermal comfort (space cooling) and stationary cooling (refrigerators) [153]. Thus, climate change becomes an issue because of higher temperatures, higher cooling needs, and without sustainable means for cooling, higher emissions from the cooling sector [4].

An increase in the frequency of heat waves becomes a problem since it means more energy demand for cooling [28]. For example, electricity consumption for space cooling doubled globally between 2000 and 2018, over fivefold in India and eightfold in China due to growth in urbanization, population and GDP [154]. The increase of this trend between 2017 and 2018 alone is particularly notable. It can be attributed to air conditioning system sales, which can be explained by record-breaking and prolonged heat waves that hit Europe, Korea, Japan, and China in 2017 and 2018 [74].

Another driver of building energy consumption to satisfy cooling needs mentioned during this review includes urban growth. The rapid development, urbanization process, and growth of the construction industry in tropical developing countries such as Malaysia have led to the construction of new high-rise, highly glazed, and thermally lightweight buildings that are unsuitable for the local hot and humid climate [155, 156]. That kind of development puts more pressure on the energy consumption link since cooling requirements are higher when those practices occur [18, 157]. With an expected 20 per cent increase of the urban population by 2050, the world will undergo the fastest rate of urbanization in history which will increase cooling demand [158].

In addition to climate change, outdoor air temperatures in urban areas have increased significantly due to rapid development for urban growth and the contribution from anthropogenic heat, such as heat release from automobiles, air conditioning, and industrial facilities [159]. These factors have resulted in urban areas having higher temperatures than their rural counterparts, known as the urban heat island (UHI) phenomenon [160].

The rapid increase in air conditioning systems as the only means of cooling, unsustainable building design that requires more cooling, increase in the frequency of heatwaves, and climate change are drivers for refrigerants used in technologies to provide cooling [16]. Refrigeration is associated with hydrochlorofluorocarbons (HCFCs) emissions [161]. Due to the Kigali amendment on substances that destroyed the ozone layer to phase down HCFC [10], according to [162], Hydrofluorocarbons (HFC) emissions, if not constrained, could potentially contribute to almost 20 per cent to total global warming by 2050Markets worldwide are transitioning away from the ozone-depleting hydrochlorofluorocarbons (HCFCs) under the arrangements of the Montreal Protocol. However, HCFCs are being replaced by HFCs, mainly R-410A in the case of room air-conditioners, which have global warming potential (GWP) magnitudes higher than that of CO2 [162].

With a warming planet, cooling becomes an urgent need [91], and guaranteeing thermal comfort to avoid a range of health problems is crucial, especially for a tropical climatic context [163]. Therefore, thermal comfort is one of the main requirements in building design. A thermally comfortable room will affect the health and productivity of residents and workers. Therefore, buildings are usually equipped with an active air conditioning system to ensure thermal comfort, especially in tropical regions. However, the use of air conditioners to increase thermal comfort has several disadvantages [164];

- High electrical energy consumption,
- Air pollution,
- High costs of investment and maintenance, and
- Additional space for the installation of equipment.

Furthermore, it seems clear that the hybridization of building materials from more sustainable to modern materials and design lead the way to increase indoor temperatures and, therefore, more Energy Consumption to alleviate those issues [18, 28, 165].

A summary of the issues identified is presented below. Energy consumption in the building sector to provide cooling is the most significant issue that authors relate to when developing strategies to reduce cooling impact. Most of the problems identified by this research are directly or indirectly linked to energy consumption, as listed below and illustrated in Figure 29.

- The amount of energy necessary to power cooling equipment
- Climate change as an indirect result of energy consumption in cooling and as a problem for future cooling demand
- Increase in heat waves frequency can lead to an increase in demand for cooling systems for space cooling in buildings
- Population and urban growth put more pressure on the energy supply and increases energy consumption.
- Unsustainable building design contributes to this issue as cooling requirements for new development are not contemplated when designing and building.
- Urban heat island effect as an outcome of the heat produced for cooling purposes.
- Contribution of refrigerant use and HFC emissions to climate change.
- Providing thermal comfort without sustainable design

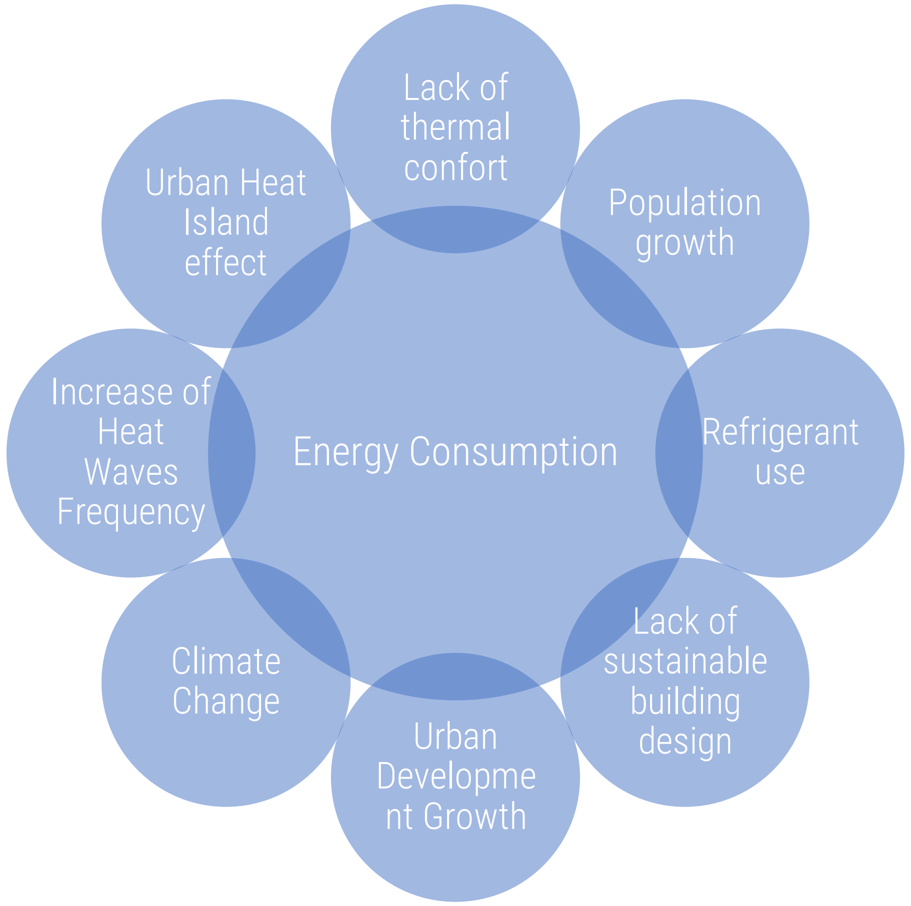


Figure 29:Issues attributed to energy consumption to satisfy cooling needs

3.7.2. Solutions Identified for space cooling

'Cooling for All' may result in different solutions and appliance preferences being expressed by diverse populations, leading to quite different equipment mixes (active cooling), building design (passive cooling), and regulations and standard (policy). One of the proven measures to increase cooling energy efficiency, specifically in the commercial and household sectors, is to introduce Minimum Energy Performance Standards (MEPs) and labelling [5, 64, 116]. MEPs helps to push energy inefficient cooling appliances out of the market, and labelling can use as a tool to increase awareness among the end-users on different energy efficiency classes.

Therefore, in the first instance, replicating North American and European norms and appliance choices effectively in those contexts should guide policymakers to understand alternatives but not always transferrable to developing country contexts [9]. Several options are summarised below.

Passive Cooling

Passive cooling is a technique that uses ambient cooling sinks like building material, air, water, or night sky to mitigate the temperature rise in the building [166]. Thus, it can help in maintaining the required comfort conditions of the building with minimum energy consumption. One aspect of integrating passive cooling in buildings is minimizing heat gains to reduce cooling loads as a first integral measure before considering active cooling strategies [167]. In general, passive cooling should be preferred overactive cooling to save energy whenever possible [113].

Figure 30 outlines the number of particular passive cooling solution strategies mentioned by different authors within the building sector. Without considering report-type documents, for the 116 documents referenced for the building sector review, 76 journal-type papers encourage passive strategies as means of energy consumption reduction. Out of 151 authors who referred to this topic with both report-type and journal-type studies, 37 per cent agree that building envelopes strategies are the most suitable solution for this sector. Natural ventilation (5 per cent), vegetation (2 per cent), and energy management passive practices (2 per cent) are amongst the common practices highlighted by the authors of papers reviewed. It is essential to highlight that one author can mention and address different issues and solutions within the same document; hence the sum of percentages is not a hundred.

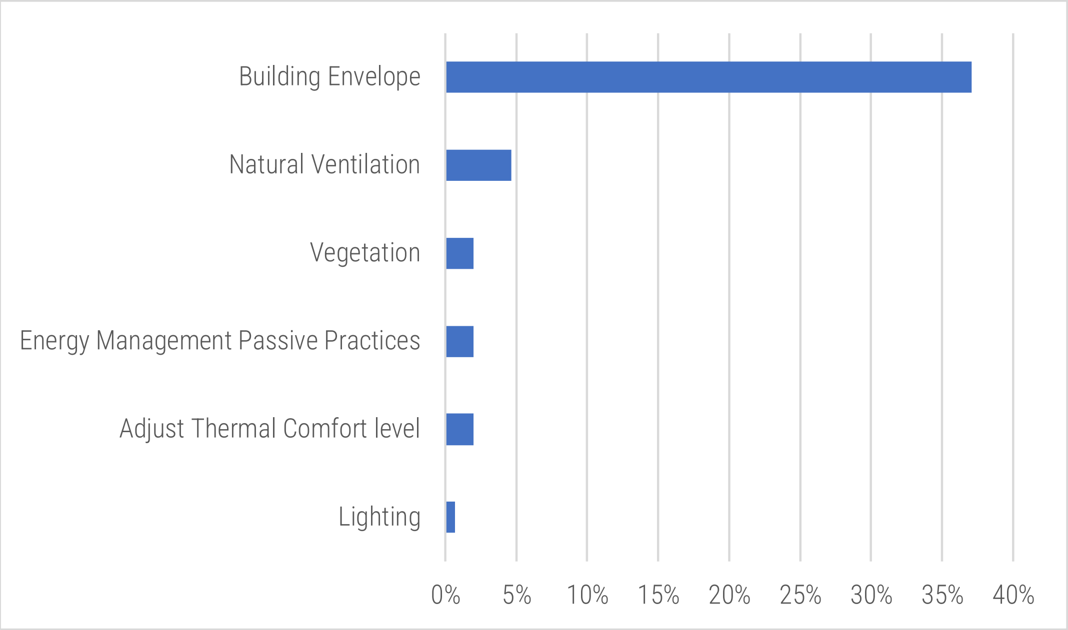


Figure 30 : Weight of Passive Cooling Strategies within the review

Building envelope

The building envelope has a considerable influence on the energy demand of HVAC systems [24] and, therefore, provides a good option for reducing the cooling load. To better understand the strategy, Figure 31 summarises different categories under building envelop in which authors mentioned passive cooling strategies as recommended solutions for cooling in the building sector.

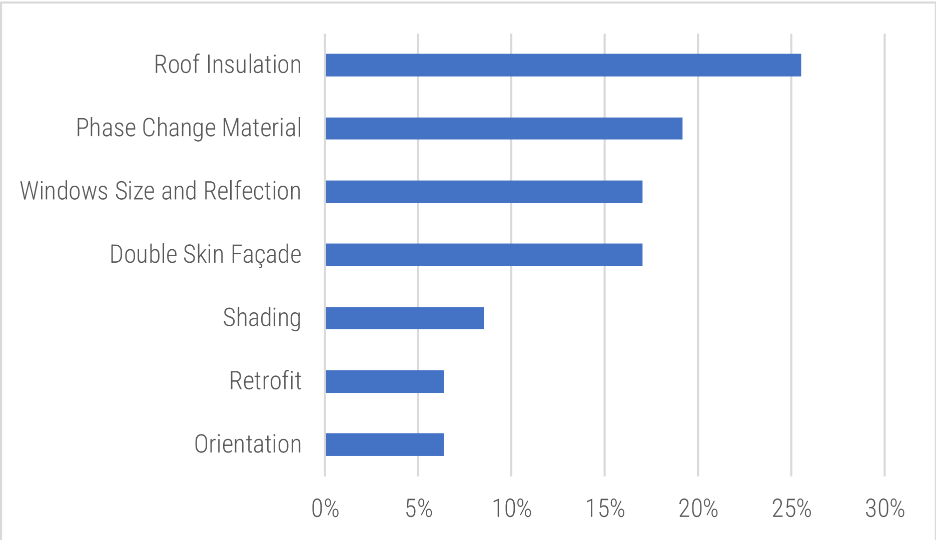


Figure 31: Passive cooling techniques on building envelop mentioned in the reviewed literature.

Significant cooling energy savings can be achieved by improving the building envelope [168], which can reduce average cooling energy demand by 10–90 per cent, compared to the typical building, with a high retrofit scenario showing the most significant effectiveness [169]. Passive strategies can be one of the best ways to mitigate the impacts of climate change in buildings located in coastal areas; they reduce energy consumption while increasing building thermal performance [66]. Globally, 1.5 billion households have access to cooling, and demand is expected to grow substantially as rising incomes and temperatures drive air conditioning ownership and, importantly, utilization. Even under the most optimistic scenarios, the ambition is to limit projected increases in electricity consumption via significant improvements in building envelopes [170].

The way buildings are designed, built, and operated can have a considerable impact on heating and cooling and the need for energy to provide those services [171]. Once a building is constructed, the amount of active cooling needed to provide a given level of thermal comfort is effectively locked in. This makes it more important that the thermal performance, including opportunities for passive cooling, is taken fully into consideration when it is being planned, designed, built, or renovated [141, 142].

Table 7 summarizes the findings of the building envelope strategy within this review. A more detailed table can be found in Annex III.

Table 7: Summary of Findings on Strategies for Building Envelope

Building Envelope Strategy	Author	Relevant Information
Orientation	(Lan et al. 2017) (Remon Lapisa 2020) (Sushil Kumar et al. 2016) (Lapisa et al. 2019)	• The orientation of building effectively makes use of the prevailing wind, and enhance the indo or airflow during inter-monsoon months. The optimal orientation for all climatic zones is the South-east. Solar radiation increased by 7.7%, when the broader side of the building faced east.
Double Skin Façade (DSF)	(Rahmani 2012) (Kameni Nematchoua, Vanona, and Orosa 2020) (Nazarian et al. 2019) (Kumar et al. 2020) (Shahin 2019) (Sushil Kumar et al. 2016)	• The risk of overheating within DSF's envelope is high in tropical climate. Therefore, accurate planning strategies must be followed in order to reduce overheating and get more benefit out of DSF layering. • An addition of 50 mm thick expanded polystyrene on the different facades of the office walls reduces the average interior temperature up to 0.6 °C and saves up to 10% of total energy consumption in the coastal tropical region. • The adaptive building facade responds intellectually and accurately to the fluctuating climatic conditions and indoor conditions requirements
Earth Sheltered Walls	(Callejas et al. 2021)	• The energy consumption and thermal analysis indicated that the use of earth-sheltered walls as a thermal mass for the bedrooms is a successful measure to improve building performance and habitability
Thermal Insulation	(Emeli Lalesca Aparecida da Guarda 2019)	• The insertion of the thermal insulation in the external walls presented lower values of consumption in the base scenario and in the future climatic projections, mainly the insulation of rockwool and glass wool.
Insulation	(Kumar et al. 2020)	• The innovation of this study lies in the comparative analysis of insulation material properties and performances, and consideration of multi-objective criteria to select optimum insulation materials in a climate zone.
Roof Insulation	(Patha 2017) (Remon Lapisa 2020) (Lapisa et al. 2019) (Pokhrel, Ramírez-Beltran, and González 2019) (Ponni 2015) (Nandapala, Chandra, and Halwatura 2020) (Dreyfus 2020) (Centre of Sustainable Cooling. 2020)	• For a climate like Bhopal, solar reflective material at roof gives enough reduction in inside temperature. If applied on walls the temperature difference increases. • Ijuk roofs are better in increasing comfort during the day and evacuating an adequate amount of heat at night. • Reflective roof coating, presents the most reasonable strategy for hot-humid tropical region, with 87.2% decrease of DH number. • During extreme heat events indicates that white roofs, reduce the cooling demand by 6.9%, • Thermal performance of roofs exercises a powerful effect on indoor ambient temperature. • Developing "stainless" light colour roof tiles will be essential to make possible a sustainable development future in country like Malaysia • White and other cool coloured roofs can stay 31°C cooler than standard grey roofs Cool roof solutions are thought to be able to reduce air-conditioning need by 35% depending on building and climate types
Green Roof	(Ebadati and Ehyaei 2018) (La Roche and Berardi 2014)	• Study results showed that by the green roofs in Tehran, Tabriz and Bandar Abbas, the basic energy consumption reduces 16.3%, 12.5% and 23%, respectively. • Green roofs with variable insulation should extend the applicability of green roofs.

Source: [7, 9, 74, 145, 158, 164, 170, 172-178]

Natural Ventilation

Six authors within the reviewed documents indicate that natural ventilation is a technique with high efficiency in providing cool indoor air through the set scenarios of ventilation depending on climate contexts [179]. A study conducted in Malaysia on effect of cooling using natural ventilation showed that, the cooling effect of night ventilation is larger than those of the other ventilation strategies during the day and night [180]. The study observed that the night ventilation technique lowered the peak indoor air temperature by 2.5 degree C and reduced nocturnal air temperature by 2.0 degree C on average, compared with daytime ventilation [180]. Also, there are some retrofit strategies used to improve natural ventilation as a passive cooling technique, as indicated by [181]. The transom window was used to enhance natural ventilation in high-rise residential buildings in tropical climates, emphasising the need to combine different passive cooling strategies to reduce cooling load before considering active cooling alternatives.

Thermal comfort and livelihood strategies are not the only drivers for household energy services in the cases studied. Social factors, such as exposure to air conditioning, human aspirations, tourism, migration, and social status, to name a few, are also important drivers for cooling services [63, 165]. Mazzone (2020) suggests that exposure to non-traditional buildings and introducing new materials in rural construction are often not suitable for the local weather [165]. Therefore, social patterns should also be evaluated before recommending natural ventilation as an appropriate strategy for passive cooling [182].

Vegetation

The outdoor thermal environment is governed by microclimate parameters, which have more diverse and complex interactions than an indoor environment. Hence, improving the outdoor thermal environment can reduce heat-related issues in urban areas, elevating pedestrians' comfort level and reducing the cooling load. Trees and urban green areas are popular solutions for mitigating the UHI effect [159]. Possible use of roadside trees in Malaysia with mitigation effects decreasing values for air temperature, globe temperature, and surface temperature on average by 4 per cent, 16 per cent, and 21 per cent, respectively, for dense roadside tree canopies. Under sparse tree canopy, the reduction of those values was slightly lower, with a reduction of 3 per cent, 14 per cent, and 18 per cent, respectively [159].

Another study also suggests using natural vegetation to mitigate problems associated with sun radiation in car parks of tropical countries in conjunction with passive solutions for the mobile cooling sector. [183].

Active cooling solutions

Active cooling solutions uses energy to cool buildings using active cooling systems such as: fans, evaporative air conditioners, and refrigerated air conditioners including 'split systems' [184]. A summary of various active cooling solution identified by different authors within the building sector is presented in Figure 32. Out of 151 authors who referred to this topic, 12 per cent agree that solar cooling is the most suitable solution for this sector. District cooling (9per cent) ground source heat pump (7 per cent), artificial intelligence for energy management (5 per cent) cooling, heating and power (CHP) (4 per cent) and evaporative cooling (2 per cent) are amongst the common practices highlighted by the authors in the papers reviewed. It is important to highlight that one author can mention and address different issues and solutions within the same document hence the sum of percentages is not a 100 per cent.

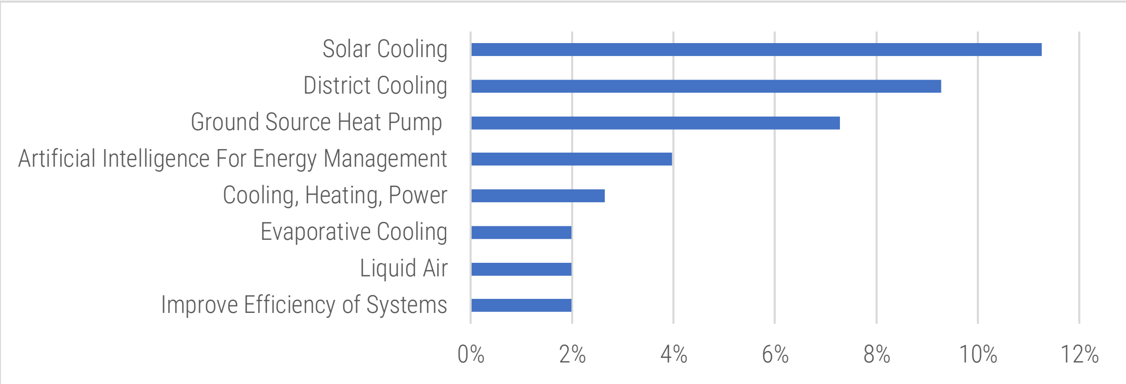


Figure 32 : Percentage of certain active cooling solutions mentioned in the reviewed documents for Cooling in Building Sector as a percentage of total reviewed literature

Solar cooling technologies is a solution for the amount of energy consumed for cooling is broadly referenced in the research literature. Implementing solar-assisted technologies for cooling may provide a short-term reduction in energy consumption, which could develop significant economic and environmental savings without compromising comfort [143, 147, 185]. Based on a study, solar technology outputs for cooling provided suitable system control and operation in response to the year-round changing climatic and loading conditions for buildings in tropical areas in Hong Kong [186]. The same study suggests that based on the best year-round total of primary energy consumption, the five types of solar cooling systems is in terms of most to less efficient are:

- Solar electric compression refrigeration
- Solar absorption refrigeration
- Solar adsorption refrigeration
- Solar solid desiccant cooling; and
- Solar mechanical compression refrigeration

As evidenced in the previous sections, solar technologies are also frequently mentioned within this review for the cold chain sector.

The number of publications found within the study for solar cooling depends largely on methodologies employed for search strategies. A detailed summary of all strategies and technologies mentioned in the reviewed documents is shown in Annex IV.

Table 8 presents some relevant publications that are referred to as solutions for the building sector.

Table 8: Summary of findings associated with solar cooling as a solution

Technology	Reference	Relevant Information
Solar Absorption	(Ali 2013)	The small-scale cooling capacity can reach up to 30kW. Major problems facing solar sorption cooling systems are higher initial capital cost (2008)
Solar Absorption + GSHP	Fong and Lee 2014)	The HRCS was found to have a remarkable energy performance with PCB in radiant cooling, its year-round primary energy consumption could be 43.8%, 53.3%, and 68.0% lower than that of the sole ground-based GHPS
Solar Desiccant Cooling	(Guo, Bilbao et al. 2020) (Mohmed F. Heider 2020) (Dezfouli 2017) (Keleher and Narayanan 2019)	With appropriate operation and sizing, the use of PV/T collectors can provide both thermal and electrical energy for the operation of the desiccant air dehumidification and cooling system
		The simulation result demonstrates that among the five proposed models, the greatest energy saving of 30 kWh per day is obtained by one of the model
		The combination of all of these criteria provides the empirical evidence and justification that the solar assisted desiccant cooling HVAC is the most sustainable HVAC system to be implementing for future use from the three systems that have been simulated using TRNSY17.
Solar Compression	(Fong, Chow et al. 2010) (Agyenim and Boero 2020) (Byrne, Putra et al. 2019)	This research shows that from their system, the year-round energy savings would be from 15.6% to 48.3% compared to the conventional electric-driven air-cooled refrigeration, while 8.0% to 43.7% to the water-cooled refrigeration
		The proposed system is capable to provide 100% of the required energy (i.e. no backup system was considered) to air-condition to a 450 m3 one-story building with low internal loads and modelled according to construction standards of the coastal zone of Ecuador.
		Solar assisted air conditioning will contribute significantly to reducing greenhouse gas emissions, fuel savings and will improve indoor air quality
		Calculations for a prototype of 25 m2 apartment showed that with a chiller of 8000 W (corresponding to a running time of 80%) and a surface of 14 m2 of photovoltaic panels, it is possible to cool a hotel bedroom with solar energy
Solar Absorption	(Baniyounes, Ghadi et al. 2013, Belizário and Simões-Moreira 2020) (Chidambaram, Ramana et al. 2011, Chua, Chou et al. 2013, Institute 2015)	The analysed system may represent a final energy bill reduction as much as 17%, mainly if the absorption system operates at peak hours (the most expensive rate) for 2 kW/ m2 power density, as analysed.
		At lower power densities, it is possible to reach up to 50% in energy savings.
		There are many pilot and demonstration experiences in solar cooling systems. However, the next few years will be the most decisive for solar cooling.
		When cooling load is high and when there is limited available installation area, solar-powered double-effect absorption cooling is appropriate on condition that the direct irradiation is high enough
		One major advantage of such systems is that the need for air conditioning and the sunshine to power it usually coincide. Solar cooling also produces minimal carbon emissions – those produced by the pumping and control systems – and can be built entirely off-grid, which is important for cold pack houses or cold storage in remote rural locations.
Solar Desiccant Cooling	(Hughes, Chaudhry et al. 2011)	The study confirmed that the overall efficiency of the system is 55% while the coefficient of performance (COP) is found to be 0.45.

Source:[23, 25, 84, 143, 147, 185-191]

District Cooling

District cooling (DC) is an environmentally friendly solution that can rely on local, natural energy sources such as seawater, surplus heat from power and/or industrial production, or renewable energy sources [192]. It saves high-quality energy, notably electricity, for other applications and reduces pressure on strained urban power grids [72]. Furthermore, adopting a district cooling system by connecting multiple buildings could safely manage alternative refrigerants. It targets much higher primary energy efficiencies through improved operation and using local renewable energy sources, free cooling (from natural cooling sources such as rivers, lakes, or seawater), and waste heat [18, 193]. For instance, in Florida, the peak electricity demand was around 50,000 MW in 2007. A 5 per cent peak demand reduction by adopting the district cooling systems utilizing sea water was achieved [194].

In areas of high urban density, district cooling systems may provide a more efficient method for delivering cooling services, centralizing plants, and sharing services leading to greater system efficiencies [195]. District cooling systems have been demonstrated to be more efficient than conventional stand-alone air conditioning unit-based cooling systems [192]. A perfect example is the Singapore DC system which supplies chilled water from a central production facility to customers via a 5-kilometer underground pipe network. It produces 600 tons of chilled water per hour to provide customers with air conditioning [14]. Moreover, rather than each building having its own chiller, buildings by sharing chillers capacity, which are operated and maintained by a technical staff team, can also benefit from cheaper costs of maintenance and operation [88, 196].

DC system can be integrated with many sustainable energy technologies such as [192, 195, 197]:

- Energy from the surface water;
- Geothermal energy (aquifer);
- Solar energy;
- Biomass;
- Waste cold energy; and
- Thermal storage system.

Table 9 summarises studies mentioned technologies mentioned in studies relevant to this topic.

Table 9: List of technologies for cooling in building sector

Technology	Reference	Relevant Information
Sea Water Air Conditioning	Arias-Gavirria (2019)	The chilled water is used to feed the AC systems in the buildings and, after cooling the building, it is returned to the cooling station as a warm water stream. Finally, the oceanwater is returned to the ocean, or it can be used for other applications. One of the main advantages of SWAC compared to traditional AC is that it can reduce the electricity consumption up to 90%
Water-Cooled Air Conditioning	Chan (2011)	Property maintenance companies, developers and consultants had the highest return rate of questionnaires and think that conversion from an ACAS to a WCAS would generate more benefits. All the respondents agreed that fresh water cooling is more energy saving (bearing in mind the constraints) yet had diverse views on the degree of energy saving (ranging from 6 to 20%). In respect of operation and maintenance, more than 60% of the respondents agreed that a fresh water-cooling tower is better than an air-cooled cooling tower.
Water-Cooled Air Conditioning	Huges et.a. (2011)`	Water-cooled air conditioning systems have a greater efficiency and the implementation of district cooling systems would generate better feasibility but would require a substantial investment on capital and resources.
District cooling using biomass	Gang et.al(2016)	DC system running on biomass, the absorber chiller generates the air cooling effect from the heat generated by utilization the biomass. The cooled air then circulates into different parts of the facility through insulated pipelines and it is maintained at a consistent temperature throughout the premises.
District cooling using solar thermal	Pintadli et.a. (2015)	The heat from solar thermal energy is used to generate the required cooling by using it in thermally driven absorption chiller machines. Due to this ease and scope of cooling by solar thermal technology, there has been an increasing number of installations worldwide.
District cooling using geothermal	Yilmaz C. (2017)	Geothermal energy is a form of energy which is obtainable as thermal heat. The waste heat resource from the geothermal power plants can also be utilized to run the absorption chiller machines in DC system.
District cooling using Solar PV	Clara Good et al. 2015	Solar PV systems can support to decrease the cooling energy requirements of buildings, to decrease the energy consumption of the artificial lighting system, to deliver visual comfort, to guarantee healthy natural lightening, and to produce solar electricity and solar heat at the same time

Source: [9, 146, 191, 192, 195, 197-200]

Cooling as a Service (CaaS)

Cooling as a service is a new innovative concept involves end-users paying for the cooling they receive, rather than the physical product or infrastructure that delivers it [31]. This concept is used in the agricultural and food sector. The idea of CaaS is to provide cooling service through periodic payments made by the customers and the technology provider installs and maintains the cooling equipment [28, 31]. As users of cooling equipment typically do not have the expertise, awareness or resources to ensure their equipment is running as efficiently as possible, by moving this responsibility to a highly focused service provider, the system could be run more efficiently [127]. There is a need for more in-depth case study research before applying this to other sectors. Out of 192 publications, only five mentioned CaaS which shows a more in-depth study need to carry out to understand the strength and weakness of this model [201].

Ground source heat pump (GSHP)

GSHP are more resilient to changing outside air temperatures since soils maintain a constant temperature profile throughout the year [202]. However, GSHP require significant space outdoors as pipes need to be buried underground leading to higher capital costs, while an air source heat pump is a more compact system, which can be accommodated in a 2 m2 surface area (however less efficient) [203]. Where feasible, geothermal heat pumps can provide a cheaper alternative to air source heat pumps, due to significantly lower operating costs [154].

As heat pumps play a more important role in delivering thermal comfort, the ground becomes a useful source of cooling and a sink for heat [9]. Parts of Europe are exploring how efficient heat pumps (providing both heating and cooling) can be paired with renewable electricity [196]. The emergence of energy service companies for cooling as a service [31] or similar business models creates opportunities for the provision of comprehensive energy packages, such as smart controls combined with heat pump technologies and appropriate building renovation measures, aimed at delivering thermal comfort and saving energy [63]. The technology also has a significant advantage of providing cooling to consumers throughout the summer [202].

A summary of documents reviewed emphasising this technology for the building sector is presented below in Table 10.

Table 10: Ground Source Heat Pump solutions for building cooling

Technology	Source	Relevant Information
GSHP	(Ghafoor 2020)	The underground temperature is relatively constant and about 23˚C for summer and 20˚C for winter. - The COP of ETHE is about 1.5 in summer and 3.25 in winter. The ETHE with 31m length buried at 3m depth covers a percentage of the total cooling and heating load of a controlled zone (class) with 20m2 surface area. An acceptable diameter of 101.4 mm can be used since bigger pipe diameter does not have an effect on temperature decrease by about 0.5˚C.
	(Hassan Mahach)	More the airflow rate is increased more the burying depth should be increased to the get the same cooling efficiency. However, beyond an air velocity of around 4 m. s-1, this efficiency tends to be constant and burying the pipe at higher depths doest EAHX is expected to supply temperature of around 26°C, which corresponds to an efficiency of 80%.
	(Liu, Qin et al. 2013)	Compared to the cooling tower system, the percentage saving of electricity consumption is about 25%. It is relatively low due to the high groundwater temperature in Singapore.
	(Shimada, Uchida et al. 2020)	Considering the high temperature during the daytime in Bangkok, the obtained result clarifies the high potential of the GSHP to reduce the energy consumption of a building over the long term (Approximately 40%).
	(Widiatmojo, Chokchai et al. 2019)	Annual power consumption reduction of up to 40% when compared with air source heat pump. It also presents an economic evaluation
	(Chokchai, Chotpantarat et al. 2018)	The highest reduction in electricity consumption using GHP was about 67.03%, which was recorded in October 2015 while the lowest reduction in electricity consumption was 7.81%, recorded in June 2016. The result indicates that the GHP and normal air conditioners consumed an average electricity of about 0.35 and 0.52 kWh, respectively. Therefore, on average, the GHP could allow about a 30%reduction of electricity consumption.

Source: [157, 203-207]

Artificial intelligence for energy management

The use of intelligent sensors with HVAC systems can reduce loadings on the system and provide lower overall energy consumption, resulting in significant cost savings [190]. Furthermore, using an integrated intelligent sensing and control system with the augmented information on temperature, occupancy, power consumption, and pollutant concentration levels via surrogate will enable the reduction of ventilation rate.

A considerable amount of lighting and HVAC system's cooling energy can be saved with a reduction of up to 45 per cent of fan electricity and 36.57 per cent of room cooling energy can be achieved by following the requirements of the relevant standards ASHRAE 62.1 2016 [68]. Energy use simulation and modelling can be used to improve energy management for cooling system [141, 142, 171].

According to experimental simulations conducted on commercial buildings, favourable results can be seen by applying intelligent sensors for energy management on ventilation systems saving 34 per cent of energy for air-conditioning compared to the standard practices for setting room temperatures [68]. When the strategy was extended to other buildings in the experiment, saving of approximately 26 per cent of energy consumption could be seen [23]. According to

Peter T. (2018), the role of Artificial Intelligence (AI) and data to manage cooling systems more efficiently and reduce maintenance to deliver performance is a necessity [14].

Advances in digital technologies result in improvements in the quality of cooling services and opportunities for conserving energy and using energy more efficiently [63]. For instance, the roll-out of smart thermostats can reduce energy consumption by automatically adjusting temperature settings according to the precise needs of occupants and in response to real-time price signals [91].

Policy solutions for Space cooling [16, 17, 27, 63, 166]:

A supportive policy and regulatory environment, including government leadership by example, is a critical enabler of the right ecosystem to scale up access to sustainable space cooling practices. Active government intervention to enable markets to operate logically toward the lowest life cycle and system cost solutions will send the necessary signals to industry, driving and accelerating the adoption of best practices and innovation in sustainable space cooling. Some regulatory examples are:

Enforce labelling: an effective, low-cost way to orient consumers toward sustainable purchasing decisions

Energy labelling of cooling products and technologies: this enables consumers to compare the efficiency of different products and consider it in their buying decisions. Effective labelling programs help increasing awareness about and drive demand for sustainable space cooling.

Establish minimum energy performance standards of cooling equipment: Establishing MEPS is a crucial foundational policy intervention.

Develop a nationwide cooling action plan or road map with meaningful targets and expected impacts: these initiatives can define a comprehensive strategic vision for the country, create alignment between the necessary solution linkages across all barrier categories, harmonize efforts to use an integrative approach to address the cross-cutting nature of cooling, and generate alignment among public and private entities to prioritize action toward sustainable space cooling.

Initiate building energy performance: It helps the market place a value on energy-efficient buildings with lower operating costs and can be achieved through building energy performance rating systems and building energy disclosure requirements.

Accelerate passive cooling strategies through national building energy codes: Building energy codes are regulations that aim to reduce building energy use. They typically apply to the building envelope and incorporate codes and standards applicable to heating, ventilation, air-conditioning (HVAC) systems, lighting, and water heating systems.

3.8. Process Cooling

Industrial process cooling means any cooling solution deployed in making a product through physical, chemical, biological processes or a combination of these processes. Process cooling systems, sometimes referred to as industrial cooling, are used in various industries, including data centers, petrochemical, pharmaceutical, food and beverage, plastics, and healthcare. The industries use at least one of the following cooling processes for manufacturing the product(s):

- Chilling
- Freezing (Low and ultra-low temperature freezing)
- Drying (Vacuum Freeze drying or Lyophilization)
- Air-conditioning
- Humidification/ Dehumidification

Apart from these processes, industries use a lot of cold warehouses for processing, raw material storage, and refrigerated chambers for thermally volatile products manufactured in the premises before shipping them out.

The cooling requirement in industries are purely defined based on the temperatures to be maintained during the manufacturing process either individually or for a combination of the raw materials, process medium, environment, additives, etc. Typically cooling requirements for individual processes in manufacturing of a product or a set of products are grouped together, leading to a large-sized cooling systems (equipment sizes of more than 1000 Ton of Refrigeration (TR) are more common in industrial cooling) with high efficiency through application of renewable energy, e.g. waste heat.

The cooling demands in the industrial processes are met with the following common types of the refrigeration equipment:

- Vapor compression Cooling
- Evaporative Cooling
- Vapor Absorption Cooling
- Adsorption Cooling

Investment in efficiency (e.g. bigger heat exchangers; better controls) makes much more sense for industrial chillers and this is reflected in the typical prices being up to 50% or more higher than an equivalent air-conditioning chiller. Medium chillers (200kW range) tend to use HFCs in 80% of cases with the rest using ammonia; larger chillers at 1 MW range tend to use ammonia in around 40% of cases. Whilst industrial chillers are usually based on a set of standard packaged products, many chillers have variants or are customized, especially for large installations. (Source: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU Strategy for Heating and Cooling)

As the industrial cooling systems differ rapidly in the type of cooling used, cooling capacity requirement, and availability of waste heat energy at the site, there is a limited number of policies around the world which, govern the efficiency of these cooling systems. Also, only five among 192 reviewed articles mentioned

Table 11. Process cooling applications

System	Capacities	Application	Refrigerants in use
Direct Expansion Systems	Small Direct Expansion (DX) (Up to 20 kW), Medium DX (Up to 80 kW), and Large DX (Up to 300 kW)	Low Temperature (between -15°C and 0°C) and Medium Temperature (between -15°C and -35°C)	R-22, R-404, R-134A
Industrial Process Chillers	Above 300 kW	For both Low and Medium Temperature applications	R-134A, R-717
Flooded systems	Above 1 MW	For both Low and Medium Temperature applications	Mostly R-717, Around 5% HFCs

'process cooling'. Even these documents have highlighted only refrigeration (for storing food and medicine) and air-conditioning (for space cooling). Due to this constrain, only limitedanalysis for the process cooling sector was possible for this report.

Issues identified for Process Cooling:

- Centralized chillers in many plants use ammonia as a refrigerant. Ammonia is poisonous in high concentrations and requires implementation of safety protocols for refrigerant management and handling.
- Most plants use open cooling towers to provide process-cooling water to the central chiller. Cooling towers use an evaporative process to cool water, making them notorious water wasters. They also result in wastewater because towers are open to the external environment. The systems also suffer from solid deposits, gases, algae, bacteria/Legionella, microbiological growth, scale accumulation on heat exchangers, and oxidation. All of these issues must be fixed with intensive maintenance and chemical treatment. (Source: https://coolingbestpractices.com/industries/plastics-and-rubber/understanding-intelligent-process-cooling)
- High upfront costs for the transition to hydrocarbon and HFO refrigerants

Some specific issues mentioned in the reviewed literature [64, 102, 103, 136, 208]:

- Limited or absence of supportive regulatory framework specifically for process cooling
- Lack of clear national requirements for adequate safety standards for the safe handling of low-GWP/ flammable refrigerants
- Lack of qualification and certification programmes
- Lack of adequate Minimum Energy Performance Standards (MEPs) and labels
- High upfront and transaction costs of cooling equipment
- Lack of capacity regarding installation, operation and maintenance of non-in-kind cooling technologies
- Lack of suitable IT systems and management software needed for operating and controlling alternative RAC technologies
- Lack of leakage controls
- Limited availability of alternative, energy-efficient technology/ low GWP refrigerants
- Lack of knowledge on environmental and/ or economic benefits of alternative RAC technologies

Solutions for Process Cooling

- Adoption of technologies like Thermal Energy Storage systems, Solar thermal-collector based Vapor Absorption Machine (VAM) Cooling, LNG-Regasification-based cooling and other cooling recovery processes, etc.
- Adoption of high energy efficiency requirements in cooling equipment components like compressors, pumps, cooling towers, etc.
- Monitoring and automation of cooling systems
- Adoption of passive cooling measures, where possible
- Whilst minimum product efficiency standards are important, they cannot properly address system design and maintenance related issues, therefore the capacity building and training for technicians are essential enabler for energy efficient cooling. A better training on safe and effective utilisation of climate friendly refrigerants is required under the Kigali Amendment to Montreal protocol.

Introducing adequate finance instruments such as subsidised loans, dedicated credit lines, guarantees, risk-sharing facilities and grant schemes, are some of the solutions mentioned to overcome the identified financial barriers. Creating information materials for distribution among end-users, awareness campaigns, integrating new requirements into existing certifications and qualification programs, are mentioned in the literature to increase awareness of more sustainable cooling options.

Common to all cooling sectors regulatory measures include tax breaks, temporary subsidies to support the uptake of alternative refrigerants and energy-efficient technology, increasing electricity prices and decreasing or removing fossil fuel subsidies are some examples mentioned in the reviewed documents.

Figure 33 : Policy options summarised by Authors

3.9. Policies and strategies as a solution to achieve sustainable cooling

Well-defined policy options can help in achieving the sustainable cooling paths needed by all governments at the national, regional, and local levels. Governments should also enable and encourage investments and mandate improvements in the energy performance of buildings and cooling equipment. This section summarises the policies discussed in the reviewed articles for all cooling sectors. The policies, which can be categorized as Regulatory, Financial and Education and Market based represent short to medium term solutions to the problems identified earlier in each cooling sector (Figure 33).

3.9.1. A holistic approach to cooling policy

Understanding the problem must be considered as the first step in finding a solution. Hence, to tackle the future cooling challenges as well as the adverse effects of climate change, National Cooling Action Plans (NCAP) are needed. In addition, for developing countries, improving access to cooling and addressing related SDGs policy will be a crucial step [16, 28]. NCAP enable policymakers to send signals to the market and create favourable conditions for a streamlined transformation that provides investment security to producers and end-users while maximizing preparation for anticipated future requirements [18]. According to K-CEP, a cooling policy strategy needs to account for national circumstances, and which includes [209]:

- The current state of the market.
- The outlook for cooling demand and energy use.
- Economic drivers, social and cultural considerations; and
- Develop and enhance regulatory measures for boosting the energy efficiency of cooling equipment.

According to [18] the world can avoid the equivalent of up to 210–460 billion tons of CO2e (GtCO2e) over three decades through efficiency improvements in cooling equipment [18]. If it is possible to replace all stationary air conditioning and refrigeration equipment starting in 2030, with the highest-efficiency and climate-friendly refrigerant technologies available [61, 64, 101] then this reduction would be achieved. This strategy is often related to the policies mentioned regarding Replacement of Refrigerant for environmentally friendly refrigerants where alternatives, including propane (R-290), HFC-32 (R-32), and CO2 and HFC/hydrofluoroolefins[1] (HFO) blends; pose a lower climate burden [10, 12, 61, 162, 210].

Develop National Cooling Action Plans

National Cooling Action Plans (NCAPs) are strategies or roadmaps that promote sustainable and smart cooling practices across a country [211]. This plan is a tool to assist countries in understanding and defining their cooling priorities. This action plan includes measures to support countries to achieve major international treaties such as the Kigali Amendment to the Montreal Protocol and the Paris Agreement [16].

3.9.2. Introduce or strengthen labelling, codes and standards

Mandatory performance requirements for air conditioning products, strategies for replacement of refrigerants and building energy efficiency code are proven tools to introduce efficient equipment needed in the building sector. According to IEA (2018), a key passive cooling approach driven by building codes have the potential to achieve a 15 per cent reduction in space cooling demand in 2050 in developing countries [63]. A good example of regulations enforcing standards of best practices in cooling is described in [12]. Retailers in France signed a code of conduct regulation with the French Ministry of Ecology, Sustainable Development, Transport, and Housing and the French Retailers Association to install doors on refrigerators in all new or refurbished stores. Codes and standards for existing buildings, including requirements

1 Hydrofluoroolefins (HFOs) are unsaturated organic compounds comprising of hydrogen, fluorine and carbon. Unlike traditional hydrofluorocarbons (HFCs) and chlorofluorocarbons (CFCs), which are saturated, HFOs are olefins, otherwise known as alkene [210] X. Wu, C. Dang, S. Xu, and E. Hihara, "State of the art on the flammability of hydrofluoroolefin (HFO) refrigerants," International Journal of Refrigeration, vol. 108, pp. 209-223, 2019/12/01/ 2019, doi: https://doi.org/10.1016/j.ijrefrig.2019.08.025.

for maintenance and operation that improve demand-side management, is another example applied in Australia [171].

According to Hill (2018) tighter regulation of Minimum Energy Performance (MEPS) and labelling reduce the electricity consumption and carbon emissions of household appliances sold in tropical regions. MEPS usually contain performance requirements for an energy-using device, limiting the maximum amount of energy that a product may consume in performing a specified task [212]. Policy makers need to consider the actual energy efficiency of air conditioners, fridges, fans, refrigerators and other cooling devices on the market and use accurate energy performance measurement standards, protocols, and testing procedures to make the MEPS efficient.

Gradually increasing MEPS requirements and regulations for refrigeration equipment manufacturers is the best approach. The steeper the regulatory requirements increase, the better the outcome. Financial penalties and bans should be implemented if targets are not reached [113]. Consumers can make informed decisions based on various indicators such as the amount of cooling the unit can produce, required energy, and details of the compressor. With developments in the performance of the equipment, labelling programmes are best designed such that they account for future improvements and provide for regular upgrades of the product testing and labelling [16, 18, 59, 63, 213].

3.9.3. Adopt Financial Policy

The policy response should also give attention to financing, which is a crucial element in the consumer decision-making process regarding purchases of new cooling equipment or renovating a building, especially if more efficient equipment or building materials are more expensive. Some examples of financial tools identified in the review are shown in Table 11 below. The types are categorized as Funding, Incentives, Investments, Subsidies or Taxes.

Table 12: Financial strategies mentioned in the reviewed documents.

Financial Tool	Author	Relevant Information
Funding	(Dreyfus, 2020) (SE for ALL, 2020a) (UN, 2015) (BEI, 2015) (UN, 2017)	Access to funding can speed the transition to low-GWP refrigerants and energy-efficient equipment in line with Kigali objectives and help capture the nearly $3 trillion in energy savings from investment and operating costs identified by the IEA. Finance solutions are intended to enable a temporary use of funds to purchase technologies or services. It is the temporary use of funds that can enable a more sustainable long-term funding approach to achieve both a lower monthly cost of solutions and the repayment of borrowed funds that can be used again for other projects. With limited funds available in many countries, finance measures can be key to creating an enabling environment for private investment in more sustainable solutions.
Incentives	(UN, 2015) (Hill, 2018)	Tax incentives can help accelerate market adoption of energy-efficient refrigerators. These incentives can offer an attractive deal for consumers and can be very cost-efficient from a public finance point of view if constructed appropriately. To help with the high cost of replacing or installing more efficient cooling units or alternatives, industry experts suggest that governments consider implementing policies that provide incentives to businesses or households. These could consist of consumer rebates, tax credits, accelerated depreciation or loan financing.
Investments	(Reiner, 2018) (Dreyfus, 2020)	At the global level, investments are needed to support innovation required to deliver on this rapid transition to a low carbon heating system and policies will be needed to support such investments. In the IEA projection which is consistent with a 2°C target (and which still does not assume full decarbonisation of the heat sector), energy investments in buildings increase from US $4.9 trillion in 2017 to US $5.4 trillion by 2050 and are mainly directed to improving building envelopes. The early timing of these investments is particularly important, to avoid 1) lock-in effects, for example, the possibility of having new inefficient buildings with lifetimes as long as 50 years, and 2) increased renovation and energy costs from delaying improvements, for example, a ten-year delay could incur $2.5 trillion in extra spending
Subsidies	(Dreyfus, 2020) (SE for ALL, 2020a) (UN, 2017) (SE for All, 2020b) (SSEF, 2019)	Subsidised "new for old" or "take-back" schemes are often used to ensure the safe and permanent removal of old appliances from the market. Such schemes must address the challenge of safe management of the waste stream, which will continue for decades to come. This type of programme is eligible under the Montreal Protocol as it is an efficient way to ensure that appliances containing ozone depleting substances are properly decommissioned and recycled. These programmes are most effective if targeted to address both energy efficiency and refrigerants. Bulk Procurement of more efficient cooling equipment should be encouraged and rewarded
Tax for Cooling	(Luerssen et al., 2020)	Space cooling could be taxed to slow down the purchase of air conditioners. It may be easier to implement high tax on the equipment than taxing the usage. The money collected from taxes and fines from mostly developed countries and urban areas could be allocated to support sustainable cooling in the food supply chain in remote and poor regions in the developing world.

Source: [16, 18, 59, 61, 65, 101, 113, 127, 214, 215]

3.9.4. Improving cooling technology through research and development

Public research related to cooling needs to aim at developing higher-performance technology solutions for meeting space-cooling needs, such as higher performance of heat pumps and air-conditioning systems; lower costs for high-performance building envelope components; reduced costs of solar thermal cooling technology; and boosted the development of solar PV coupled to ACs [63, 130].

3.9.5. Awareness development on sustainable cooling

Governments have a significant role to play in raising awareness of the environmental and economic importance of cooling. A snowball effect of the labelling strategies is seen as a way to raise of awareness of consumers. Local and national governments also have an essential role in educating the public on affordable and sustainable cooling solutions [59]. Awareness-raising campaigns support the promotion of and transition to more energy-efficient cooling technologies through good governmental policies and programmes [61]. In addition to these, behavioural change from an end-user perspective can also contribute to energy savings by making consumers more energy-aware through communication and education programmes [101]. To deliver effective policies involving stakeholders through public consultations is essential [10].

3.9.6. Knowledge and Skills Development

Knowledge is required to improved installation and servicing practices to reduce the refrigerant charge and leakage. Improved practices will also maintain the energy performance of equipment and lower the cost of ownership through reducing the frequency of servicing [18, 61, 64]. For instance, cooling-as-a-service or district cooling methodologies can increase the likelihood that cooling equipment is effectively serviced and maintained and upgraded, lowering the risk of unplanned breakdowns and creeping inefficiency. In addition, proper maintenance can deliver electricity savings up to 20 per cent [14, 31]. Table 12 below summarises the strategies and the actions from literature reviewed.

3.10. Best Practices for Cooling Thematic Areas

The analysis described here aims to summarize best practices found within the revised documents in terms of working sustainable cooling strategies within the literature. Based on the review results, decisions on the application of strategies are effective in the short term. The best practices mentioned in this section should be interpreted as strategies with positive outcomes that when applied considering the different national, regional or community context could represent feasible strategies to counteract some of the cooling issues identified previously.

The solutions identified and recommended for all sectors have common ground of generating a positive change in reducing energy consumption, reduction of emission of greenhouse gases, or improved thermal comfort after implementation. Annex V summarises the 42 best practices found within the review. In this review, best practices are understood as policy strategies or technologies that, through experience and research, have been shown to lead to reliable sustainable cooling. Based on the PICO's framework, the result criteria to identify best practices rely on proven strategies with proven results for energy reduction, emission reduction, or improved thermal comfort standards or enhance access to cooling.

Table 13 shows the possibility of using a best practice to mitigate problems for different sectors.

Table 13: Summaries of strategies and action

Strategies	Action
Develop National Cooling Action Plans	Implement national policy on cooling technologies improvements
	Implement and introduce national policies of low emission cooling technologies
	Rebates and incentives to promote cooling efficiency in the built environment
	Implement policy on accelerating the transition to low-GWP and high-efficiency cooling
	Introduce national policies on HFC phase down energy efficiency improvement
Implement MEPs and labelling	Develop/enhance/introduce or strengthen MEPs for cooling equipment
	Develop/enhance/introduce or strengthen label strategies for cooling equipment
	Develop/enhance/introduce or strengthen label strategies for cooling equipment
Introduce or strengthen codes and standards	Introduce or strengthen building energy codes for new building construction
	Introduce or strengthen standards for existing buildings and cooling equipment
	Establish mandatory requirements for building energy efficiency for all building sectors
	Modify existing regulatory, fiscal or local planning policies that inhibit the uptake of energy-efficient and renewable energy solutions for buildings
	Ensure regulations are enforceable and enforcement mechanisms are properly funded.
Adopt financial policy	Introduce financial incentives for energy efficiency, low emission cooling including financial backing for banks.
	Introduce ESCOs and PPP mechanisms that supply or finance the purchase of efficient materials, cooling technologies in efficient buildings, transport, refrigeration and district cooling systems
	Introduce non-financial incentives for energy efficiency, including the use of innovative mechanisms for bulk purchase to increase market availability of efficient best available technology in the market
	Step up funding for cooling research, focusing on emerging technologies that have the potential to lower drastically emissions from cooling in the long term
Awareness development on sustainable cooling	Develop/enhance/introduce or strengthen label strategies for cooling equipment and make them mandatory
	Support information and capacity-building efforts that encourage consumers to opt for energy-efficient products and services
	Harmonise international test procedures, labelling and reporting requirement to make transparent comparisons between cooling technologies when possible
	Improve data collection and statistics on energy efficiency indicators
Knowledge and skills development / Improve cooling technology through research	Support information and capacity-building efforts in educating architects, engineers and cooling-system installers.
	Collaboration between utilities, industry, government and university researchers on cooling research to help to use scarce financial resources effectively and accelerate learning through shared experiences while avoiding the need to "reinvent the wheel"

Table 14: Best practice technologies and policies and its applicability to different sector

Solution	Thematic Area				
	Access to Cooling	Buildings	Mobile Cooling	RAC	Cold Chain
Cooling as a Service	√	√	√		
Solar Cooling	√				√
Drones as transport for vaccines	√				√
Refrigerant Replacement		√	√		√
Funding	√	√	√		
Incentives	√	√	√	√	√
MEPs		√	√	√	
Regulations	√	√	√	√	√
Developing Skills	√	√	√	√	√

Based on the review Figure 34 highlights the distribution of best practices and density of occurrence around the world. Although there is no distinctive pattern within the graph, the conclusions of the review of best practices are [12, 14, 28, 59, 65, 72, 80, 88, 115, 116, 118, 127, 145, 157, 158, 175, 212, 216]:

- Application of solar cooling-based technologies are good examples which prove that access to cooling can be guaranteed in countries where rural electrification is an issue. For instance, solar cooling in rural areas in African countries such as Ghana, Ethiopia, Senegal, among others, are mentioned 18 out of 42 times within the different best practices identified. Ghana is mentioned 5 times with different application of technologies to alleviate issues regarding lack of access to cooling in the cold chain sector, including food and healthcare [86].
- China and Mexico are identified as leader countries that have implemented working policy strategies such as policy regulations MEPS or economic incentives to promote the improvement in the efficiency of end-user cooling equipment with proven results on reducing energy consumption from cooling equipment and hence GHG emissions [10, 72].
- The most common practices mentioned in European countries are related to strategies and policies encouraging the replacement of refrigerants within the supermarket industry with positive outcomes reducing energy consumption from cooling equipment (especially fridges).
- Current Australian building code had the most stringent efficiency requirements for exterior walls and chiller COP performance, compared to the USA standard ASHRAE 90.1-2016 .

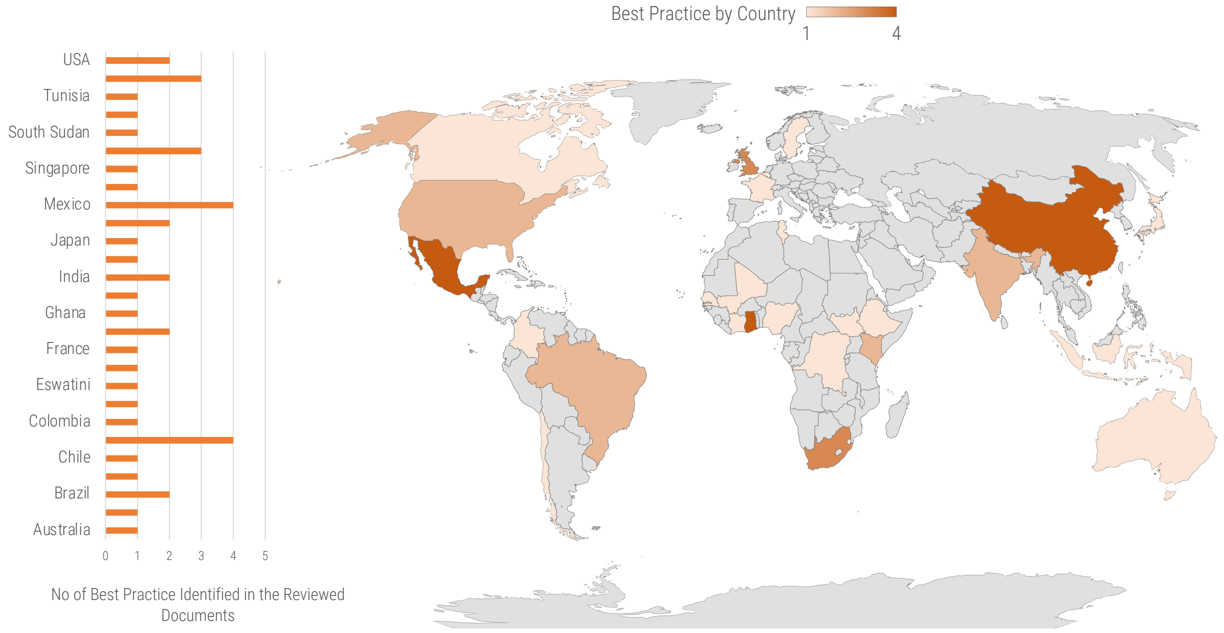


Figure 34 : Distribution of best practices mentioned in the reviewed literature by country

The best examples to solve both access to cooling and difficulties in supporting cold chains are generally seen through the implementation of solar cooling systems, which have been proven in a number of African countries. The sector with the lowest occurrence of mentions for best practices is mobile cooling. Most of the best practices mentioned for this sector have to do with the use of policies and regulations to replace refrigerants. No best practices were identified to serve as an example to improve efficiency or replace air conditioning systems in vehicles. Figure 35 shows the best practice studies by strategies. It represents data values of different strategies mentioned in the reviewed documents as the area of rectangles.

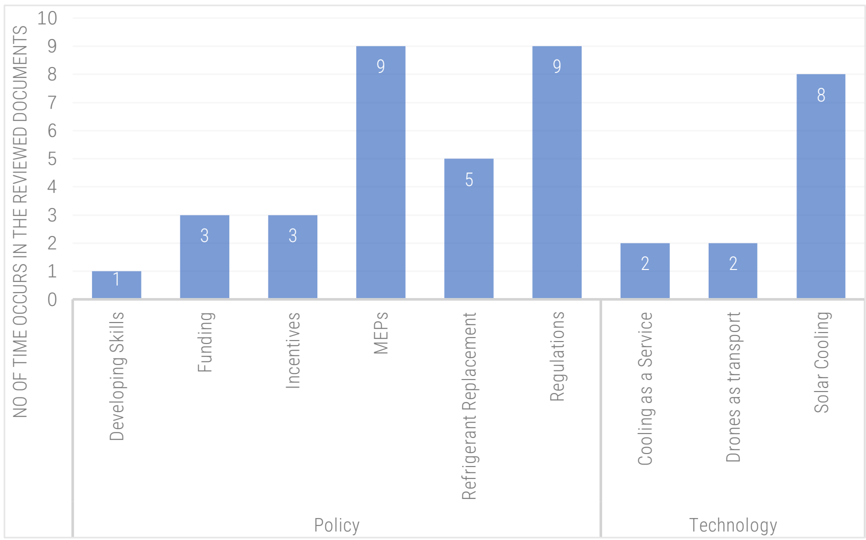


Figure 35: Best practice strategies mentioned in the reviewed literature

For policy solutions, best practices for Refrigerant Replacement and Regulations are the most common. For instance, the Kellogg Company as a part of their commitment to the Consumer Goods Forum's second resolution on refrigeration in 2016 (USA) is aiming to replace its HFC refrigerants with ultra-low GWP alternatives. In line with its pledge, the Kellogg Company installed the first R-514A ultra-low GWP chiller in its Cincinnati (Ohio) plant in April 2017, replacing a R123a refrigerant chiller [128]. The introduction of the chiller was driven by the phase-down timing for HFC refrigerants, along with an expectation of increased efficiency.

While this strategy is categorised within this summary as a policy methodology to replace hazardous refrigerants, the application of the solution also relies on the improvement of efficiency of chillers. This supports the statement that the application of one solution can impact or be related to multiple different solutions.

Policy strategies regarding Minimum Energy Performance are also associated with the policy strategies applied through legislation or regulations. For instance, MEPs for Mexican residential refrigerators are currently specified by NOM-015-ENER-2002 which was first published on January 15, 2003 [217] These standards were substituted for the previous standards which were enacted in 1997 due to the positive outcomes of the application of best practices. Such an approach encourages the tightening of applied policies to keep either reducing energy consumption or continuing to improve energy efficiency of equipment and systems. The current standards are very similar to USDOE 2001 MEPs for residential refrigerator/freezers.

China adopted efficiency standards for refrigerators and freezers in 1989 using the same approach as the U.S., Canada, and Mexico [72]. Namely, the maximum electricity use of a given type or model is a function of the adjusted volume plus a constant. New standards went into effect in 2000 and covered nine different product categories (five types of refrigerators and four types of freezers). The standards were revised again with the more stringent standards taking effect in two phases, the first tier in 2003 and then a second tier taking effect in 2007. The 2003 standards resulted in approximately a 10 per cent reduction in maximum electricity consumption relative to the 2000 standards, and the 2007 revision will result in a further approximate 10 per cent reduction [12].

Best practices are often accompanied by policy regulations to guarantee not only the application of the strategy but its effectiveness and duration after been applied. For instance, the Brazilian Government introduce appropriate technical standards and regulations after implementing a policy aiming to provide incentives to replace and recycle refrigerants. These regulations aim to guarantee that the pilot plants and other plants that commence operations recycling refrigerants could maintain high quality practices and comply with environmental standards [165].

Application of policies through investments are also seen as best practices when correctly applied. In Mexico, low-income households were incentivised to purchase efficient equipment, including energy-efficient air conditioners, through the Program INFONAVIT Green Mortgage [31, 217]. The programme offered an additional loan to mortgage loans specifically for the acquisition of energy-efficient equipment. The equipment had to be more efficient than the minimum standards specified in the energy efficiency regulations to become eligible. The amount of the loan was dependent on the monthly income of the recipient, who then paid back the loan along with the repayment of the mortgage loan. The programme was successful and is therefore considered a best practice for this research. In August 2016, the Mexican Government announced plans to expand it under the Programme for Sustainable Integral Improvement in Existing Housing, run by the government.

Solar Cooling is the most common strategy for the technology applications. Solar cooling as mentioned before is a proven technology not only to provide access to cooling but to guarantee successful cold supply programmes in off-grid rural areas. For example, solar freeze programmes are proven strategies to reduce food loss and waste in the fresh produce agricultural sector in Kenya by 90 percent [80]. Increased incomes for rural smallholder women and youth farmers by 70 percent linking both, application of sustainable cooling practices and closing gaps for Sustainable Development Goals.

Cooling as a service has a significant potential although not mentioned many times within the best practices so further research is recommended. Likewise, the Zipline program in Rwanda to counteract problems of last mile when it comes to delivering cooling in vaccine cold chain is underestimated and requires further research also [4].

Chapter 04

Discussion and Conclusion

Of the all documents reviewed in the sustainable cooling set, most articles were being published recently, i.e., since 2017. International goals and agreements have been found to have an immense impact in accelerating the research in sustainable cooling. The volume of publications focusing on sustainable cooling has increased substantially following the ratification of the Kigali Amendment of the Montreal Protocol in 2019, with about 38 per cent of all articles in just two years compared to 62 per cent during 2007-2018. The cluster analysis of keywords, titles, and abstracts in the sustainable cooling articles studies was found to have highlighted the following key terms: building thermal comfort and air conditioning, cooling systems efficiency and performance, and energy use simulation and modelling. These terms have been used in sector analyses to identify technological best practices and enabling policy measures in each sector, which are discussed below.

4.1. Main results by cooling sectors

This section summarises the findings from the review broken down by thematic area.

Access to cooling

Access to cooling is a critical element in achieving most SDGs, however, if not managed sustainably, an increase in cooling load will create a feedback loop by increasing demand for electricity and associated emissions, leading to increased global warming. The high-level of HFC (a potent greenhouse gas) consumption in air conditioning shows the importance of addressing room air conditioners. The solutions of highly efficient and low GWP technologies already exist, but they require urgent policy actions to enable uptake by consumers. In addition, there is a need for research to make these technologies available and affordable to low-income countries. Lower GWP refrigerants to replace HCFCs and high-GWP HFCs are used in most energy efficient air conditioners and refrigeration which are widely available in the current market. Policy measures and government incentives can help accelerate this transition. Demand side management and design initiatives should be implemented to reduce the cooling demand of the potential cooling users. Lack of awareness and knowledge of the cooling sector as well as the benefits of cooling access among manufacturers, governments, users and investors are mentioned across all publications. The right policy and financing environments are essential for the growth of access to cooling.

Cold Chain - Healthcare and Food

Despite political, financial, and human implications of vaccine and food cold chain issues, thus far the overall decision-making challenges in technology-supported cold chain management have received little attention in research. Maintaining the cold chain is important to ensure that effective and potent vaccines are administered to patients. Vaccines exposed to temperatures that are too high or too low can lose their effectiveness and even be deadly to the vulnerable populations they are intended to protect. Most recently, cold chains are playing an important role in the delivery of COVID-19 vaccines to enable populations to reach herd immunity. Failure of cooling equipment (15.25 per cent), lack of training (10.17 per cent), human errors (6.78 per cent) and lack of standards for cooling equipment (5.08 per cent) are amongst the most common barriers that faced in low income countries. Some solutions identified in the literature include solar cooling, phase change materials, drones as a transport option, equipment reliability, reliable monitoring and maintenance programs, access to finance and research and development of new cooling technologies. Equipment failure, lack of spare parts or maintenance are also considered to be critical risks for the use of vaccine cold storage in remote locations.

The role of the cold chain in the supply of food is expanding and can reduce waste in the supply chain. While efficient equipment is important for cold chain management, other aspects such as availability of trained personnel, as well as effective and efficient management practices also play a crucial role in efficient management of the healthcare and food cold chains. Storage design considerations such as the ratio of surface area compared to storage volume, surface albedo, exposure of storage to sun and wind, on-site climatic conditions like temperatures, incident solar radiation, wind speeds and humidity are found to be the most critical factors influencing energy demand in cold chain applications. Lack of access to electricity for cooling and operating appropriate equipment to cover for cold chain issues (including transportation) is a major challenge to widening the supply chain for food and healthcare.

The role of the cold chain in the supply of food is expanding and can reduce waste in the supply chain. While efficient equipment is important for cold chain management, other aspects such as trained personnel, effective and efficient management practices also play a crucial role in efficient management of the healthcare and food cold chains.

The most critical factors impacting food cold chain issues are:

- Lack of awareness of the needs of the cold chain and the knowledge of benefits of providing efficient means of supply chain for food among manufacturers, government, users, and investors.
- Lack of understanding of the energy demand for the cold chain and cooling needs to provide effective solutions.
- Lack of monitoring of practices within the cold chain. and
- Lack of standards to regulate and verify the efficiency of the cold chain.

Some solutions for food cold chain found in the documents reviewed are solar cooling, community cooling hub, insulated refrigeration system, enforcing standard in cold chain management, and access to finance for research and development.

Space Cooling (Residential and Commercial Buildings)

The building sector is responsible for consumption of around one-third of the total primary energy supply and releasing 30 per cent of global CO2 emissions. A summary of the reviewed documents in this area concludes that space air conditioning is responsible for approximately 40 per cent of the total energy consumption in residential and commercial buildings globally. Space cooling, typically using an electric-powered fan or air-conditioning and refrigeration system, contributes increasingly to global energy demand. Furthermore, energy demand for cooling buildings is projected to increase by about 80 per cent by 2050 compared to 2010 baseline.

Energy consumption in the building sector to provide cooling is the most significant issue that authors relate to when developing strategies to reduce cooling impact. The amount of energy to satisfy cooling needs becomes an issue because energy generation is still highly carbon-intensive and, cooling becomes an indirect carbon emitter. The rapid increase in air conditioning systems as the first choice means of cooling, unsustainable building design that requires more cooling, increased frequency of heatwaves as a result of climate change are drivers for increased energy consumption. Improving building energy performance can substantially reduce the building cooling load. The amount of active cooling needed can be reduced by introducing a passive design and therefore, it is important to consider the thermal performance of the building, including opportunities for passive cooling. This also equally applies when buildings are newly built or renovated. To reduce building energy consumption, building code have proven to be playing a major role in showcasing better practices in the use of building materials for heating, cooling, ventilation, and lighting. Cooling as a Service and district cooling are examples of other ways of providing an efficient cooling service.

Mobile Cooling

Mobile cooling is energy intensive and represents as much as 20 per cent of vehicle energy consumption. Mobile cooling devices for passenger and goods transport currently consumes about 1,040 TWh of energy per year for refrigeration and air conditioning applications [127]. Consumption of fossil fuels in refrigerated vehicles and direct emissions via leakage of refrigerant are also significant problems identified in the literature. Impact of emissions from bus Mobile Air condition (MAC) is disproportionately large compared to the number of vehicles. Measures such as changing the refrigerant and improving mechanical parts of the MAC in transport vehicles can improve energy efficiency by 50 per cent which shows a significant need for research in this area. Several technologies such as seat ventilation, cabin ventilation, solar glazing of windows and windscreens, or climate control seating were discussed as potential solutions in the reviewed documents. Other technological solutions include vapour compression cycle, thermal storage, vacuum cooling, and absorption chilling. Renewable energy (RE) was suggested as a cleaner and more efficient mode of supplying cooling energy in this sector. Despite the share of RE in transport being low, it has recently attracted policy makers' attention in many countries. Decarbonizing transport, fuel tax, standards (such as fuel and emission standards), regulations (such as F-gases, phase down of HFCs), research and development and shifting to low GWP refrigerant, were also mentioned as solutions.

4.2. Multi-sectoral policy and regulation in Sustainable Cooling

High Efficiency and Low GWP Cooling Equipment

Increasing energy efficiency and lowering GWP of refrigerants are essential to reduce emissions from the cooling sector. In some countries, MEPs are introduced without considering the transition to lower GWP refrigerants, leading to continued use of high GWP refrigerants. Many developing countries without MEPs, especially those without manufacturing capacity, only have access to low EE/high GWP imported RAC equipment - this increases energy consumption and emissions. Access to high-efficiency products with lower-GWP refrigerants depends on the local supply chain. Access is higher in countries with local manufacturing and lower in import dependence countries. Therefore, appropriate financing aimed at enhancing local manufacturing could drive best practices in delivering EE gains during HFC phasedown.

MEPS and labelling development and enforcement

MEPs have been proven to be the single most effective policy measure for boosting the efficiency of appliances and equipment, including ACs. There is a need for testing labs to enforce MEPS. MEPS require a minimum performance requirement for energy-consuming devices, limiting the maximum amount of energy that a product may consume in performing a specified task. In setting and applying MEPS, policymakers need to consider the actual energy efficiency of cooling appliances available in the market and use accurate energy performance measurement standards, protocols, and testing procedures. Building codes have been proven to play a major role in driving better practices in the use of materials for building envelope, heating, cooling, ventilation, and lighting to reduce cooling energy consumption.

Limitation of technology transfer and economies of scale

As technology is evolving continuously ongoing technological updates are essential, otherwise, the one-time transfer will result in obsolescence. Furthermore, there is a relationship between the volume of manufacturing and the possibility of technology adoption. Therefore, it is evident that the larger the volume, the better for a manufacturer to absorb the additional cost of new technology and develop the products.

Capacity building and skill development

Skills and training are required across all cooling sectors. Identifying the skills gap for each country and customizing training to fulfill that gap in delivering a cooling solution is essential. Knowledge is required to improve installation and servicing practices to reduce refrigerant charge and leakage and maintain the energy performance of equipment and lower the cost of ownership through less frequent service. The key focus areas that need skill developments are:

- Capacity building on designing and implementing passive cooling measures in building and infrastructure planning and design for investors, regulators and policymakers.
- Appropriate sizing and maintenance of super-efficient equipment and appliances for effective operation; and
- Increasing skills around health and safety for safe handling of ultra-low GWP refrigerants.

Improving cooling technology through research and development

Strong public support such as R&D funding and creating a regulatory environment for cooling-related research will be needed to ensure the rapid development and deployment of highly energy-efficient AC equipment, as well as efficient building solutions. Unfortunately, most equipment and building material manufacturers have a lower research-to-investment ratio than other sectors of the economy. This is mainly due to the commodity-based nature of building materials and products, the time it takes to change to new technology, and relatively low-profit margins. The review identified the following recommendations regarding research to enhance a low carbon cooling environment:

- Develop sectoral roadmap to identify research priorities.
- Design, testing and trailing novel and innovative cooling products (such as new energy efficient cooling technologies, Internet of Things (IoT) based energy management).
- Development and implementation of innovative business models for finance and product deployment.
- Development and implementation of sustainable disposal methods for cooling technologies.
- Investigate ways to reduce heat gains in buildings (e.g. passive solar design, sustainable building materials). and
- Targeted research at individual country level about access and current practices including policies and technologies and what strategies and solutions are needed.

Supply chain economies of scale: imports versus local manufacture

Developing local manufacturing industries will benefit from economies of scale, which will not only reduce the cost but also make spare parts more easily accessible. This will eventually accelerate the uptake of EE equipment. For example, in Thailand and Vietnam, multinational companies and local joint ventures are manufacturing air conditioners, which increases the uptake of EE equipment faster than other countries in the region.

Tax Incentives and subsidies

Tax incentives can help accelerate market adoption of EE refrigerators and cooling equipment. If constructed appropriately these incentives can offer an attractive deal for consumers and can be very cost-efficient from a public finance perspective. To help with the high cost of replacing or installing more efficient cooling units or alternatives, industry experts suggest that governments should consider implementing policies that provide incentives to businesses and households. These could consist of consumer rebates, tax credits, accelerated depreciation or loan financing. Introducing "new for old" or "take-back" schemes are often used to ensure the safe and permanent removal of old appliances from the market. Such schemes must address the challenge of secured management of the waste stream, which will continue for decades to come. Bulk procurement of more efficient cooling equipment should be encouraged and rewarded. Space cooling could be taxed to slow down the purchase of inefficient air conditioners and encourage EE equipment. It may be easier to implement higher taxes on equipment than taxing the usage. The collected tax can be used to support sustainable cooling.

Role of Government

A snowballing effect produced by labelling strategies is seen as a raising of awareness strategy for consumers. Local and national governments also play an essential role in educating the public on affordable and sustainable cooling solutions. Governments have an important role to play in raising the awareness of the environmental and economic importance of cooling. Should the governments around the world recognize the strategic importance of cold energy resilience and develop long-term commitment to the adoption of clean cold technologies it will increase the confidence of investors in manufacturing efficient and sustainable cooling technologies.

In summary, is evident across the research articles reviewed, that there is a lack of ongoing monitoring, evaluation, reporting and reflection on the impact of changes in access to cooling. Changes to strategies and policy implemented across the sustainable cooling spectrum required continuous monitoring, evaluation and reporting so as to provide feedback as to the success or failure, and to highlight factors for the success or failure of the changes.

4.3. Strengths, weaknesses, contributions, and gaps of included studies

This scoping review shows that despite the growing body of literature in the cooling sectors, there appear to be gaps in the literature. For example, studies have not considered the issues of cooling load increase while providing access to cooling to all. Few studies have examined the changes in efficiency improvement and market saturation of other heating and cooling technologies into the future.

Many studies demonstrate simulated results with cooling technologies and their management but have failed to provide action-based research results. These findings clearly show the need for research to develop cooling system designs and technologies based on a complete inventory of local input factors, including social and micro-climate issues, culture, technical capacity, affordability, and resource availability.

Therefore, future studies need to identify the sectoral demand due to an increase in cooling load. A few studies considered energy-efficient equipment and strategies used for cooling, but the authors of this report found no study examining the actual impact of increasing cooling load and its implication on global warming. Many studies analysed the opportunities of new adaptative building design strategies utilising natural energy flows in air materials, however, fewer studies examined mobile and cold chain improvement. The authors found limited studies exploring the following topics:

- The impact of the HFC phase-down on climate mitigation.
- The substitutes of HFCs use in refrigerators and other cooling technologies.
- Current status of cooling energy efficiency and its potential for improvement.
- The technologies and policies that are needed ready to transition to energy-efficient cooling by 2030.
- Policies and measures that demonstrate the multiple benefits of energy-efficient cooling. and
- Deep dives into the country- and city-level data needed to understand current cooling access issues and evidence-based outcomes for sustainable cooling solutions.

4.3.1. Strengths and limitations of the scoping review

This scoping review applied a rigorous and transparent approach. It follows protocols reviewed by the research team with expertise in literature synthesis and scoping review. First, a broad search of the literature was conducted using three electronic research citation databases, an internet search engine, and the snowball technique. Then, the reviewers reviewed the articles independently and regularly met to resolve conflicts.

The review was conducted systematically, with Endnote software being used to manage and account for all citations retrieved from the various databases. An updated search was conducted in March 2021 to ensure the inclusion of recent publications. This scoping review has several limitations:

- The searches were limited to articles published in English, potentially resulting in language bias and excluding relevant studies published in other languages. This for example could rule out more localised, country specific research that has been undertaken.
- The cooling area is associated with energy consumption, cooling and refrigerants, which are used across many scientific domains.
- The citation databases used are multidisciplinary databases that broaden searches across domains. There could also be other databases that may contain additional studies relevant to this review that may not have been reached for screening.
- Scoping reviews are not meant to assess the quality of the literature evaluated.

However, the eligibility criteria utilized in this review ensured that the studies included relevant cooling sectors. Therefore, this scoping review provides a comprehensive overview of sustainable cooling, reporting individual results on each cooling sector's issues and solutions for the review. A weakness that is evident across the research articles reviewed in this study is the lack of ongoing monitoring, evaluation, reporting, and reflection on the impact of changes in sustainable cooling and not identifying detailed best practices.

4.4. Implication for policy and practice

Based on the findings of this review, the following list of implications for policy and practice have been concluded. The listed conclusions (not in priority order) summarise the lessons learned from the qualitative findings and several best practices reported in various individual studies.

- This review shows that providing cooling for all will represent a substantial challenge to energy budgets, CO2 targets, and climate goals. Therefore, to meet everyone's cooling needs for affordably, reliably, and sustainably, there is a requirement for sustainable cooling technologies.
- Because most researches undertaken theoretical study e.g. simulation, there is a need for empirical studies based on local input factors, including social and micro-climate issues, culture, technical capacity, affordability, and resource availability.
- Strategy optimisation is needed to address the cooling demand reduction and the deployment of efficient technologies are required to manage the future challenges.
- Lack of evidence-based research on the importance of awareness and knowledge of the cooling sector and benefits of cooling access among manufacturer, government, users, and investors has failed to attract private sector investment and, therefore, urgently needs the attention of policy makers.
- Fundamental research is needed on RAC technologies, minimum standards for equipment and infrastructure, transport cooling technologies, and low-cost cooling technologies for all cooling sectors. ;
- There is a lack of evidence-based research on the impact and interventions of cooling technology access which requires funding to showcase pre-commercial technologies. There is a lack of evidence from market research on the demand

for sustainable products and services to create market pull and to disseminate and encourage manufacturers to use as input for product development.

- Because few studies are devoted to mobile-cooling and cold-chain, there is a need for further research into technological improvement to reduce the emission and energy demand in the sector.
- Identify the policy interventions required to deliver the sustainable cooling strategy and enable incentives to be aligned to provide the optimum technology and operations packages.
- Skills development and education are needed to support the research to enable the deployment and maintenance of cooling technologies in developing countries.
- National cooling action plans should be linked to SDGs and NDCs.
- Evidence-based research are needed on the benefits of the use of energy-efficient cooling technologies for health and food cold chain.
- Innovation is required in the energy system, thermal energy storage, including transport, and novel business models (e.g., district cooling or cooling as a service) as the transition to renewables continues and therefore finance in research and development is advocated.
- There is a need for development and implementation of "Fit-for-market" business and financial models which are the key to successful intervention. This will enable access, affordability and return on investment, ensure effective policy interventions, and development of the skills and workforce to design, install and maintain the volume of appliances.

4.5. Subgroup analysis and investigation of heterogeneity

The review was committed to reporting findings from original studies by sectors where available. Results are reported narratively because quantitative pooling of data across studies was limited and data were not generally available at a subgroup level.

4.6. Potential biases in the review process

The rigorous search, screening, and extraction process, conducted by at least two review authors independently at all stages, allowed the authors to identify all applicable studies as defined by our inclusion criteria. An up to date search (March 2021) ensured the capture of the evidence base as it currently exists across a wide variety of academic journals and sources of grey literature.

Further, although we explored many sources of grey literature (non-peer reviewed), we did not locate any eligible studies in the grey literature, which may also indicate reporting bias.

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Chapter 05

Annexes

5.1. Annex I. PRISMA checklist

Section and Topic	Item #	Checklist item	Reported on Page
TITLE			
Title	1	Identify the report as a scoping review.	1
Executive summary			
Executive summary	2	See the PRISMA 2020 for checklist.	1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	20-22
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	22
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	27
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	25
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	24
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	26
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	28
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	Annex Vi
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	N/A
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	30
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	N/A
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	N/A
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	N/A
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	Bibliometrics analysis
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	NVivo for qualitative analysis
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	N/A
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	N/A
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	N/A
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	N/A
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	31
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	N/A
Study characteristics	17	Cite each included study and present its characteristics.	Annex Vi
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	N/A
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	Section 4.1
Reporting biases	20	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	N/A
Certainty of evidence	21	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	N/A
DISCUSSION			

Section and Topic	Item #	Checklist item	Reported on Page
Discussion	22a	Provide a general interpretation of the results in the context of other evidence.	106-112
	22b	Discuss any limitations of the evidence included in the review.	115
	22c	Discuss any limitations of the review processes used.	115
	22d	Discuss implications of the results for practice, policy, and future research.	113-114
OTHER INFORMATION			
Support	23	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	UNESCAP and Murdoch University
Competing interests	26	Declare any competing interests of review authors.	N/A

5.2. Annex II. Search query used to retrieve articles for review

Search query used to retrieve articles for the review Query	Scopus (2000-2021) TITLE-ABBS-KEY	Web of Science (2000-2021) Topic Open Access only
("cooling" AND ("Sustainab*" OR "low-energy" OR "Low Carbon" AND (healthcare cold chain" OR "Food cold chain") AND (Access* OR "renewable" OR "building" OR "facade" OR "night" OR "solar" OR "district" OR "passive" OR "active" OR adsorption" OR "absorption" OR "heat pump")))	207	1346
("cooling" AND ("Sustainab*" OR "low-energy" OR "Low Carbon" AND ("healthcare cold chain" OR "Food cold chain" OR "Access*" OR "renewable" OR "building envelope" OR "active facade" OR "night purging" OR "solar cooling" OR "district cooling" OR "passive cooling" OR "active cooling" OR "adsorption cooling" OR "absorption cooling" OR "heat pump")))	58	1359
("Cooling" AND ("Sustainab*" OR "low-energy" OR "energy-efficient" OR "Green" OR "Carbon Zero" OR "carbon neutral" AND ("Refrigera*" OR "Space Cooling" OR "Cold chain" OR "Renewable" OR "Evaporative cooling" OR "Desiccant Cooling" OR "Free Cooling" OR "building envelope" OR "active facade" OR "night cooling" OR "Solar Cooling" OR "passive cooling" OR "active cooling" OR "HVAC" OR "absorption cooling" OR "adsorption cooling" OR "emission*" OR "night ventilation")))	1345	1776
("Cooling" AND ("Sustainab*" OR "low-energy" OR "energy-efficient" AND ("Refrigera*" OR "Space" OR "Cold chain" OR "Renewable" OR "Evaporative" OR "Desiccant" OR "Free" OR "building envelope" OR "active facade" OR "night" OR "Solar" OR "passive" OR "active" OR "HVAC" OR "absorption" OR "adsorption" OR "emission*" OR "night ventilation")))	33	207

5.3. Annex III. Strategies for building envelop Strategies for building envelop

Building Envelope Strategy	Author	Relevant Information
Orientation	[217]	The orientation of the CGH main building effectively makes use of the prevailing wind, but wing walls enhance this effect, particularly the indoor airflow during inter-monsoon months (April, May, October and November).
Orientation	[159]	The optimal orientation for all climatic zones is the South-east. In Marrakech the insulation reduces the consumption only in the south while in tangier the optimal orientation for the insulation is the southeast
Orientation	[6]	The solar radiation on different surfaces of a building was calculated. It was found out that a building aspect ratio close the golden rule resulted in least amount of solar radiation for a given floor area. It was also found out that the solar radiation increased by 7.7per cent, when the broader side of the building faced east.
Double Skin Façade	[173]	Previous researches have suggested that the risk of overheating within DSF's envelope is high in tropical climate. Therefore, accurate planning strategies must be followed in order to reduce overheating and get more benefit out of DSF layering.
Double Skin Façade	[167]	The energy consumption and thermal analysis indicated that the use of bermed earth-sheltered walls as a thermal mass for the bedrooms is a successful measure to improve building performance and habitability
Double Skin Façade	[168]	In this way, the results show that the effects of global warming modified the energy consumption for all studied typologies. However, the insertion of the thermal insulation in the external walls (T1 to T3), presented lower values of consumption in the base scenario and in the future climatic projections, mainly the insulation of rockwool and glass wool.
Double Skin Façade	[65]	The addition of 50 mm thick expanded polystyrene on the di erent facades of the office walls reduces the average interior temperature up to 0.6 ◦C and saves up to 10per cent of total energy consumption in the coastal tropical region.
Double Skin Façade	[169]	The innovation of this study lies in the comparative analysis of insulation material properties and performances, and consideration of multi-objective criteria to select optimum insulation materials in a climate zone.
Double Skin Façade	[153]	Although the energy saving potentials and air quality benefits of cool roofs, green roofs, and cool pavements have been rigorously evaluated for various climates, to date there has been no detailed evaluation of cool walls, particularly in tropical climates
Double Skin Façade	[218]	The adaptive building facade responds intellectually and accurately to the fluctuating climatic conditions and indoor conditions requirements
Double Skin Façade	[6]	Heat transfer in to various building materials was studied, and it was found that white coloured walls made of rammed earth resulted in least amount of energy required for cooling.
Roof Insulation	[219]	For a climate like Bhopal, solar reflective material at roof gives enough reduction in inside temperature. If applied on walls the temperature difference increases.
Roof Insulation	[159]	The results of the experiment confirm that between the two alternative materials, ijuk roofs are better in increasing comfort during the day and evacuating an adequate amount of heat at night.
Roof Insulation	[165]	The last one, reflective roof coating, presents the most reasonable strategy for hot-humid tropical region, with 87.2per cent diminution of DH number.
Roof Insulation	[170]	A 20per cent of peak cooling load reduction was observed on a typical sunny day in tropical climatic conditions.
Roof Insulation	[171]	Finally, comparison of different mitigation alternatives to reduce cooling load during extreme heat events indicates that white roofs, reduce the cooling demand by 6.9per cent,
Roof Insulation	[172]	Thermal performance of roofs exercises a powerful effect on indoor ambient temperature.
Roof Insulation	[170]	In addition, developing "stainless" light colour roof tiles will be essential to make possible a sustainable development future in Malaysia.
Roof Insulation	[17]	White and other cool coloured roofs can stay 31°C cooler than standard grey roofs
Roof Insulation	[8]	Cool roof solutions are thought to be able to reduce air-conditioning need by 35per cent depending on building and climate types.
Green Roof	[140]	Results showed that by the green roofs in Tehran, Tabriz and Bandar Abbas, the basic energy consumption reduces 16.3per cent, 12.5per cent and 23per cent, respectively.
Green Roof	[220]	The hope is that green roofs with variable insulation should extend the applicability of green roofs. The active green roof system described in this paper is being implemented in a classroom of a high school in Southern California.
PCM	[65]	The addition of 74 mm of PCM thickness on the different facades of the office walls and roof allows the average indoor air temperature to be reduced by up to 0.5 ◦C and to save up to 19per cent of total energy consumption in coastal tropical regions.
PCM	[221]	The PCM cool coloured coating registered the largest annual energy saving of 8.5per cent and a consistent monthly energy saving of 5–12per cent throughout the entire year in tropical Singapore.
PCM	[66]	Results showed that PCMs can effectively reduce heat gains through building envelopes in a range of 21–32per cent throughout the whole year, indicating the significant advantage of the use of PCMs in tropics over other regions where PCMs are only effective in certain seasons.
PCM	[215]	In this study, the additional cooling system is still required since the heat gain is massive and PCM is not able to supply latent cooling.
PCM	[222]	but the comfort rate generated by the solution with insulation and PCM is only 2per cent higher than the comfort rate produced by the solution with insulation and shading.
PCM	[223]	Therefore, the weather conditions must be considered for the application of proposed passive air conditioner, because if the outdoor temperature variations were not enough like as observed in the wet season in Bandung (warm nights), outdoor night discharging can be only choice to keep running the system. Thro
PCM	[147]	The results showed that the model with PCM could reduce the peak temperature with and without using fan by 4 °C and 1 °C respectively.
Retrofit	[224]	While energy efficiency policies for cooling equipment are essential, the best first step is to reduce the need for cooling through improved building design, construction, retrofitting, and operation
Shading	[224]	Therefore, solar shading should be used in conjunction with other strategies in order to meet thermal comfort criteria.

Windows	[139]	Hence it can be stated that cooling load of a building can be reduced by judicial selection of window glasses as Relative Heat Gain (RHG) depends upon the thermal properties of window glasses.
Windows	[225]	Smart windows have shown to be an impressive and promising way to control solar radiation transmitted through openings to the building interiors, however, the initial cost problems still prevent their widespread use in the buildings.
Windows	[144]	Smart Water-filled glass (SWFG) technology builds on the existing Water-filled glass (WFG) system and takes it further by changing the transparency of the fluid as a response to changes
Windows	[150]	An improvement of 73per cent and 7per cent in the number of hours, with less than 28.6 °C per annum, can be achieved in unventilated and ventilated rooms, respectively, by replacing the single clear glass in the base case with single reflective glass. However, a maximum improvement of 107per cent and 14per cent can be realized in unventilated and ventilated rooms, respectively, if the single clear glass is replaced with a double coated reflective glass.
Windows	[158]	Changing the existing sliding windows to pivoting windows can reduce overheating by up to 15per cent of working hours in FS, 12per cent in SS and 2per cent in CS.
Windows	[148]	Double glass has lower U value which reduces the heat gain into the building.
Windows	[217]	The louvered window alone offers a 32per cent improvement of thermal comfort. It is incorporated into all other solutions since the current awning windows have low effective ventilation area

5.4. Annex IV. Solar Cooling Technologies

Technology	Reference	Relevant Information
Solar Absorption	(Ali 2013)	The small-scale cooling capacity can reach up to 30kW. Major problems facing solar sorption cooling systems are higher initial capital cost (2008)
Solar Absorption + GSHP	(Fong and Lee 2014)	The HRCS was found to have a remarkable energy performance with PCB in radiant cooling, its year-round primary energy consumption could be 43.8per cent, 53.3per cent, and 68.0per cent lower than that of the sole ground-based GHPS
Solar Desiccant Cooling	(Guo, Bilbao et al. 2020)	With appropriate operation and sizing, the use of PV/T collectors can provide both thermal and electrical energy for the operation of the desiccant air dehumidification and cooling system
Solar Absorption	(Mohmed F. Heider 2020)	Using of 17250 sq. (185582 sq. Ft.) of solar collectors provides the energy required for 2500 TR which means that for each ton of refrigeration, it is required to have 6.9 sq. (74.2 sq. ft.) of solar collectors.
Solar Desiccant Cooling	(Dezfouli 2017)	The simulation result demonstrates that among the five proposed models, the greatest energy saving of 30 kWh per day is obtained by model A2
Solar Desiccant Cooling	(Keleher and Narayanan 2019)	The combination of all of these criteria provides the empirical evidence and justification that the solar assisted desiccant cooling HVAC is the most sustainable HVAC system to be implementing for future use from the three systems that have been simulated using TRNSY17.
Solar Compression	(Fong, Chow et al. 2010)	The year-round energy savings would be from 15.6per cent to 48.3per cent compared to the conventional electric-driven air-cooled refrigeration, while 8.0per cent to 43.7per cent to the water-cooled refrigeration.
Solar Compression	(Agyenim and Boero 2020)	The proposed system is capable to provide 100per cent of the required energy (i.e. no backup system was considered) to air-condition to a 450 m3 one-story building with low internal loads and modelled according to construction standards of the coastal zone of Ecuador.
Solar Absorption	(Baniyounes, Ghadi et al. 2013)	From the literature review using solar assisted air conditioning will contribute significantly to reducing greenhouse gas emissions, fuel savings and will improve indoor air quality.
Solar Absorption	(Belizário and Simões-Moreira 2020)	The analysed system may represent a final energy bill reduction as much as 17per cent, mainly if the absorption system operates at peak hours (the most expensive rate) for 2 kW/ m2 power density, as analysed. At lower power densities, it is possible to reach up to 50per cent in energy savings.

Solar Compression	(Byrne, Putra et al. 2019)	calculations for a prototype of 25 m2 apartment showed that with a chiller of 8000 W (corresponding to a running time of 80per cent) and a surface of 14 m2 of photovoltaic panels, it is possible to cool a hotel bedroom with solar energy
Solar Absorption	(Chidambaram, Ramana et al. 2011)	There are many pilot and demonstration experiences in solar cooling systems. However, the next few years will be the most decisive for the success of solar cooling technologies that depend on the encouragement and promotional schemes offered by the policymakers, and the efforts undertaken by the manufacturers to improve the cost efficiency as well in developing better technologies.
Solar Absorption	(Chua, Chou et al. 2013)	They highlighted that when cooling load is high and when there is limited available installation area, solar-powered double-effect absorption cooling is appropriate on condition that the direct irradiation is high enough
Solar Absorption	(Institute 2015)	One major advantage of such systems is that the need for air conditioning and the sunshine to power it usually coincide. Solar cooling also produces minimal carbon emissions – those produced by the pumping and control systems – and can be built entirely off-grid, which is important for cold pack houses or cold storage in remote rural locations.
Solar Desiccant Cooling	(Hughes, Chaudhry et al. 2011)	The study confirmed that the overall efficiency of the system is 55per cent while the coefficient of performance (COP) is found to be 0.45.

5.5. Annex V. Details of the Best Practices in Cooling Sector

Sector	Best Practice	Project Name	Reference	Relevant Information
All	Policy - Skills Development AND Maintenance	University Training	(Kigali Cooling Efficiency Program 2018)	The Superior School of Apan, part of the Autonomous University of Hidalgo State in Mexico, trains engineering students interested in cooling and refrigeration technologies about the study, evaluation, calculation, design, operation and maintenance of refrigerating and cooling systems. The courses prepare students for the real needs of the refrigeration industry. For this reason, the National Association of Manufacturers of the Refrigeration Industry is a partner to the programme. Students visit their testing facilities and participate in conferences and other events to put their research skills into practice.
All	Policy - Needs-based assessment	'Cooling for All': Needs-based assessment Country-scale Cooling Action Plan Methodology	(Bing Xu 2019)	The entire document outlines an strategy/methodology of how to We aim to enable the accelerated roll-out of fit-for-market, financeable, clean and sustainable cooling solutions that are attractive to end-users, civil society, governments, policymakers, industry and the finance community to ensure impact, lasting legacy and scalability. Policy and financing choices vary by geography, desired economic, societal and environmental outcomes and different cooling needs. Successfully meeting the cooling demand via affordable, renewable energy, efficient solutions that deliver societal and economic impact to everyone (small and marginal groups) with minimal pollution and environmental impact, will be critically dependent on an integrated 'fit for market' suite of interventions.
Buildings	Policy - Regulations	Cool Biz Campaign	(Peters 2018)	Cool Biz campaign in Japan instigated by the government from 2005 onwards has saved significant amounts of energy and CO2
Buildings	Policy - Ban AND Policy - MEPs	MEPs, Labels and Import Restrictions Secure Savings	(UN Environment Program 2015)	The government of Ghana introduced a ban on importation of used refrigerating appliances in June 2013. This was successful.
Buildings	Policy - Improve Energy Efficiency AND Policy - Financial Tools		(UN Environment Program 2015)	The government of Mexico launched a refrigerator substitution programme in 2009 offering consumers both a loan (for purchase), and a subsidy of up to $60 towards disposal of the old refrigerator. Appliances replaced must be older than 10 years, the replacement must meet the prescribed efficiency class, and financing is paid through the electricity bill.

Buildings	Policy - Labelling AND Policy - MEPs		(UN Environment Program 2015)	In Turkey, the gradual year-on-year improvement of the market under the influence of labelling, MEPs, and some other supporting policies has been documented by the Turkish Home Appliance Manufacturers' Association since the year 2000. In 2000, only 15 per cent of sales were of class A, with the balance spread across classes B, C and D. Improvements in efficiency meant that by 2010, classes C and D had disappeared from the market. In 2011 Turkey introduced the first tier of its MEPs. They are a close transposition of the earlier EU regulation. This first tier removed all C and D label appliances and the 10 per cent of sales that were rated class B. The second tier of MEPs, introduced in 2012, meant that all appliances had to be class A or better. This led to a sudden jump in sales to the A+ and A++ classes.
Buildings	Policy - Labelling AND Policy - MEPs	Mandatory Star Rating, Refrigerator: BEE	(UN Environment Program 2015)	India's energy-labelling programme offers significant benefits to consumers, enabling them to reduce their energy bills by providing critical information on energy use at the time of purchase. BEE is working to promote the efficient use of energy and its conservation across India. The number of stars on a refrigerator can vary from 1 to 5, with more stars indicating higher energy efficiency and more savings for consumers.
Buildings	Policy - Refrigerant Replacement AND Active Cooling - Solar Cooling	Converting the Production of Refrigeration Equipment to Natural Refrigerants	(UN Environment Program 2015)	The project converts the entire production of domestic and commercial refrigeration appliances of the manufacturer Palfridge in Swaziland to hydrocarbon refrigerants (domestic fridges, commercial refrigerators for supermarkets and bottle coolers, solar refrigerators including a solar powered vaccine cooler). With the successful conversion of the production line, Palfridge impressively demonstrates that the environmentally friendly technology can be handled safely in a developing environment. The project is an important demonstration showcase for the whole region

Buildings	Policy - Refrigerant Replacement AND Policy - Financial Tools	Investment Project for Phasing out CFCs at Haier S.A., Qingdao	(UN Environment Program 2015)	GIZ Proklima and the German company Liebherr assisted the Chinese refrigeration manufacturer Haier with the conversion of a production line from CFC to HC technology in 1995. For the implementation of the "Investment Project for Phasing out CFCs at Haier S.A., Qingdao," a total of $2.2 million in funds was made available through Germany's contribution to the Multilateral Fund of the Montreal Protocol and through the US Environmental Protection Agency (USEPA). Through the project, the traditional foaming agent for polyurethane insulation, CFC-11, has been replaced with cyclopentane, and the refrigerant CFC-12 has been replaced with isobutane. Both are HCs. HCs do not deplete the ozone layer and do not contribute significantly to global warming.
Buildings	Policy - Improve Energy Efficiency AND Policy - Financial Tools	Utilities' Refrigerator-Replacement Programme	(UN Environment Program 2015)	Brazil has introduced several programmes to increase the energy efficiency of appliances. Electricity distribution companies are required to invest part of their revenues in energy efficiency programmes. Since 1998 these funds were often used by the distribution companies to invest in energy efficiency programmes to support low-income households. Frequently used programmes were refrigerator-replacement programmes. Around 30 per cent of Brazilian refrigerators are more than ten years old. Most of these old refrigerators belong to low-income households.
Buildings	Active Cooling - District Cooling	Singapore District Cooling, Marina Bay	(UN Environment Program 2015)	Singapore District Cooling supplies chilled water from a central production facility to customers via a 5-kilometre underground pipe network. It produces 600 tons of chilled water per hour in order to provide customers with air conditioning
Buildings	Policy - Financial Tools AND Active Cooling - District Cooling	South African Fruit Packing Company Upgrades Ammonia System	(Kigali Cooling Efficiency Program 2018)	Upgraded ammonia plant to provide better, more reliable cost-efficient cooling. The upgrade involved the installation of a new liquid receiver (including valves and instrumentation) and new stainless-steel glycol tanks. Existing mechanical controls were replaced with a new computerised control system with remote monitoring capabilities and a full re-commissioning process commenced. This was all financed through a Cooling as a Service (CaaS) agreement, with no upfront cost to the client.
Buildings	HVAC Solution for Colombian Commercial Building	HVAC Solution for Colombian Commercial Building	(Kigali Cooling Efficiency Program 2018)	The solution: MGM Innova Group designed an HVAC solution that included a high efficiency centralised air-conditioning system complete with valves to measure the amount of cooling delivered to each user. The investment was fully carried out by MGM Innova Group and a monthly payment is billed to every office on a Cooling as a Service (CaaS) model.

Buildings	Policy - Raise Awareness	Communication Tools	(Kigali Cooling Efficiency Program 2018)	India has developed a comprehensive set of communications tools, including a product database with a linked mobile application that users can easily use to check. The Indian product database provides the gateway for manufacturers to register their products on the market and stay up to date with policies and government initiatives.
Buildings	Policy - Improve Energy Efficiency AND Policy - Financial Tools	Using Domestic Sources of Finance for Incentives	(Kigali Cooling Efficiency Program 2018)	To support the move to a higher level of efficiency, China's National Development and Reform Commission and the Ministry of Finance funded the "Promotion of Energy Efficient Products to the Benefit of the People" programme from June 2009 to June 2013. The programme had dual goals: boosting sales of home appliances to help the economy recover from the 2008 financial crisis and promoting energy-efficient products to "the benefit of the people". It encouraged consumers to buy energy-efficient products by lowering the up-front price of these products.
Buildings	Policy - Improve Energy Efficiency AND Policy - Financial Tools	Investing in energy efficiency to strengthen the cold value chain of small and medium enterprises	(Kigali Cooling Efficiency Program 2018)	Accelerating transformation of Chile's markets to more energy efficient (EE) residential refrigerators/ freezers thereby achieving reduction of GHG emissions and contributing to improved energy access and energy security.

Buildings	Policy - Improve Energy Efficiency AND Policy - Financial Tools	Leapfrogging Chilean's Markets to More Efficient Refrigerator and Freezers	(Kigali Cooling Efficiency Program 2018)	When the voluntary programme for energy-efficient air conditioners was first implemented by the Electricity Generating Authority (EGAT) of Thailand in 1996, a budget of 500 million Baht (~$12.5 million) was invested in encouraging consumers to purchase air conditioners with a level 4 or 5 energy rating. Consumers were provided with interest free loans of 5,000 Baht (~$125) and 10,000 Baht (~$250) respectively. Repayment of these loans was to be made within 20 months, through credit cards issued by banks participating in the programme. Extensive interest-free loans from 5,000 Baht to 10,000 Baht and from 10,000 Baht to 20,000 Baht were also offered to customers purchasing air conditioners of 18,000 BTU upward labelled with energy efficiency ratings of 4 and 5 respectively. Again, repayment was expected within 20 months. This extensive interest-free loan programme could only be implemented during February 1-28, 1998 due to the credit limitation policy of the Bank of Thailand to restore the economic recession of the country. The extensive interest-free loans were terminated and the initial approach was revived, but with repayments expected within a 10-month period. In addition, to stimulate the market, a promotion bonus of 500 Baht (~$12.) and 700 Baht (~$17.) was also offered to retailers selling air conditioners with less than 18,000 BTU and 18,000 BTU upward with energy efficiency level 5 respectively. This campaign was implemented from time to time during January to April 1998.
Buildings	Policy - Refrigerant Replacement AND Policy - Financial Tools	ESCO Project for Air Conditioners, Indonesia	(Kigali Cooling Efficiency Program 2018)	The Adi Husada ESCO in Indonesia undertook a project to retrofit old air conditioners by changing the refrigerants to hydrocarbons. The project managed to achieve energy savings and payback on the investment. As part of the project, an evaluation was carried out to measure the amperes of each retrofitted air conditioner before and after the change of refrigerants. Results showed a total savings of 22 per cent with a payback period of one year, with the air conditioners measuring at 451 Amps before the retrofit and 354 Amps after the retrofit.

Buildings	Policy - Improve Energy Efficiency AND Policy - Financial Tools	Green Mortgage Loans	(Kigali Cooling Efficiency Program 2018)	In Mexico, low-income households are being incentivised to purchase efficient equipment, including energy-efficient air conditioners, through the Program Infonavit Green Mortgage. The programme works by offering an additional loan to the mortgage loan specifically for the acquisition of energy-efficient equipment. The equipment must be more efficient than the minimum standards specified in the energy efficiency regulations. The amount of the loan is dependent on the monthly income of the recipient, who then pays back the loan along with the repayment of the mortgage loan. The programme has been a success. In August 2016, the Mexican government announced plans to expand it under the Programme for Sustainable Integral Improvement in Existing Housing, run by the government.
Buildings	Policy - Refrigerant Replacement	HCFC Phase-Out Policies, China	(Kigali Cooling Efficiency Program 2018)	China started implementing policies regulating ozone-depleting substances (ODS) in 1999. In 2010, the State Council formally approved the "ODS Management Regulation" which aimed to reduce and ultimately phase-out ODS. The regulation became effective on June 1, 2010. The legal basis for this regulation is the "People's Republic of China Law on Prevention and Control of Atmospheric Pollution" first published in 2000.
Buildings	Policy - Improve Energy Efficiency AND Policy - Financial Tools	"Old-for-New" Appliance Replacement Programme, China	(Kigali Cooling Efficiency Program 2018)	From June 2009 to December 2011, the Chinese government implemented a national "Home Appliance Old for New Rebate Programme" which covered five products including air conditioners, televisions, refrigerators, washing machines and personal computers. The objectives of the programme were 1) to stimulate domestic economy and spending; and 2) to improve resource utilisation, reduce environmental pollution, and promote the development of a circular economy.
Buildings	Policy - Refrigerant Replacement	Adopting Natural Refrigeration has become a standard to Sainsbury's	(Ecoact 2017)	Sainsbury's has a strategy to phase out HFCs by 2030 and to replace them with natural refrigerants (primarily R744) for new systems and R448A/R449A as a "drop in" replacement for existing assets. The decision was made after an in-depth analysis of government policy and the regulatory environment, including the Montreal Protocol, Kigali Amendment and the revised F-Gas regulation. In 2009 Sainsbury's decided to limit the amount of new R404A equipment installed and migrate straight from R22 assets to natural refrigerants. Dual temperature trans critical CO2 booster plants were adopted as "business as usual" in 2010 for supermarkets and in 2017 for convenience stores. Today, 216 supermarkets and 8 convenience stores have converted to such plants, compared to 605 convenience stores and 806 supermarkets in total.

Buildings	Policy - Refrigerant Replacement	Colruyt: Remote Propane System	(Peters 2018)	Colruyt decided in 2014 to eliminate all HFCs from its estate of almost 240 supermarkets and 140 smaller store formats. HFC emissions currently account for 12per cent of the company's total emissions. Colruyt considered CO2 but opted for remote hydrocarbon systems (mainly propane and some propene). The company's stores are unusual in that they contain no refrigerated display cabinets, but cold rooms where customers select fruit, vegetables and other chilled products. The cold room is kept at temperature by air cooled by remote chillers, each containing 2.5kg of propane. Cold air is prevented from escaping through the door by an 'air curtain'. The smaller store formats need one chiller, supermarkets two, and all stores have a spare for emergencies. Frozen products are kept in standalone integral freezers.
Buildings	Active Cooling - District Cooling	ASDA: Mistral Air Cooling	<Files\\Retail Refrigeration Making the transition to clean cold>	The Mistral cooling system developed by ASDA replaces much of the refrigerant gas of a conventional remote system with air, and this produces big savings in energy, emissions and cost. As in a conventional system, cold is generated in a plant room. The difference is that the cold refrigerant gas is pumped not to the cabinets in the store, but rather to a large air handling unit on the roof directly above the aisles. Here the cold is transferred to air through a heat exchanger, and the cold air blown through ducting down to the cabinets below.
Buildings	Passive Cooling - Energy Management	Godrej Industries: EP100 Cooling Challenge	(Peters 2018)	Reduce annual load and create energy savings by upgrading to a more efficient chiller, turning off chiller when possible, reducing set point of compressor, new venting system and maintenance
Buildings	Passive Cooling - Energy Management	Mahindra & Mahindra: EP100 Challenge	(Climate Group EP100 2020)	Acting on a recommendation from an ASHRAE Level 1 Audit this year, the company will save more than 227 MWh of energy and US$22,000 annually by using an improved heat transfer fluid in its chillers. By improving its cooling systems, M&M is also reducing emissions, improving worker comfort, and minimising dust and bacteria build-up which can be harmful to manufacturing machinery.
Buildings	Policy - Improve Efficiency AND Passive Cooling Energy Management	Majid Al Futtaim EP100 Cooling Challenge	(Climate Group EP100 2020)	To help achieve its climate goals, the company is implementing two cooling related strategies: upgrading systems to use both more efficient equipment and lower global warming potential (GWP) refrigerants.

Cold Supply - Food	Policy - Refrigerant Replacement	Waitrose: Water-cooled Hydrocarbons Integrals	(Bastian Lange 2016)	Waitrose opted for integrals running on propane or propene, and has now converted 133 of its 292 stores, including 37 of its 50 convenience stores. Most of Waitrose's stores measure up to 2,300m2 (25,000ft2), but the company has extended the system both to its largest store (3,700m2 / 40,000ft2), and some of its smallest (280m2 / 3,000ft2). The third-generation system that Waitrose has installed comprises hydrocarbon integrals for store cabinets with a water-cooling loop connected to an external dry air cooler – reducing the power needed to cool the water
Cold Supply - Food	Active Cooling - Solar Cooling	Cold Hubs	(Peters 2018)	Modular Solar Cold Room
Cold Supply - Food	Active Cooling - Solar Cooling	PEG Africa to make solar refrigeration products available in West Africa	(Peters 2018)>	Our innovation, Cold Hubs, is a "plug and play" modular, solar-powered walk-in cold room, for 24/7 off-grid storage and preservation of perishable foods. It adequately addresses the problem of post- harvest losses in fruits, vegetables and other perishable food. Cold Hubs is installed in major food production and consumption centres (in markets and farms), farmers place their produce in clean plastic crates, these plastic crates are stacked inside the cold room. This extends the freshness of fruits, vegetables and other perishable food from 2 days to about 21 days. The solar powered walk-in cold room is made of 120mm insulating cold room panels to retain cold. Energy from solar panels mounted on the roof-top of the cold room are stored in high capacity batteries, these batteries feeds an inverter which in turn feeds the refrigerating unit.
Cold Supply - Food	Active Cooling - Solar Cooling	Environmentally friendly cold storage for fish	(Bastian Lange 2016)	PEG Africa to make solar refrigeration products available in West Africa
Cold Supply - Food	Active Cooling - Solar Cooling	Field testing of an innovative solar powered milk cooling solution	(Bastian Lange 2016)	Environmentally friendly cold storage for fish
Cold Supply - Food	Active Cooling - Solar Cooling	Mitigating emissions from refrigerated transport	(Bastian Lange 2016)	Field testing of an innovative solar powered milk cooling solution
Cold Supply - Food	Active Cooling - Solar Cooling	How off-grid cold storage systems can help farmers reduce post-harvest losses	(Bastian Lange 2016)-	How off-grid cold storage systems can help farmers reduce post-harvest losses
Cold Supply - Vaccines	Active Cooling - Solar Cooling	GVR99 Lite	(Jones, 2011) (BEI, 2015)	Solar Direct Drive Cooling

Cold Supply - Vaccines	Active Cooling - Solar Cooling	Ultra16 SDD	(Provost, 2021)	Solar Direct Drive Cooling
Cold Supply - Vaccines	Monitoring Cooling Equipment	RTL	(Provost, 2021)	Remote Temperature Logger
Cold Supply - Vaccines	Active Cooling - Solar Cooling	HTDC-90	(Burton, 2007) (Pedersen, 2017)	Solar Direct Drive Cooling
Cold Supply - Vaccines	Dulas Solar Refrigeration	VC88SDD	(McCarney et al., 2013)	Solar Direct Drive Cooling
Cold Supply - Vaccines	Active Cooling - Solar Cooling	R718	(Kühn, 2020)	Solar Direct Drive Cooling
Cold Supply - Vaccines	Drone delivery for supply chain	Zipline Drone	(Comes et al., 2018) (SE-forAll, 2018) (Peters, 2018) (Bing Xu, 2019)	An innovative solution to the need to transport vaccines and medicines is Zipline, launched in Rwanda in 2016, which operates a drone delivery system to send urgent medicines to patients, delivering in less than 30 minutes from dedicated distribution centres and negating the need for refrigeration. Medical supplies can be ordered by text message and cost roughly the same as vehicle delivery, except that supplies are delivered in a fraction of the time.
Industry	Policy - Regulations	Carrefour reduces energy losses from refrigeration units	(Kigali Cooling Efficiency Program 2018)	Since 2014, Carrefour has been implementing a programme to retrofit its cabinet doors (for both positive and negative temperature cabinets), with a target of 75per cent of its cabinets retrofitted by 2020 in France. Retrofitted doors on positive and negative temperature cabinets can save energy as they dramatically reduce heat exchanges between ambient air and refrigerated air, significantly reducing cold losses.
Industry	Policy - Refrigerant Replacement	Kellogg Company uses ultra-low GWP chillers	(Ecoact 2017)	As part of The Consumer Goods Forum's second resolution on refrigeration in 2016, Kellogg Company is working to replace its HFC refrigerants with ultra-low GWP alternatives. In line with its commitment Kellogg Company installed the first R-514A ultra-low GWP chiller in its Cincinnati (Ohio) plant in April 2017, replacing a R123a refrigerant chiller. The introduction of the chiller was driven by the phase-out timing for HFC refrigerants, along with an expectation of increased efficiency.
Industry	Policy - Refrigerant Replacement	ICA Sweden switch to natural refrigerants	(Ecoact 2017)	ICA Sweden is committed to leadership in the phasing out of its HFC refrigerants. Refrigeration is an essential part of their business, providing fresh, high-quality food to customers. Therefore, they are working hard to reduce the environmental impacts of their contribution from refrigerant use, in line with the consumer Goods Forum. Early on, ICA began working to convert the use of CFC/ HCFC to natural refrigeration systems. In 1995, it built the first store in Sweden with 100per cent natural refrigerants - ammonia and CO2 use natural refrigerants as standard in a few years' time. By 2010, ICA adopted natural refrigeration