Mapping Existing Solutions and Best Practices on Sustainable Cooling

Scoping review

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The authors of this review include Tania Urmee, Julian Hernandez-Manrique, Darryl Fitzgerald, Ksenia Petrichenko, Kanagaraj Ganesan, Olivia Baldy, and Mona Onstad.

The cover and design layout were created by Xiao Dong and Siqi Li.

Tania Urmee, Associate Professor in the Engineering and Energy discipline and Deputy Director of the Centre for Water Energy and Waste at Murdoch University, designed the research, developed the methodology, performed data analysis, developed the search strategy, screened the articles, did substantial writing of the report, reviewed and edited the report after the external review.

Julian Hernandez, Research Associate at Murdoch University, contributed to the development of the search strategy, undertook Internet and hand searches, undertook the electronic database searches, assessed documents for review, reviewed documents, analyzed the results.

Darryl Fitzgerald, Researcher at Murdoch University, conducted bibliometrics analysis, writing, and reviewed the report.

Ksenia Petrichenko, an Economic Affairs Officer with Energy Division of the UN ESCAP, initiated the project and prepared its conceptual design, performed management of the overall project, organized the external review and conducted the review of the whole report.

Kanagaraj Ganesan, Technical Consultant with the UN ESCAP's Energy Division, wrote the section on Process Cooling, verified technological information, and reviewed the whole report.

Olivia Baldy, Consultant with the UN ESCAP's Energy Division, performed document screening and review of the whole report.

Mona Eide Onstad, former Intern at UN ESCAP's Energy Division, performed document screening and reviewed the whole report.

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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 CO2 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.

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

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.

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.

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].