

## Review

## Circular economy for cooling: A review to develop a systemic framework for production networks

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## ABSTRACT

Cooling energy demand is expected to undergo exponential growth in the upcoming decades with important implications for greenhouse gas (GHG) emissions, indirectly from electricity use and directly from refrigerants. The Kigali Amendment to the Montreal Protocol addresses some of the challenges of managing GHG emissions associated with refrigerant gases – aiming for countries to reduce them by 85% by 2047 (from a 2019 baseline for developed countries). This paper presents the first holistic framework for transitioning cooling towards circularity, with an emphasis on the global production network of cooling. It serves to analyse active technologies (including but not limited to air conditioners) to inform such a transition. This circular cooling production network framework is based on an extensive and systematic literature review including text-mining algorithms to analyse word correlations and detect topics. The application of the framework reveals the long-term interactions between cooling macro-drivers and the various stages of the cooling lifecycle. For example, currently the energy used by cooling technologies dominates their carbon footprint reporting but shifting to cleaner energy supply solutions will make components' production and end-of-life stages more important for circularity. Working proactively to address, and not only some, but all stages of the production network is thereby critical. Three cooling energy-intensive cases are used to describe the analysis: cold chains, commercial refrigeration, and air conditioning in buildings. Specific intervention points are examined for each which can improve the circularity of the production network, for instance, using passive measures to reduce the need for active cooling, recycling appliances, and raising awareness to improve users' behaviour. As the expanding global requirements of cooling unfold, this paper lays forth pathways to influence its growth as a system in alignment with achieving a circular economy.

## 1. Introduction

Cooling is critical for a large number of essential human activities: from maintaining fresh food and safe vaccines, to keeping people thermally comfortable, and industries and transport infrastructure functioning. However, mainstream cooling technologies also contribute significantly to climate change as they are energy intensive to use, and require insulation foams and refrigerant gases with high Global Warming Potential (GWP) which are harmful if leaked or not recovered and recycled carefully (Carbon Trust, Cool Coalition, K-CEP, Oxford Martin School, Race to Zero, 2020). This is particularly relevant given that the global demand for air conditioners (ACs) will triple by 2050 (IEA, 2018).

Already, the carbon emissions combined across all sectors of cooling is considerable. Estimates vary from seven percent of global Green House Gas (GHG) emissions (K-CEP, 2018), up to fifteen percent of the world's carbon emissions being generated by cooled buildings (Birmingham Energy Institute, 2020). Cold chains (food and vaccines) currently account for 2–4% of the GHG emissions in the UK (Ravishankar et al., 2020). In addition, with global temperatures increasing (Spinoni et al., 2018) current and future cooling units will need to function more intensely, for more days in the year and for longer periods. International agreements are taking heed of the growing cooling concern. The Kigali Amendment to the Montreal Protocol (2016) aims to gradually reduce the consumption and production of Hydrofluorocarbon (HFCs) refrigerant gases. By 2047 it aims to reduce global HFC consumption by 80%

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**List of acronyms**

AC	Air Conditioner
CO <sub>2</sub> eq	Carbon Dioxide Equivalent
CFC	Chlorofluorocarbon
CaaS	Cooling-as-a-Service
C2C	Cradle-to-Cradle
EIA	Environmental Investigation Agency
GPN	Global Production Network
GWP	Global Warming Potential
GHG	Green House Gas
HVAC	Heating, Ventilation and Air Conditioning
HFC	Hydrofluorocarbon
PSS	Product-Service System
RDC	Refrigerated Display Cabinet
SDG	Sustainable Development Goal
UNFCCC	United Nations Framework Convention on Climate Change
WEEE	Waste from Electrical and Electronic Equipment

(EIA, 2016). The reductions of HFC emissions have been reported (K-CEP, 2020; Xu et al., 2013) to potentially avoid between 0.4 and 0.5 °C of global warming. Others (Lickley et al., 2020) have estimated that this equates to 53 billion tonnes of CO<sub>2</sub>eq between 2030 and 2050. Analogously, countries under the Paris Agreement pledged a reduction of 7 billion tons of CO<sub>2</sub>eq from phasing out HFCs by 2030 (Sovacool et al., 2021).

Understanding and preparing for the future of cooling requires a long-term and systemic view. As countries move towards net-zero targets around mid-century, the increasing presence of renewable energy will likely reduce the carbon intensity of electricity-based mechanical cooling. However, the rapidly increasing demand for cooling will result in a continued use of energy inefficient AC units with climate hazardous components, alongside inadequate waste collection and reprocessing systems of the appliances at their end-of-life. Currently, in all major markets, the units sold are less than half as efficient as the available highest efficiency AC units (IEA, 2018). Super-efficient cooling appliances will likely dominate regions that are guided by minimum energy performance standards (Blumberg et al., 2019). While there is growing policy and business emphasis on the supply-side and operational energy solutions of cooling, the problem of extracting materials for equipment still remains largely unexplored.

The major economies are likely to vary in their energy use and GHG emissions for the different cooling sectors. For example, in developed countries with mild climates like the UK, the role of refrigeration (e.g., display cabinets) will likely be more urgent than the role of residential AC for carbon neutrality, as opposed to “hot and high-income” countries like Singapore and the UAE, where all sectors of cooling are intensely required. As observed in Table 1 there are also countries closer to the geographical tropics, which are expected to experience even more severe heating due to their humidity, putting their populations at health

risk and requiring further increased cooling-related electricity demand (Zhang et al., 2021). In Mexico for example, expected increasing temperatures and rising income will result in the demand for ACs being considerably larger than previously believed (Davis and Gertler, 2015). Table 1 shows data used from the (Green Cooling Initiative, 2021) to support the examples in the application of the framework introduced in this paper. The data is in Mt of CO<sub>2</sub>eq for the 2016 baseline and two projected scenarios for 2050: Business As Usual (BAU) and mitigation (MIT).

Further, the concept of circular economy for cooling will not be limited to manufacturing elements. It is also about up- and down-stream circular supply chains, delivery and practices at all stages of the life-cycle (i.e., production, operation and appropriate disposal). Currently, no comprehensive and systematic review exists that synthesises existing research on the distinct stages of the production networks for cooling. This paper proposes a framework to understand the potential systemic effects of circular cooling based on extensive literature on the subject. Specifically, it asks: how does the existing literature assess the different stages of the cooling production network to inform a transition towards a circular economy? This paper is among the first studies to help address the significant gap in the circular economy literature on cooling. Table 2 presents a short overview of recent research addressing topics relevant to a circular GPN of cooling.

The remainder of the paper presents the key concepts on circularity and production networks, and the rationale of their application to cooling (Section 2). Then it provides a comprehensive literature review of all stages of the lifecycle of cooling (Section 3) (including design, production, use and end-of-life) and the key socio-political features (policy, technology innovation, new business models and consumers). It also details the methodology used for the systematic literature review and the use of algorithms to analyse word correlations and topic modelling. The literature topics are then mapped into the novel framework in Section 4 to show the connections between each feature of cooling studied, including the scope and breadth of environmental and social impacts, and the potential strategic intervention points within the production network so as to move it towards circularity. This section not only introduces the framework but also analyses the key areas of the broader cooling system (production and use) to advance circularity. Section 5 explores the possibilities and impacts of circular cooling production and use for three major cooling sectors: cold chains, commercial refrigeration and room ACs. Conclusions about the challenges and opportunities for developing a circular economy for cooling are discussed in Section 6.

## 2. Conceptualising circular economy for cooling

The framework in the paper draws on the intersection of literature on circular economy in business and engineering, and production networks in economic geography. Therefore, the literature was reviewed to introduce the concepts of circularity and a production network approach. First, it is described how manufacturing stages operate or could operate as a circular economy (Section 2.1), and second, present the rationale for a whole system approach to pursuing a circular

**Table 1**  
Total emissions from cooling sectors – Adapted from the (Green Cooling Initiative, 2021).

Scenarios		Commercial refrigeration			Unitary AC			Industrial refrigeration		
		2016	BAU	MIT	2016	BAU	MIT	2016	BAU	MIT
Region	North America	30.2	~35.3	~19.5	233.0	~320.0	~210.0	27.0	~23.2	19.8
	Europe	90.5	~63.5	~51.0	51.4	~38.0	~29.0	33.7	~22.0	~19.5
	India	84.0	123.0	75.2	152.0	642.0	458.0	30.9	39.6	28.1
	China	77.7	96.3	48.0	535.0	3070.0	2110.0	88.3	79.8	57.1
	Japan	22.4	15.8	10.2	31.0	22.6	16.3	6.9	4.4	3.7
	Africa	42.1	~115.0	~47.0	74.5	~330.0	~180.0	20.2	~37.0	~21.5
	<b>World</b>	<b>474.0</b>	<b>612.0</b>	<b>339.0</b>	<b>1280.0</b>	<b>4980.0</b>	<b>3360.0</b>	<b>258.0</b>	<b>263.0</b>	<b>186.0</b>

**Table 2**  
Summary of previous research on relevant circular cooling production topics.

Author(s)	Cooling topic(s)	Suggestions/ recommendations
Song et al. (2017)	Developed a method to select the most sustainable solar AC manufacturer.	Consider economic, environmental and social evaluation criteria for a better selection of suppliers.
(Shashi Cerchione et al., 2018)	Framework to design strategies that will increase the sustainability of food cold chain management.	There is a need for more performance assessment metrics and limited understanding of the negative factors affecting food cold chains.
Bhamare et al. (2019)	Review of passive cooling in buildings and differences in climatic regions	Pathways to ensure indoor temperature is thermally comfortable while minimising the building cooling load.
Nizetić et al. (2019)	Smart technologies that contribute to reducing the energy demand from cooling use and its appropriate waste management.	Application of technologies to improve sustainable waste management, improvement of living standards, and barriers to more sustainable processes and products.
Khosla et al. (2020)	Developed a framework to the future of cooling for sustainable development based on the relationships of cooling with the 17 Sustainable Development Goals (SDGs).	Make cooling decisions based on the interest of people, especially the most vulnerable. All regions need to prepare to more extreme heat events. Verify the long-term sustainability of implementing passive cooling solutions.
Sovacool et al. (2021)	Review of f-gases reduction influence by policy and sociotechnical developments	More work is needed to assess f-gases in the non-Western locations, where emissions are projected to skyrocket in the upcoming decades.
Dong et al. (2021)	Review of current and expected expansion of cooling demand in developing countries	Effect of new and upgraded cooling. Regulations to be implemented. Impact of cooling in socio-economic conditions.
(Carbon Trust, K-CEP, Race to Zero, Cool Coalition, 2021; EIA, 2021a)	Circular production of cooling – both manufacturers and products	Make ambitious commitments to decarbonise cooling production. Specify strong actions to these commitments. Standardise definitions and timelines for decarbonisation.

economy for cooling (Section 2.2).

### 2.1. Circular economy and Global Production Networks (GPNs)

The literature on cooling mainly focuses on operational energy use of smart technologies (Nizetić et al., 2019), sensitivity analysis in lifecycle of cooling units (Ross and Cheah, 2017), extended product durability (Iraldo et al., 2017), and energy efficiency (Nishijima et al., 2020), and consumer behaviour towards refurbished units purchase (Muranko et al., 2019b) and cooling waste management (Murray et al., 2017), and it is largely disjoint across these aspects. The majority of the cooling literature fails to connect the stages of cooling production with the sustainable uses of cooling. A leading approach for integrated and system-based sustainability is that of the circular economy. The aim of a circular economy is more than recycling; it is to reduce raw materials consumption. For this, design of products is critical to ensure they can be easily reused, maintained and repaired to extend their product lifetime. One example is Design for X which targets specific objectives and characteristics when practicing design (Kuo et al., 2001), and its impact on other characteristics such as aesthetics and cost (Pigosso and McAloone, 2017). Circularity ensures maintenance and repair to extend

product life (Gu et al., 2018), and also creates socio-economic value and promotes the conservation of natural resources (van Buren et al., 2016).

The Global Production Network (GPN) is “the set of economic and non-economic actors coordinated by a global lead firm to create, transform and capture value through dispersed economic activity” (Yeung and Coe, 2015). GPN involves the inextricable linkage of global economies’ chains of production in different regions specialising in certain product manufacturing or service delivery (Coe and Hess, 2013). Economic globalisation is the process via which economic relationships between places are being reworked and shrunk (Bryson and Henry, 2005). Applying this to cooling, the network is comprised of several leading firms producing cooling products and services across multiple geographies and for worldwide markets. It encompasses the procurement of resources, manufacturing, sale, use, reuse, and end-of-life of cooling appliances, in other words, the full life-cycle of the appliance as well as its socio-economic contexts. Current production network in the cooling sector operates as a linear economy; that means, cooling equipment is made, used, and then disposed (Geissdoerfer et al., 2017).

When considering how to make the production and use of cooling more circular, evaluating the GPN shows the impacts of cooling beyond the time when appliances are in use. The dominant approach to improve the sustainability of the full life-cycle of cooling is changing the current linear economic system to one that is circular. In a circular economy, minimal new inputs are used in production and products are kept in use for as long as possible before reuse and recycling. If some parts need to be disposed of, they are done so in the safest possible way (Baxter et al., 2016). Ideally, before cooling appliances are manufactured, it should be known what will happen to them when they reach the end of their useful lives. In other words, to design products thinking of dealing with waste even before it is generated (Kirchherr et al., 2017). A circular economy for cooling is depicted in Fig. 1 and it aims to capture the remaining value in the waste generated from all the stages in the consumption process (Palafox-Alcantar et al., 2020). The distinctiveness of the cooling sector in Fig. 1 is the use of environmentally harmful gases as refrigerants (f-gases), metals for vapor-compressor technologies/hardware, and the potential recoverability of the other materials used if the appliances are redesigned appropriately (Karkour et al., 2021).

For GPNs, embracing circularity means facilitating innovation to drive the spatial structure of actors, institutions, infrastructure and material flows (Jedelhauser and Binder, 2018). Thus, the networks transition in parallel to their incrementing adaption, and to how this innovation affects their geographies (Bridge et al., 2013). In addition, a circular production network will consider waste as resources which can be allocated a secondary use. This reflects the true environmental and social costs of producing cooling, making it more accessible, ethical and sustainable for everyone especially those most vulnerable to extreme heat and climate change.

For cooling, a circular GPN would include recovery plants and recycling centres that add a new functional and structural phase to the cooling GPN (Lanza et al., 2019). To achieve a closed-loop supply chain, both optimisation and simulation techniques are required. The configuration of circular production networks and the relationship between GPNs and circularity is not examined in detail yet; and research is required on integrating production networks and business models for implementing circular economy (Klenk et al., 2020).

Finally, creating a circular economy of cooling and a more sustainable cooling system overall is not only a technical transition. Policy and behavioural changes are also necessary. Cooling production companies will act faster to improve the circularity of their products with specific regulatory incentives and obligations (Coe and Yeung, 2019). Waste and disposal systems can be conducted at scale within countries and coordinated globally (Murray et al., 2017). Customers can learn about their options for effective, circular and cost-efficient cooling (Muranko et al., 2019a), and these principles are not limited to cooling appliances. The next section introduces a complete system approach to pursuing a

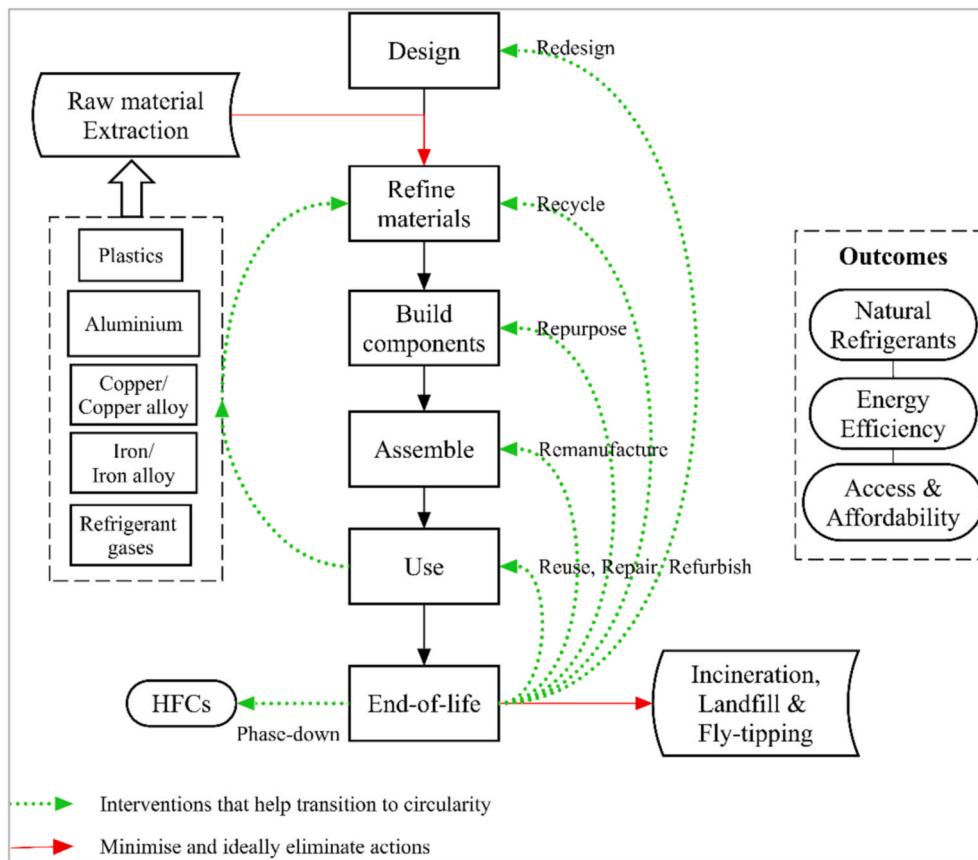


Fig. 1. A circular production network for cooling – adapted from (Khosla et al., 2022).

circular economy for cooling.

## 2.2. Circular economy for GPN of cooling

A circular economy approach for GPNs helps to connect the sustainability impacts of the many distinct stages of the cooling system and its siloed research. The cooling literature framework created for this paper is a first step in identifying the connections between these aspects. The topics of the framework that serve as its pillars are policy, technology, business models and consumers. It draws upon some emerging work on the literatures of circularity of cooling such as:

- Extending the life of appliances, for example, exploring life extension strategies (Bakker et al., 2014), consequences of price-induced product lifetime extension (Nishijima et al., 2020), and premature and programmed obsolescence of cooling appliances (Wang et al., 2019).
- Energy use phase in buildings, specifically in Heating, Ventilation and Air Conditioning (HVAC) systems, for example, coupling passive and active cooling measures in supermarkets (Mylona et al., 2018), integrating solar panels in the smart AC network of households (Masiukiewicz, 2017), and the HVAC use in airports (Gomri and Mebarki, 2016).
- Cooling Waste Electrical and Electronic Equipment (WEEE) management, for example, its optimal collection (Baxter et al., 2016), recycling insulation foam to insulate hospitals (Briones-Llorente et al., 2020), material recycling and energy recovery (Golsteijn and Valencia Martinez, 2017), remanufacturing old appliances and incentivising their sales (Muranko et al., 2019a), and leakages of refrigerants (Saif and Elhedhli, 2016; Stemmler et al., 2004).

Circularity principles are embedded by finding a second use to the

otherwise environmentally hazardous materials, decreasing costs, and avoiding carbon emissions by minimising energy use from both heating and cooling buildings. For example: the construction industry is increasingly under pressure to construct low-carbon buildings. One way of achieving this is by making use of insulating materials. Old and obsolete refrigerators contain insulating foams that have been proven to be recovered and recycled into insulation material when constructing hospitals for instance, to increase their thermal comfort capacity (Briones-Llorente et al., 2020).

To advance the circularity of cooling manufacturing, ideally, cooling appliances need to be designed to make them easier to disassemble and recover the materials in them once they reach their end-of-life – a Cradle-to-Cradle (C2C) approach (McDonough and Braungart, 2003). In this case the literature around circular design and simulation (Desing et al., 2021; Moreno et al., 2016) can help to support the transition of WEEE to circularity (Bressanelli et al., 2020). For example, avoid any appliance obsolescence by designing them to be easily repairable and upgradable when needed, or make their parts easy to disassemble and recover to build refurbished units (e.g., smartphones have been treated similarly for years (Mugge et al., 2017)), and the last option to use recyclable materials for an alternative use diverting their incineration or abandonment in a landfill site (Geyer and Blass, 2010).

Another approach is to use the servitisation of cooling which can result in production companies needing to extract, refine, process, manufacture and assemble less units, consuming fewer resources and reducing their expenses. Circular cooling manufacturers could also consider innovative business models that minimise resource extraction and consumption. For instance, through a leasing system, in which an AC unit is not bought, the customer pays to use it unlimitedly and individually until the manufacturer decides that it is time to be returned (Tukker, 2015). The AC unit could be replaced with an upgraded version, or the parts needed for a new or remanufactured AC or



materials could be recycled. These are Product-Service Systems (PSS) which are business models that support the adoption of circularity (Bocken et al., 2014). PSS aim to provide a better approach for products to fulfil their necessities, by turning the focus into the final consumer need, demand or function required to be satisfied (Tukker, 2004). In addition, there are examples of addressing business models particularly in the WEEE sector, such as: the enablers and barriers in their supply chains (Bressanelli et al., 2021), the finance factors that affect the take-back systems (Uhrenholt et al., 2022), and practices related to the 10R hierarchy (Pan et al., 2022).

In spite of the growing literature, a full GPN of cooling has not yet been studied. This paper addresses the gap in the academic and grey literature by mapping the systems of active cooling (ACs and other equipment such as refrigerators and display cabinets) using the production network and circularity literatures. The intersection of these two literatures reveals the impacts from circular economy interventions and influences on the production of cooling appliances in distinct geographies. By looking at the full manufacturing and usage cycles, the framework makes evident how to best place efforts to minimise materials and energy consumption and achieve circularity.

### 3. Systematic literature review

This section presents the systematic literature review methodology and description of findings from the search, which is used as input to the

systemic circular cooling production networks framework (Section 4). It also describes the use of algorithms in a supportive role to detect the major topics of cooling research under development and others which are currently receiving less attention.

#### 3.1. Methodology

To ensure quality of the data, articles were gathered (in November 2021) from three platforms that collect mainly peer-reviewed publications: International Bibliography of the Social Sciences (IBSS), Web of Science, and SCOPUS. As cooling is a still an early but fast developing research area (Adams et al., 2016), the review also captures the grey literature (relevant conference proceedings, working papers and business, consultant and government reports) from these platforms. Key search words were applied to find the literature covering production network of cooling appliances. Appendix 1 shows the terms used that could capture more results without compromising the analysis. It also provides the search word combinations used to narrow the search. The criteria considered for the search were: publications in the English language only; all dates; and that the terms are included in the abstract, title or keywords.

With the search results, five steps were carried out manually (see Fig. 2) to assess whether publication content addressed the production network of cooling appliances. An additional 10 articles were included based on the references already in the search results. In Fig. 2, the

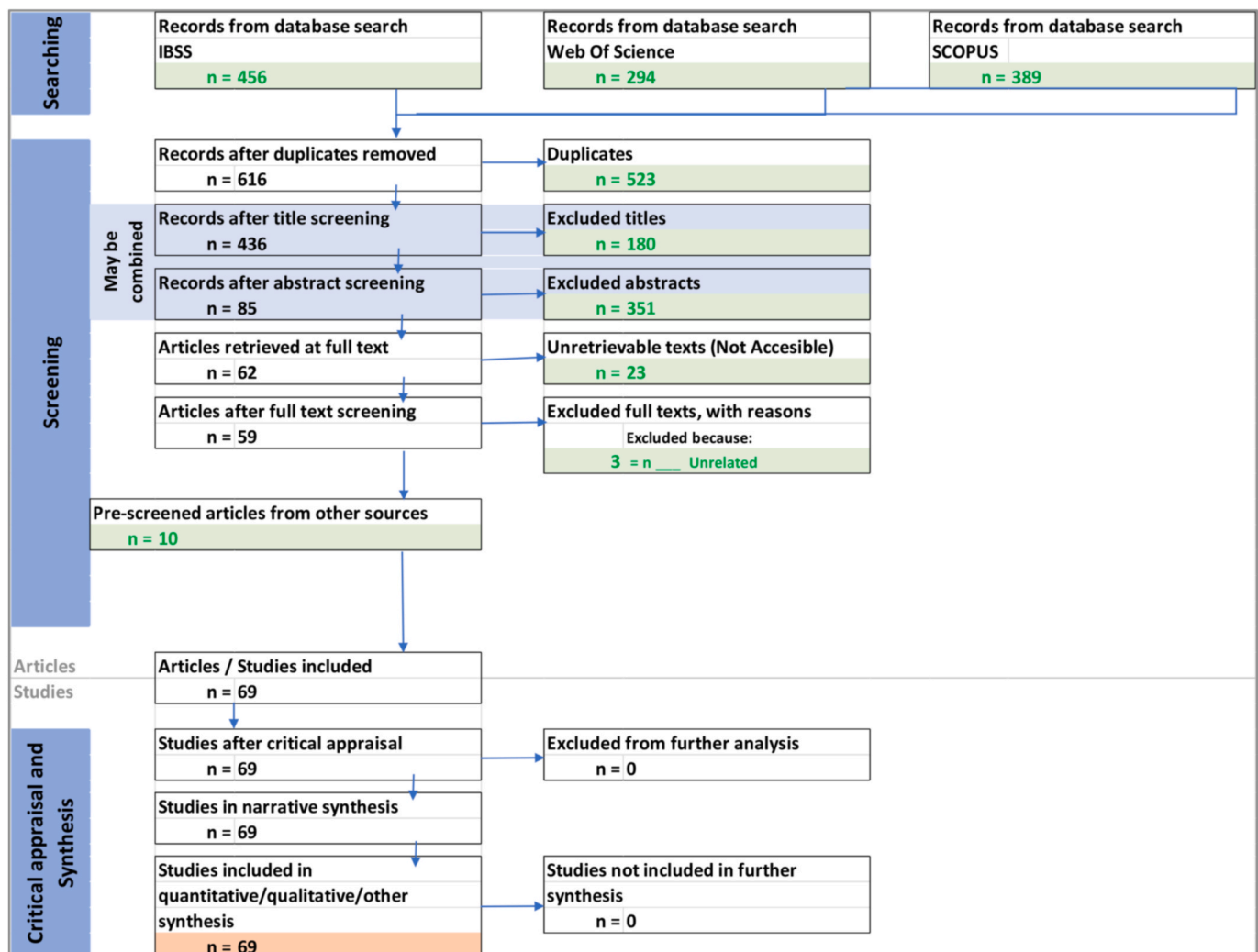


Fig. 2. Systemic review diagram – adapted from (Haddaway et al., 2017).

studies below the grey line were considered for the construction of the framework. It is a diagram of the number of publications selected in each stage of the systematic review process (Haddaway et al., 2017). As initially expected, because three different databases were searched, a large number of the results were duplicates ( $n = 523$ ). Thereafter, the vast majority of articles reviewed were discarded at the abstract stage because they focused on different topics, such as, the postharvest and initial storage stage of the food supply chain of agricultural products ( $N = 180$ ), rather than on the production network of cooling. Many ( $N = 351$ ) studies also focused on the vaccine or industry manufacturing supply chains which are outside the scope of this review. For the studies included in the review ( $N = 69$ ), the oldest was from 2003, showing that the academic literature has only covered the subject for 17 years.

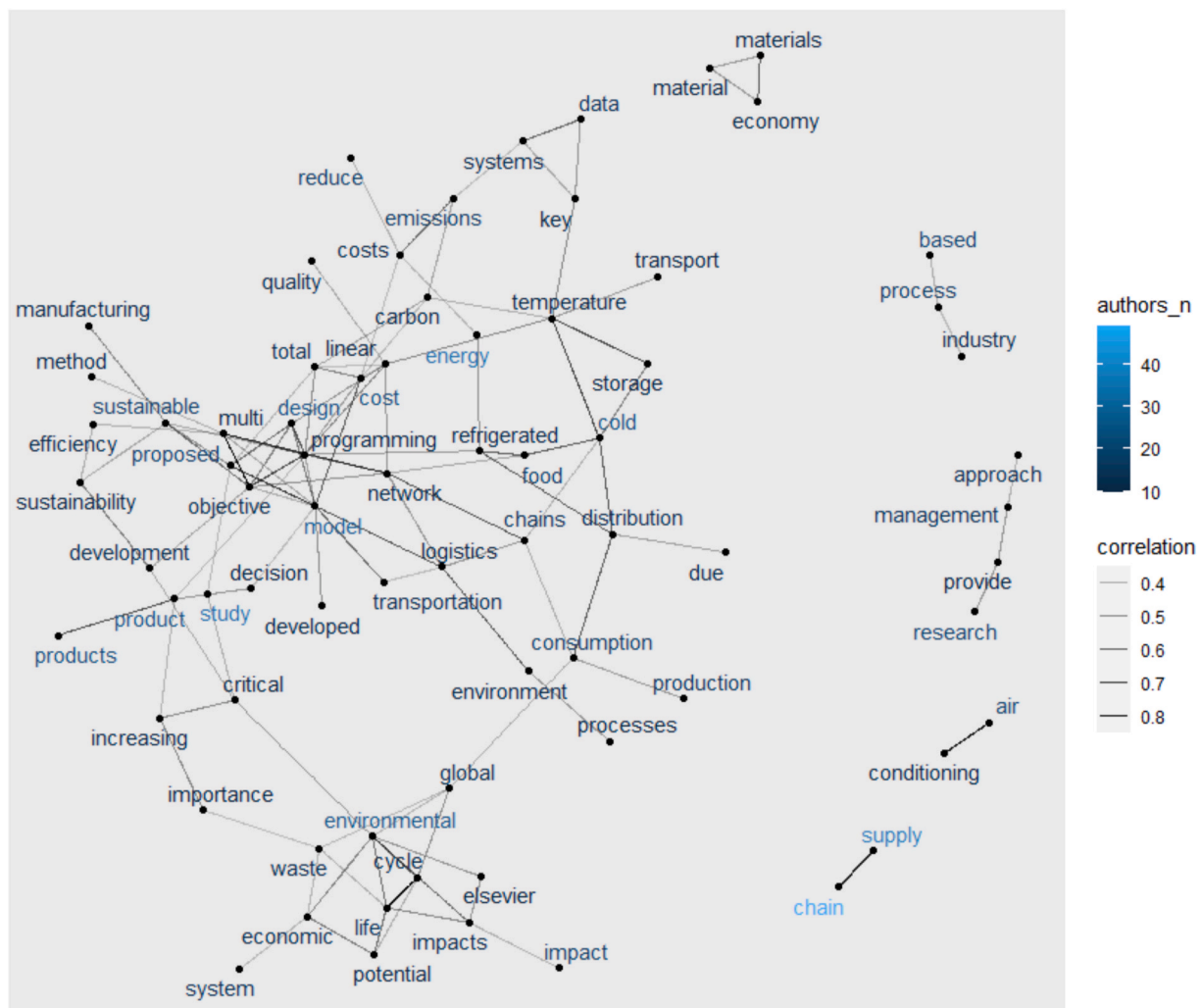
### 3.2. Description of search results and initial findings

The final search yielded 1139 papers from the three databases. There were a large number of results for the two-terms combinations (see [Appendix 1](#)): circular economy and cooling (N = 521,156), cooling and GPNs (N = 2647), and circular economy and GPNs (N = 68,160). In particular, the search yielded over half a million results for the circular economy and cooling combination. For this review, the combination of interest was the intersection of all three terms (N = 1139). Further refining was explained in the previous section to narrow down the

review to a smaller number of publications ( $N = 69$ ). Algorithms were then used to describe and visualise characteristics of the large text datasets from the final set of publications. For this, the R package used is *tidytext* (Silge and Robinson, 2016) and the analyses had a minimum number of 10 titles and a minimum Pearson correlation of 0.3.

After tidying the abstract database, calculating the word counts and their correlations, a word network plot was built to show the correlations of words and their frequency (Fig. 3). The colour of the word shows how many authors used the word (the lighter blue the more authors used it) and the thicker the line between words, the higher their likelihood to appear in the same abstract (highly correlated). In terms of common words in abstracts, Fig. 3 presents word frequency and grouping of bigrams. It indicates that there is fragmented research on circular cooling networks. Initial hints to topics can be observed such as, maintaining materials in the loop, industrial processes, air conditioning, and supply chains (as the most commonly topics used by authors). Other important circular economy related bigrams are found around energy efficiency, food storage and refrigeration, transportation and logistics, life cycle studies, and waste associated research.

Next, topic modelling is used for finding sets of words that are characteristic of multiple documents. This means calculating the probabilities of words being used in the abstracts to separate and distinguish likely topics in the literature. When screening documents it was observed that several publications ( $N = 7$ ) focused on technologies to



**Fig. 3.** Network of most common words found in the abstracts.

The colour of the word represents the number of authors that used the word (*authors\_n*) and the line represents the likelihood that two connected words will appear in the same abstract (*correlation*).

improve the energy efficiency and improve energy consumption in buildings (Ben-Nakhi and Mahmoud, 2002, 2004; Chan and Tzempelikos, 2013; Congedo et al., 2020). The text-mining results on topics are presented in Fig. 4 which shows the main six topics extracted from the abstracts. The topics are not named because they are left to the researcher to interpret. The most common words in Topic 1 include the words “energy”, “air conditioning” and “sustainable”, which suggests it might represent climate-friendly energy use in the cooling of buildings. Another noteworthy topic is Topic 4 which includes the words “product”, “design” and “waste”, which could represent the circularity of cooling production in terms of their end-of-life. It is important that some words are common across multiple topics such as “chain” and “sustainable”. It should be noted that topics could be present across multiple abstracts and have some overlap in terms of words (Silge and Robinson, 2016).

The systematic review reveals aspects of the cooling system with surprising connections as well as specific topics where there is a notable density or absence of knowledge production. It also reinforces the importance of a systemic approach to cooling for circularity as well as the potential for using the framework to identify system-based interventions for a circular economy. In order to examine the transition towards a circular economy of cooling, the literature review is used as an input for the creation of the framework of the full active cooling GPN system (next section).

#### 4. Active cooling systemic framework

Using the systematic literature review as a basis, a framework of the full active cooling GPN system is constructed (Fig. 5). The framework aims to be an analytical tool to help identify potential strategic pathways within cooling production networks and move towards circularity. A more detailed framework is depicted in Fig. 6 showing the interconnections identified in the literature from single or multiple publications. In addition, the authors include further interactions based on expert knowledge. It is worth mentioning that even though the framework attempts to be comprehensive, it is not exhaustive of all aspects that both influence and are influenced by cooling but rather is based on existing literature.

The following sub-section focus, first, on how to shape (i.e., enable) the uses and solutions to cooling needs (left-hand side of the framework) from a socio-political perspective. Second, it discusses the GPN of cooling (right-hand-side of framework), including how cooling is manufactured and the issues encountered in this entire process from an economic geography perspective.

##### 4.1. How cooling use is shaped – socio-political enablers

The left-hand side of the framework (Fig. 5) categorises the socio-political enablers that influence the use of cooling and are the factors

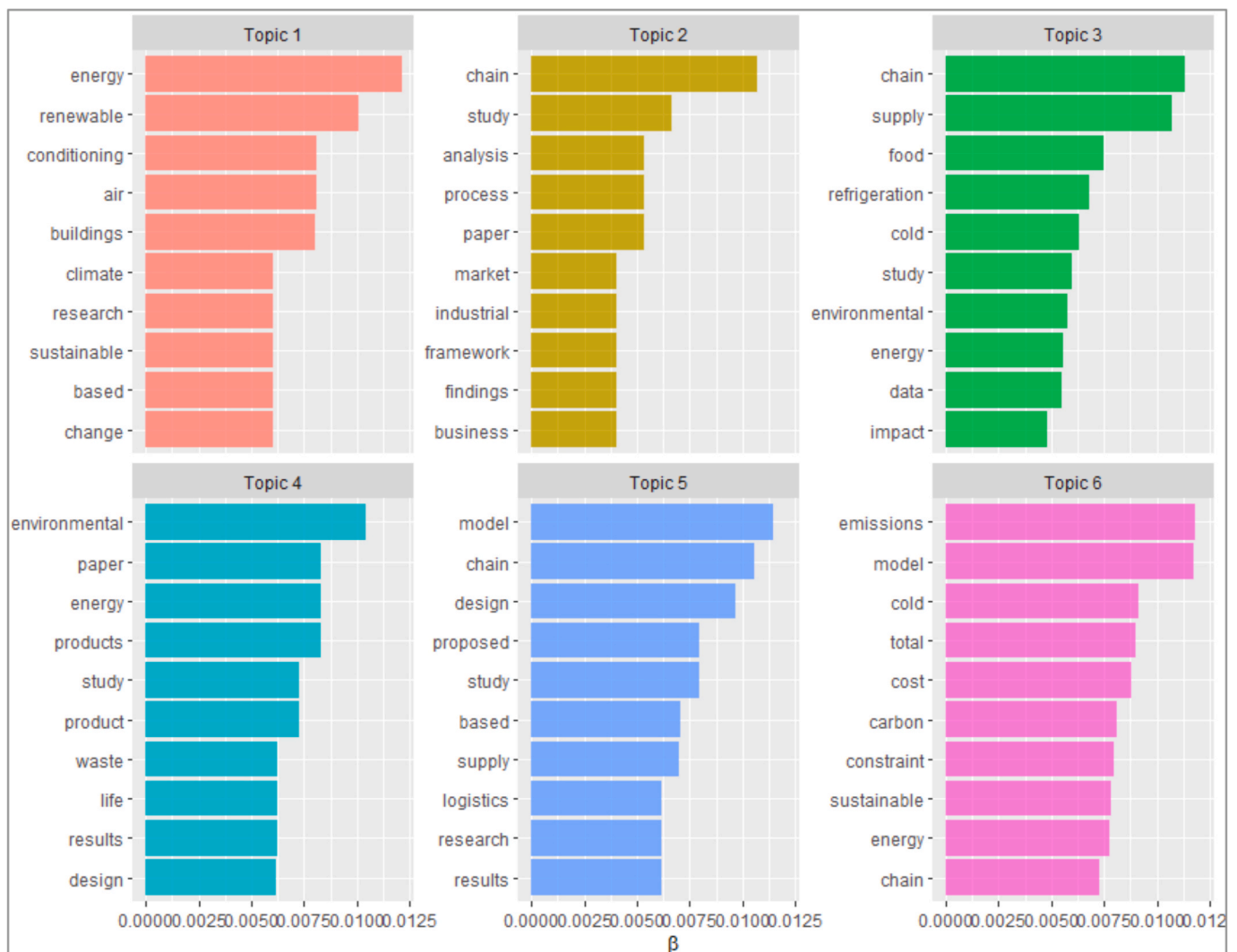


Fig. 4. First six topics in abstracts and the 10 top words therein.

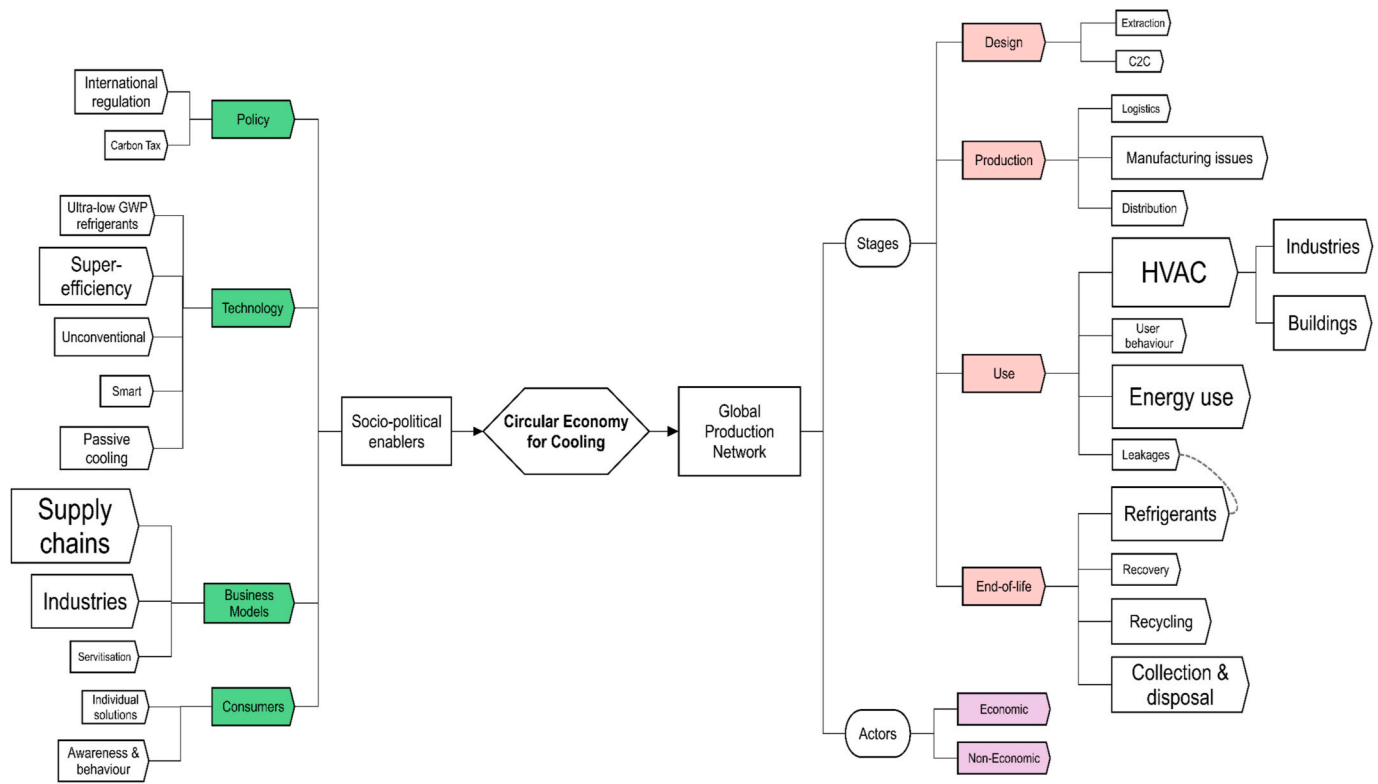


Fig. 5. Systemic framework for circular cooling production networks.

The size of the nodes symbolises the number of publications related to that specific topic. The colours represent the groups of enablers (green – Section 4.1), and GPN stages (pink – Section 4.2) and actors (purple – Section 4.2.4). These are the main topics that are discussed throughout this Section 4.

that shape cooling production. Based on the analysis, this section presents the contributions towards future circular cooling from the perspective of these socio-political enablers. It provides examples from the literature review of how to change the use of cooling units with different scales such as room AC, commercial refrigeration and district grids. The section is divided into policymaking, technology development, business models and consumers behaviour, following the order on the left-hand-side of the framework.

#### 4.1.1. Policy and international regulation

Regulations and policies from all levels of governance have an impact on cooling manufacturing, especially those that are international, given the multinational nature of cooling production and its GPNs. The United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COPs) are important avenues for cooling proposals to reach circularity, net-zero emissions and the Paris Agreement targets. When Chlorofluorocarbon (CFCs) gases were found to deplete the ozone layer, the Vienna Convention (1985), a multilateral agreement, provided frameworks to reduce the production of these gases. Shortly after, the Montreal Protocol (1987) was signed by over 200 countries which committed to no longer produce these environmentally harmful chemicals (IEA, 2018). Refrigerants were replaced by HFCs; however, these were subsequently found to have a worse effect on global warming than CO<sub>2</sub> with most having hundreds and thousands of times the GWP of CO<sub>2</sub>. The Kigali Amendment was signed in 2016, agreeing to reduce HFCs consumption by 80% by 2047, to avoid between 0.4 and 0.5 °C of global warming (K-CEP, 2020; Xu et al., 2013). As a direct consequence to future production of cooling appliances, suppliers are now turning towards natural and ultra-low GWP refrigerants (Carbon Trust, K-CEP, Race to Zero, Cool Coalition, 2021; EIA, 2021a). Further, international agreements shape the internal political economy of the manufacturing of cooling. It is argued that to provide a full spectrum of sustainable cooling solutions, a framework needs to

consider the political economy of countries including their national conditions (the composition of the real economy), the political system, and the countries' external geopolitical projection ((E3G, 2021).

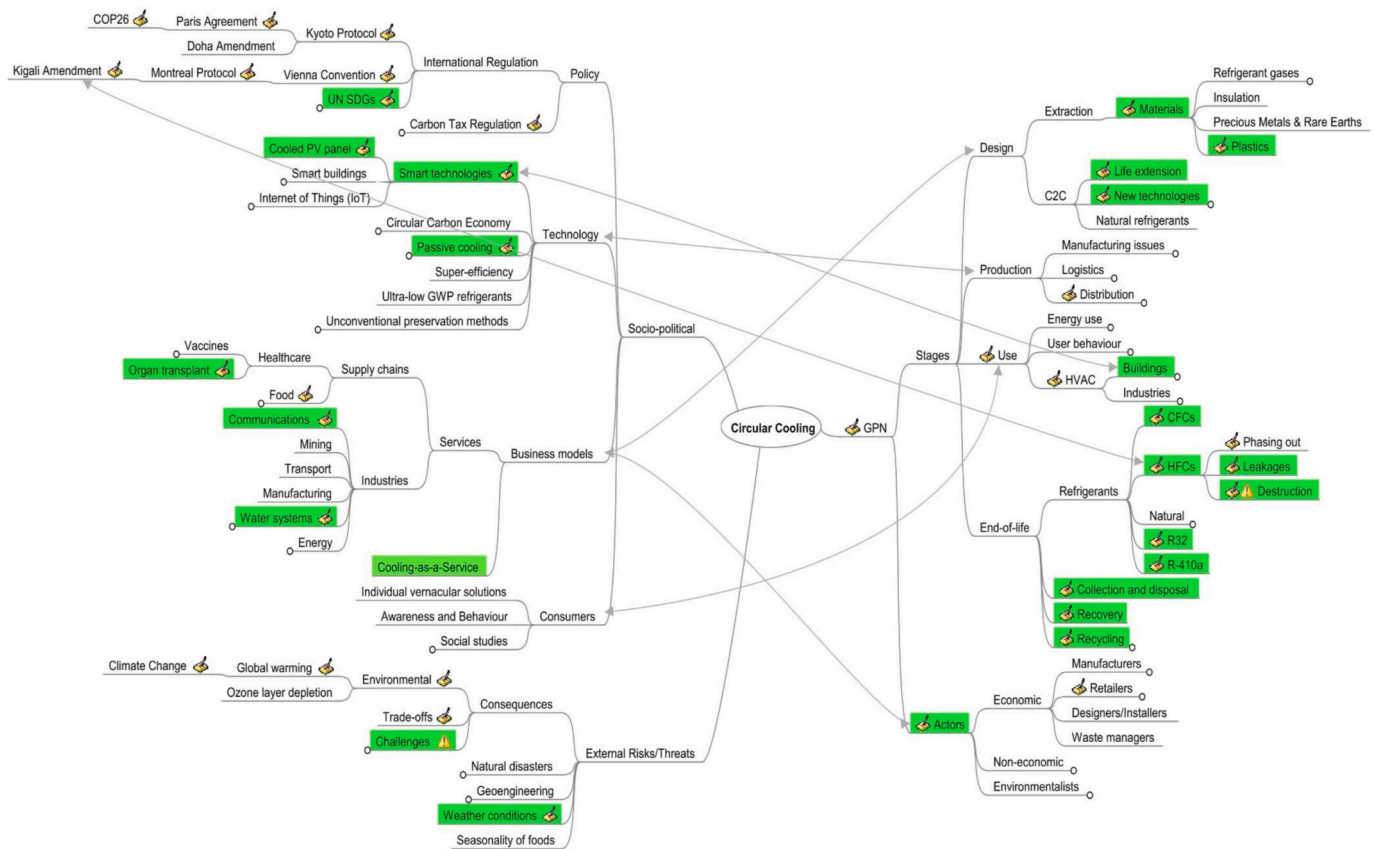
#### 4.1.2. Innovative technologies

Within the literature on enabling circular economy through innovative technologies, three main themes were detected: the use of passive cooling; the coupling of smart systems to both passive and active technologies; and unconventional technologies. Passive cooling technologies keep temperatures down while avoiding or reducing the use of mechanical energy (Miranda et al., 2021). They are classified by their ability to protect buildings from solar and heat gains (e.g., plants, gardens, green corridors); modulate heat (e.g., phase change materials) or dissipate heat (e.g., windcatchers) (Bhamare et al., 2019). For example, façades of buildings can be designed to have good ventilation that helps to cool their temperature in climates with hot summers and mild winters (Pujadas-Gispert et al., 2020). Night ventilation and the orientation of apartments can play a key role in achieving thermal comfort during hot summer months (Encinas and de Herde, 2013). Furthermore, adopting appropriate construction materials can be synergetic as insulation can decrease the demand of buildings for both heating and cooling (Briones-Llorente et al., 2020). Although they hold important potential to reduce the demand of active cooling, they are currently not found to be a go-to (e.g., off-the-shelf) solution.

Innovative technologies such as smart technologies can complement both passive and active cooling. For example, sensors that adjust shading orientation and thermostats that control room temperature, respectively. Smart technologies also advance cooling energy efficiency, sustainable resource use and waste management (Nižetić et al., 2019), and the Internet of Things allows for industrial collaboration opportunities to arise in the cooling manufacturing process (e.g., building smart refrigerators, (Wu et al., 2020)).

Other more “unconventional” innovative technologies include





**Fig. 6.** Detailed systemic framework for circular cooling production networks. The green highlighted nodes are supported by grey literature. The arrows show the interconnections between both sides of the framework.

magnetic refrigeration, which does not need a refrigerant to function and potentially reduces energy use up to a third (CIBSE Journal, 2016). However, circularity issues remain present for the supply of magnetocaloric materials, which are extremely scarce and difficult to recover and reintroduce in the production system. An increasing alternative is the use of heat pumps, which can deliver heating and cooling while paired with renewable electricity generation (Bernath et al., 2019). Finally, a promising stream of research is to capture carbon and water from the atmosphere using advanced AC technology, and converting it into hydrocarbon fuels. (Dittmeyer et al., 2019). The resulting synthetic hydrocarbons, such as Propane R-290, Isobutane R-600a and Propylene R-1270, can be used as natural refrigerants or fuels if captured appropriately (Dehoust and Schüler, 2010).

#### 4.1.3. Business models

A big task to achieve circular economy is reforming business models to minimise environmental impact. This is done by reducing material and energy use, maximising social cohesion by increasing consumer satisfaction, and keeping economic benefits by maintaining companies' profits. Supply chains and industries are the main themes covered for business models in the cooling sector (as seen in the framework Fig. 5). Within these, the two main sectors where research on business models for cooling is vast are the food and vaccines supply chains. Other industries include: sustainable trigeneration and management of district electricity, heating and cooling (Vasudevan et al., 2013), communication base stations (i.e., large consumers of energy in terms of their operation and their need for cooling (Ni and Bai, 2017)), water desalination processes (Lefers et al., 2020) and solar photovoltaic energy generation systems (Byrne et al., 2015).

Another crucial factor found to achieve circular economy in cooling through business models is servitisation. PSS aim to do this by shifting

the mindset from owning products to hiring services. It allows needs to be met and do not require customers to buy appliances (Gaiardelli et al., 2014). Cooling-as-a-Service (CaaS) is such an example of servitisation and involves customers paying for an amount of cooling delivered by a provider rather than purchasing equipment (K-CEP, 2019a). This idea is not recent, but it has been developing in practice slowly and the academic literature does not explore its barriers and opportunities in detail yet. Furthermore, CaaS makes access to cooling more affordable specially to impoverished consumers in hot and low-income regions (Climate Finance Lab, 2019). It also presents the chance to capture other benefits, such as more profitability to providers, reduced materials and resources demand, and promote efficient technologies (Khosla et al., 2020). Another benefit not mentioned in the reviewed papers is that CaaS could influence and help to improve consumer benefits from reducing food waste obtained by the affordable and widespread of cooling (e.g., monetary savings).

#### 4.1.4. Consumer behaviour

The most important contribution of consumers to a circular economy for cooling is their ability to avoid the use and need of mechanical cooling solutions. They can embrace passive cooling technologies, shifting towards the use of non-energy intensive strategies to reach thermal comfort, and improved use of cooling through more efficient technologies and individual solutions when appropriate.

In terms of individual solutions, people in different geographies have traditionally had different techniques to subjectively cope with heat and reach thermal comfort (Mazzone and Khosla, 2021). For example, it has been found that shifting diets to spicy and hot meals can help individuals to transpire and lose body heat quicker in certain geographies (Liu et al., 2021). On the other hand, techniques such as showering in cold water, the use of wet flannels and consuming chilled drinks, all help individuals

mitigate extreme heat (Hendel et al., 2017).

Consumer awareness and behaviour can also improve cooling circularity. For example, by utilising mechanical alternatives only when none of the individual and passive solutions are sufficient and not overstressing their energy use (e.g., setting ACs to cool rooms at higher temperatures and only when occupied (Ross and Cheah, 2017)). Increased consumers awareness on the benefits of remanufactured cooling appliances can also encourage purchase attitudes to more circular solutions (Muranko et al., 2019a). In another example, Refrigerated Display Cabinets (RDCs) (which are used to stock and display chilled, frozen food and beverages in the retail sector (Muranko et al., 2019a)) can help educate consumers and influence the decision to purchase this type of remanufactured products. The consumer behaviour interventions can be useful as marketing campaigns, and as guideline for governments' regulations (Muranko et al., 2019b).

#### 4.2. How build cooling is built – cooling production networks

The right-hand side of the framework (Fig. 5) showcases the phases of active cooling production networks and their actors. This part of the framework is now analysed while highlighting key intervention points in the production and supply of cooling equipment that would considerably change its circularity. The section is addressed by grouping into four parts: design and production, use and energy efficiency, end-of-life and GWP control (including refrigerants) and actors. It highlights the importance of addressing both material consumption and embodied carbon emissions throughout the entire product lifecycle.

##### 4.2.1. Design and production

From a circular economy point of view, it is key to rethink how products and their manufacturing processes are designed. Particularly, to make it easier to disassemble equipment and to recover their materials once they reach their end-of-life. For this, concepts of the well-recognised Cradle-to-Cradle (C2C) approach (McDonough and Braungart, 2003) can be applied. This comprehensive and systemic thinking to the production of cooling appliances can result in designing them to be easier and more circular to handle when a problem arises in the next stages of their use.

Refrigeration equipment can be designed to extend its useable life (Bakker et al., 2014) but also refrigerant gases, insulation materials, precious metals, rare-earth materials and plastics used in the manufacturing process can be redesigned to minimise their virgin extraction (Wagner et al., 2019). Some trade-offs to be considered are between designing cooling units to have a longer useable life and their energy efficiency being reduced over time. A related example was reported when increasing the price of AC units in Japan (Nishijima et al., 2020) which led to an expected decrease of sales and a correlated decrease of material consumption; however, it results in an increase of GHG emissions as users extend the durability of the product which becomes less energy efficient over time.

Distribution is a key aspect following production. It intersects with many aspects of the cold supply chain studies (Section 5.1). Logistics is a major components of distribution and some noteworthy studies are: the use of "Internet+" to improve the real-time management of agricultural products in cold chains (Huang et al., 2020); the selection of best delivery route of frozen food aiming to minimise fuel consumption for both transportation and refrigeration (Meneghetti and Ceschia, 2020); and to best select logistic third party providers with automation processes to make them more competitive (Singh et al., 2018).

Optimising production has been a trending research topic for cooling appliances (Meneghetti and Monti, 2015; Nujoom et al., 2018; Yang et al., 2012). As new and more efficient technologies are introduced into the market, consumers replace them more often. To model the potential to create a closed-loop supply chain (i.e., they used parameters such as modularity, reparability and recyclability), the design can consider both the structure of refrigerators and their logistic network (Krikke et al.,

2003). In this sense, designing for modularity means to build refrigerators with detachable modules that are easier to reuse, recycle and remanufacture as a paramount circular strategy (Kremer et al., 2013).

##### 4.2.2. Use (or operational stage)

The operational cooling phase is found in research covering cooling in buildings and for cold chains of food and vaccines. Efficiency of technologies is particularly important in this stage to minimise GHG emissions. It is of major importance to explore the environmental benefits of extending the operational lifetime of such energy intensive products, like ACs. Deeper examination of efficiencies will hence enable the analysis of trade-offs between maintaining an old unit (potentially less efficient) versus replacing it with a new one (Iraldo et al., 2017).

Buildings are key places that require HVAC, while having important carbon emissions contributions with 30% of global GHG emissions coming from the building sector (Intergovernmental Panel on Climate Change, 2018). There is research attempting to estimate interior temperature in buildings using data-driven multi-step approach and data from weather, interior temperature and calendar seasons (Villa and Sassanelli, 2020). Energy conservation in buildings is thus critical for circularity. For residential buildings, one study in Sichuan, China showed that the peak summer power demand for the AC in households can be satisfied with photovoltaic cell generators and a cold storage tank (Zheng et al., 2017). In addition, pairing ACs and energy storage in batteries during the summer or largest sunlight hours has been shown to meet increasing residential cooling demand in Poland (Masiukiewicz, 2017).

Supermarkets are also an interesting case which cover both needs for cooling buildings and providing food through refrigeration as part of cold chain. In the UK alone, the supermarkets energy use accounts for 3.5% of the total UK energy consumption (Mylona et al., 2018). Literature found for supermarkets includes: active cooling and night ventilation coupled to reduce supermarket energy use (Mylona et al., 2018); the environmental impact of storing food in retailers (supermarkets) and perishable distribution centres (Burek and Nutter, 2020); case studies to measure the energy performance of the meat supply chain (Fattahi et al., 2013), and; viewing supermarkets as a network to make frozen food transport more energy-efficient and address the refrigerated routing problem (Meneghetti and Ceschia, 2020).

Some industries, such as the steel and cement manufacturing, require large amounts of heating and cooling to operate (Boldyryev et al., 2016). Research of minimum temperature differences between cement production streams is nascent, as it presents a potential synergy to embrace by heating and cooling central district systems, an Industrial Symbiosis pillar of the circular economy at the meso scale (Boldyryev and Varbanov, 2015).

##### 4.2.3. End-of-life (including GWP control)

Waste Electrical and Electronic Equipment (WEEE) from cooling and freezing appliances can be optimally recycled for its materials and when recycling is not possible, alternative energy recovery could be adopted (Golsteijn and Valencia Martinez, 2017). If re-using or recycling the whole refrigeration equipment is not possible, it is important that the CFC and HFC gases used in them be destroyed properly to avoid their release in the atmosphere (Dehoust and Schüler, 2010). An unexpected link was found in the literature between end-of-life cooling equipment and the construction sector. Specifically, the recovery of polyurethane foam panels inside refrigerator chambers can be recycled as insulation construction material in buildings (Briones-Llorente et al., 2020).

Problems of cooling waste landfill and fly-tipping have not yet been addressed in the peer-reviewed literature. There is no assessment of dumping old cooling and inefficient technologies from developed to less developed countries either. Although there is some work on the illegal trade of WEEE between countries, it is not disaggregated and does not present figures on cooling appliances specifically (Efthymiou et al., 2016). Thus, for appropriate handling of appliances at their end-of-life,

it is critical that safe and planned WEEE collection is carried out. For such, an example by (John et al., 2018) modelled input variations of materials, using a used refrigerator recovery network with different options such as product remanufacturing, repair of components and recycling of materials. It is beneficial to collect, recycle and dispose of refrigeration appliances, including the refrigerants and precious and rare metals (Baxter et al., 2016). Regulatory environmental bodies can help with this if laws are enforced as necessary.

Also, recovering trace components such as plastics (Wagner et al., 2019) and metals from cooling appliances and other WEEE brings environmental and potentially, financial benefits. This is especially the case for rare metals found in circuit boards for ACs as virgin material extraction is technically difficult (Baxter et al., 2016). This last stage is critical so that active cooling waste is handled appropriately at its end-of-life.

Refrigerants contained inside vapour-compressor technologies are a major threat if not managed carefully. Many refrigerant gases currently in use have a significant climate detrimental impact (high GWP). International agreements such as the Kigali Amendment aim to reduce and gradually phase-out the use of f-gases used as refrigerants (K-CEP, 2019b). Studies around these include: (Golsteijn and Valencia Martinez, 2017) who described the avoided emissions after appropriate removal and destruction of HFCs in cooling and freezing appliances; (Dehoust and Schüller, 2010) who were pioneers in studying the life cycle of treatment and recycling of refrigeration equipment containing CFCs and HFCs; (Wang et al., 2019) who concluded that current natural refrigerant-based systems can only be a suitable replacement of aging and obsolescence approaching systems; and (John et al., 2018) who argue that the extremely complicated recycling of polyurethane is due to the presence of CFC gases in them which contribute to the ozone layer hole and global warming.

Just as there is a gap in the literature on the topic of quantifying the waste from cooling appliances, there is currently no peer-reviewed study that discusses HFC banks worldwide (e.g., landfills with AC waste). There has been important work on the quantification of CFC banks to minimise the impact on the ozone layer (Lickley et al., 2020). However, as HFC banks are expected to increase exponentially their assessment is urgent, especially if they cannot be recovered and recycled and need to be safely thermally destroyed (The Green Cooling Initiative, 2020). This is another example of the risks of not researching cooling problems systematically; and it makes it that much more challenging to capture these gases at appliances' end-of-life - addressing one issue but creating another for the future.

#### 4.2.4. Actors

The final part of the GPN framework are actors that underpin and enable transition of cooling towards a circular economy. They are embedded within the previous stages of GPN. Economic actors correspond to those which may profit or have investment (time or money), usually the firms involved in the value creation process (e.g., manufacturers, retailers, designers, installers, service providers and waste managers). There exist a few studies around these practitioners, for example, the product data for a low-carbon supply chain of the main manufacturer Carrier-Toshiba (Jaegler and Burlat, 2012), and the impact on retail prices variability on the bullwhip effect involving the MIDEA manufacturer and two of their retailers (Ma and Bao, 2017).

Non-economic actors are usually the state, international organisations, labour groups, consumers and civil society organisations (Yeung and Coe, 2015). Studies involving these are still scarce but the organisations actively working in cooling, for example, in the healthcare sector, Gavi and Covax are active organisations participating in the vaccine logistics (Azimi et al., 2017) and transport of medicines (Lowe et al., 2020). However, they can influence the circular development of the GPN through their external work. For example, the Environmental Investigation Agency (EIA) is a consistent actor studying the life cycle cost-benefit analysis of replacing refrigerants (Wang et al., 2019),

reporting the invisible climate threat of HFC leakages from the cold chains in supermarkets (EIA, 2021b), and uncovering the HFCs black market that emerged from the EU's f-gases ban in 2016 (EIA, 2021c).

## 5. Framework examples in active cooling towards circularity

This section applies the systemic framework to three case studies that contribute towards circularity for cooling. The linkages discussed below and presented in the diagrams are not exhaustive but rather examples of the interactions between nodes of the framework. The structure of the discussion for each example follows a brief description of the challenge, key current knowledge in the reviewed literature, and research gaps.

### 5.1. Cold chains

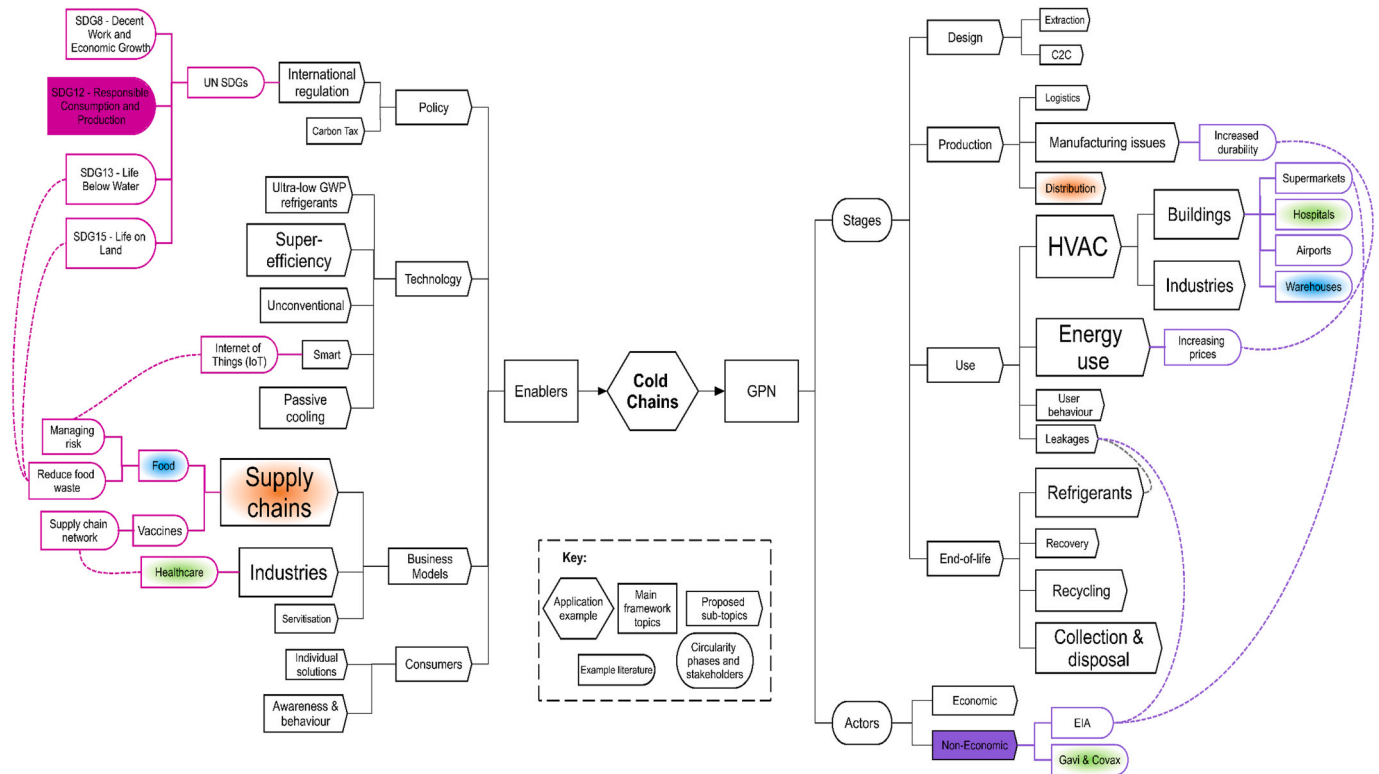
The most commonly known cold chains are the vaccine, medicine and food cold supply chains (Fig. 7). As expected, there is an important overlap between cold chains and the activities/uses phase in the GPN (Section 4.2.2).

The framework points to important cooling services where there is a considerable amount of work across multiple disciplines: transportation of vaccines and medicines (Lowe et al., 2020). These are paramount for example to Gavi, the Vaccine Alliance, to provide efficient, sustainable vaccine supply chain equipment where it is most needed in eligible low-income countries (Azimi et al., 2017).

There is vast literature on food supply chains. Some examples are in storage of food to prevent mass losses (Heard and Miller, 2019), the initial refrigeration and packaging of post-harvest fruit (Boschiero et al., 2019), and affordable storage technologies for small farmers (Ambuko et al., 2018). Also there is great emphasis on reducing food waste (Burek and Nutter, 2020) and agricultural related studies that improve the environmental performance of techniques such as controlling temperature and humidity (Fabbri et al., 2018). The cold supply chain network management is a pillar in cooling production (Saif and Elhedhli, 2016), and managing its risks (Tsang et al., 2018) overlaps with the distribution and uses stages of the cooling GPN.

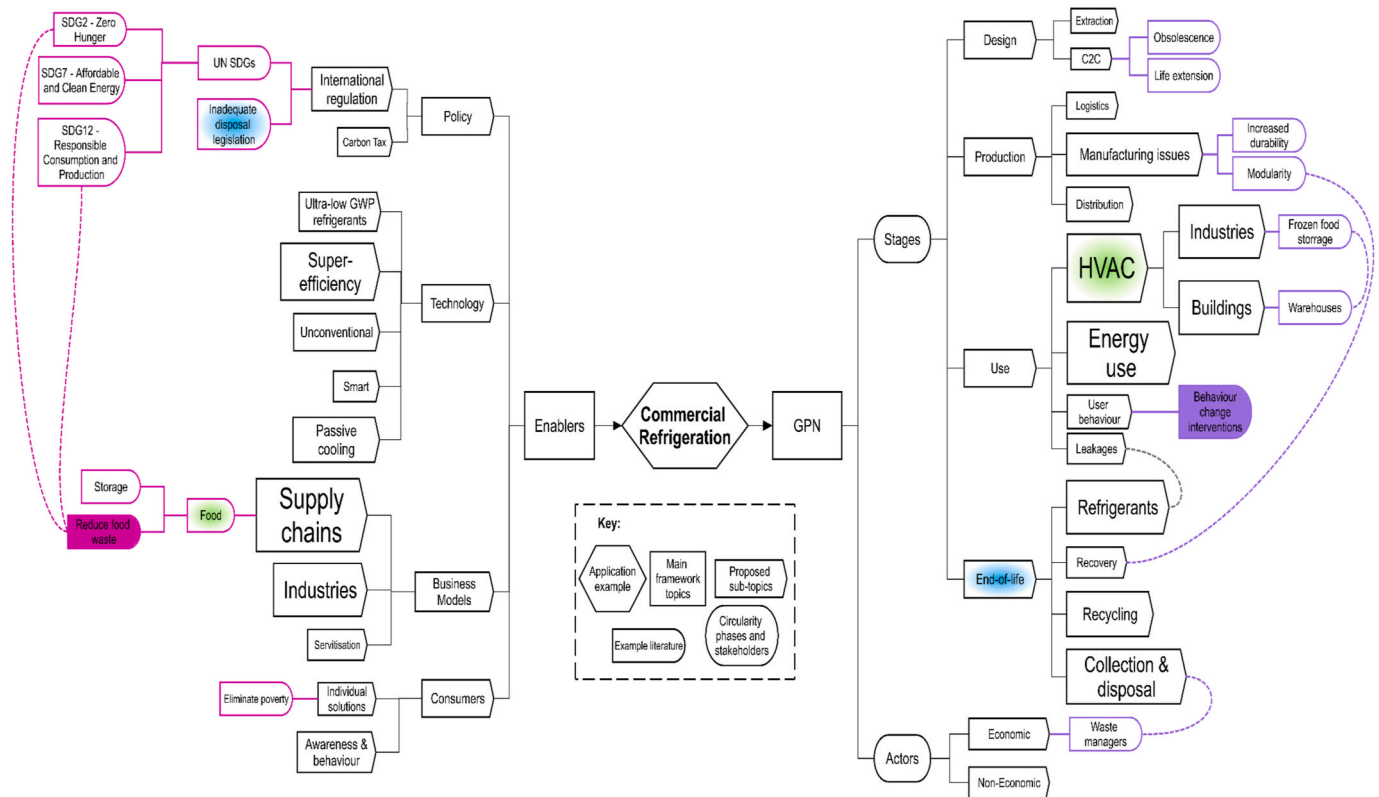
One underpinning challenge for all the applications, however, is obsolescence when fast advancing technologies are released often. In terms of improving cold chains performance, they are usually hampered by the high use of obsolete equipment and chains which fail to deliver the efficiency benefits from more recent designs (Ashok et al., 2017). Designing equipment using natural refrigerants, was found to be a suitable replacement only to aging systems that are approaching obsolescence (Wang et al., 2019).

With regards to research needs, the main trade-offs of food cold chains are still not well understood. In other words, on the one hand the capacity to minimise food losses and on the other the increasing materials and energy use, and generation of GHG emissions. Heard and Miller (2019) concluded that GHG emissions of cold chains in sub-Saharan Africa are greater than the food loss related emissions, but (Hu et al., 2019) found that GHG savings from avoided food loss outweigh the footprint of the extra energy required to cool the food in China and the US. These opposing findings suggest that to reach circularity for food supply chains much work is still needed that considers the context, in other words, the design of the cold chain, source of electricity generation, and the food to be cooled. Finally, detailed and comprehensive models, in which external risks are considered (e.g., natural disaster risk factors) are required for effective organ transplant supply chains (Aghazadeh et al., 2018). As for the food supply chain, the Environmental Investigation Agency (EIA) is a consistent actor in the studies about life cycle cost-benefit analysis of replacing refrigerants in supermarkets (Wang et al., 2019), as more research is needed despite recently having released a report uncovering the invisible climate threat of HFC leakages from the cold chains in supermarkets (EIA, 2021b).



**Fig. 7.** Systemic circular cooling production networks framework applied to cold chains

The green, blue and orange shaded nodes are example connections of both sides of the framework. The purple and pink nodes are explained in the main text of this application.



**Fig. 8.** Systemic circular cooling production networks framework applied to commercial refrigeration

The green and blue shaded nodes are example connections of both sides of the framework. The purple and pink nodes are explained in the main text of this application.



## 5.2. Commercial refrigeration

This application of the framework considers retail refrigerators, display cabinets and freezing appliances used to store food for commercial purposes. Even though it was not a major result in the topic modelling (Fig. 4), the authors decided to develop an application of the framework as it is an important area of cooling with an evident lack of discussion in the reviewed literature. Fig. 8 showcases the nodes related to commercial refrigeration and the links between them.

Herein some examples of key knowledge within the GPN and circularity literatures, these represent the right-hand side of the framework. The most common use of commercial refrigeration is in the food retailing and supermarket sectors. To make frozen food storage greener (Meneghetti and Monti, 2015), designs need to integrate rooftop photovoltaics to generate electricity in warehouses (Meneghetti et al., 2018) to minimise carbon emissions. Designing to extend the lifecycle of cooling appliances results in increased durability but risks the products to reach obsolescence (and inefficiency) in the longer term (Iraldo et al., 2017).

Currently, the most used refrigerant for commercial refrigeration in developed countries is R-410a. If all R-410a were converted to R-32 by 2030 it would be equivalent to reducing CO<sub>2</sub> by approximately 800 million tons (19%). R-32 is receiving much attention and it is expected to be a next generation of refrigerants (Chen et al., 2015; Fang et al., 2018). It holds the potential to reduce electricity demand, easy recyclability and one-third lower GWP compared to R-410a. A number of major manufacturers (Daikin, 2021; Mitsubishi, 2017) are at the forefront of implementing its use. However, quantifying the true benefits of the transition between refrigerants is under critique as the metric of CO<sub>2</sub>eq may not be suitable (Lynch et al., 2020). Debates around the use of GWP with 100 year time horizon and its CO<sub>2</sub> emission-equivalent can miss-represent many short-lived HFCs (Lynch et al., 2020).

In line with circularity principles to avoid leakages from cooling, it is important to track and control leakage. For example, in tunnels in Switzerland leak data from road traffic vehicle ACs is collected (Stemmler et al., 2004); and in cold chain models an average HFC gas leakage is considered for shipping a product between a production plant and a warehouse (Saif and Elhedhli, 2016).

Natural refrigerants are increasingly being used as an alternative to phase-out f-gases. Some include ammonia and hydrocarbons (propane, isobutane and propylene) (Blumberg et al., 2019; Dehoust and Schüller, 2010). Refrigeration is also an important contributor to the GWP impacts from the ready-made meal industry. Ammonia use in commercial refrigeration systems in the US is a mature technology (Burek and Nutter, 2018). However it is not compatible with copper pipes and it is toxic in high concentrations and its manufacturing generates high carbon emissions (Schauburger et al., 2018). More research is needed to fully understand its broader impact on its global warming.

With regards to the research gaps in commercial refrigeration, more research is also needed on the contribution towards net-zero via replacing refrigerants, especially as the GWP and the new resources required to build more efficient-naturally refrigerated appliances still outweighs the amount of energy consumed by ageing refrigeration appliances (Wang et al., 2019). However, it remains of critical importance to handle refrigerator waste; in other words, to prevent leaks and the effective recovery of refrigerants, as it is by far the most important factor of GWP of the whole production network (Baxter et al., 2016). Finding ways to fight illegal trade of HFCs cooling systems is necessary to manage such cooling waste appropriately at their end-of-life (EIA, 2019). Additional work is needed on the implementation of smart technologies for refrigeration to help improve energy efficiency and building performance (Nizetić et al., 2019). Finally, although there are no social studies relating to commercial cooling production networks, from studying potential behaviour change interventions to purchase remanufactured Refrigerated Display Cabinets (Muranko et al., 2019a), user behaviour would benefit from such research – for example, on the

inequalities and poverty dimensions of commercial cooling access.

## 5.3. Space air conditioning

This application of the framework focuses on AC for cooling rooms, rather than ACs embedded in transport (cars, buses, etc.) and commercial and industrial AC. Fig. 9 depicts the nodes of AC and their interactions. Although nodes are similar to those in the commercial refrigeration application, there are major differences which are discussed.

Key knowledge available on ACs is on their delivery of thermal comfort in a wide range of buildings, for example, hospitals (Briones-Llorente et al., 2020), airports (Gomri and Mebarki, 2016), offices (Shih and Wen, 2005), and education buildings (Ben-Nakhi and Mahmoud, 2017). All of these can be upgraded to smart buildings with technology that improves their energy performance and reduces their environmental footprint, such as smart homes (Costanzo et al., 2012; Cottone et al., 2015). At the same time, balancing cooling supply and demand is particularly challenging in buildings. Indoor air quality is also another issue to consider for AC systems. Energy conservation in buildings can help relieve some of the strains on ACs (Ben-Nakhi and Mahmoud, 2002). Likewise, if considering the potential contribution of ACs to circularity, refrigerants at the end-of-life stage of appliances is as critical as commercial refrigeration.

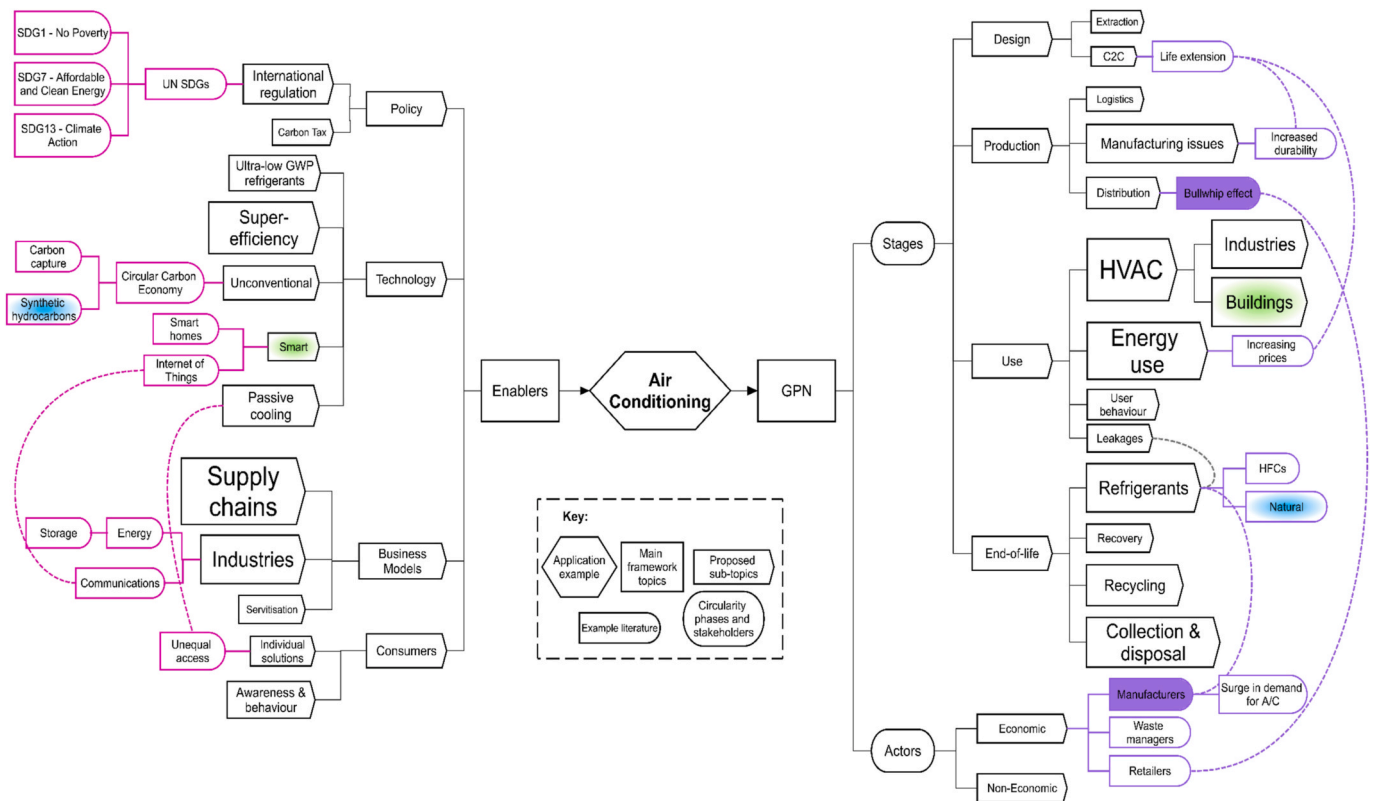
As seen in Fig. 9, the framework shows how one aspect of the production network is affected by multiple nodes. However, these are the areas where research needs are identified. For example, the deliberate decrease of price in AC appliances by manufacturers (MIDEA in alliance with Toshiba-Carrier) causes a large increase of sales, but also problems for retailers (GOME and SUNING) in terms of storage and satisfying the demand (Ma and Bao, 2017). It would be helpful to research why the industry is innovating slowly; if and why policies are failing to encourage more efficient AC use; and given that the market demands low cost technologies it is difficult to enter the sector by new competitors (RMI, 2018), while legislation on safe disposal is still under development (EIA, 2019).

## 6. Conclusions

This review paper developed a framework based on a systematic review of the literature on circular economy of cooling production networks. The framework helps to visualise the interrelationships between the GPN of active cooling and current viable solutions. Most importantly the framework sheds light on influencing the production and use of mechanical cooling as a system that is interconnected with many other less developed research areas, for example, cooling business models, social science studies and international regulations. The paper explored in depth three sub-sectors within this systemic cooling framework: cold chains, commercial refrigeration, and room AC.

Overall, the title and abstract analysis revealed that most of the publications focused on agricultural products (food) supply chains, postharvest, vaccine supply chains, and manufacturing (primarily steel and cars) supply chains. A smaller part of the publications focused on cold supply chain management – an area which overlaps with cooling GPNs in the user/service/activities phase. Knowledge gaps and the need for further research were detected in social impacts and interconnections, circular economy for cooling production networks, safe disposal and reuse of cooling appliances at their end-of-life stage.

The proposed framework can help understand and also shape the future of a circular economy for cooling. Contextual differences need to be considered in the adoption of circularity for cooling production networks, as major economies may vary their material use and GHG emissions for the different cooling sectors. For example, in developed countries with mild climates like the UK, the role of refrigeration (e.g., display cabinets) will likely be more urgent than the role of residential AC for circularity, as opposed to hot and high-income countries like



**Fig. 9.** Systemic circular cooling production networks framework applied to room air conditioning

The green and blue shaded nodes are example connections of both sides of the framework. The purple and pink nodes are explained in the main text of this application.

Singapore and the UAE, where all sectors of cooling are intensely required. Currently, the energy used by cooling technologies during their operational stage is by far the largest share of their carbon footprint reporting but shifting to cleaner solutions will make the components production and end-of-life stages more important for achieving circularity, especially as the f-gases used as refrigerants represent a large climate hazard.

This review was limited mainly to the intersection of the Global Production Networks (GPN), cooling and circular economy literatures. This proved to be a constrained number of publications ( $N = 69$ ) that resulted to be useful for the framework development, thus, it was necessary to draw upon high quality grey literature to complement the analysis. Despite a large amount of circular economy literature, studies that apply it to cooling are still largely missing. This highlights the need for more research that connects all stages of the cooling equipment (and refrigerants) entire lifecycle.

Further research avenues identified from this review include: 1) the impacts of policy and international regulation on the production of cooling, both in terms of efficiency and HFC gases; 2) the illegal trade of HFCs, dumping of less efficient and high-GWP appliances (especially developed to developing countries), and flawed disposal of cooling waste (fly-tipping and landfill); 3) the delivery of cooling through servitisation as it would help to understand the efficiency improvements, broader environmental and social benefits, and scalability of these new business models in the cooling sectors; and 4) pathways to support a circular production and use of cooling, such as the circular design for recoverability and end-user engagement and circular behaviours.

In spite of its multiple pressing sustainability issues, cooling research is still in its infancy and in fact its professional practice is developing at a

much faster rate. The systemic framework proposed in this paper showcases the extent of the systemic cooling issue and its connections across different aspects of society. As the paper shows, approaches to decarbonise cooling and reach circularity need to consider easily recyclable and ultra-low GWP refrigerants. Rethinking manufacturing and servitisation are both complementary efforts to achieve circularity for cooling. Such transition can be facilitated by the balanced efforts from policymakers, technology developers, innovative business model entrepreneurs and end-users. Also, to reduce the expected rise in energy demand more passive cooling and super-efficient appliances are a top priority. Further, international and national policy standards directly or indirectly around cooling and assessment tools and materials calculators can aid towards circular cooling production and use.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

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## Appendices.

### Appendix 1. Search strategy, terms, criteria and results for the systematic review

Research Topic: Circular Economy in Cooling Global Production Networks			
Row 1	Concept 1: "Circular Economy"	Concept 2: Cool* Refrig* Fridg* "Air cond*" Freez* Cold	Concept 3: "Global Production Network*" "Value chain*" "Global Commodity Chain*" "Global Value Chain*" "Supply chain*"
Row 2	Recycl* Reduc* Reus* Redesign* "end?of?life" 3Rs* "Waste management" Sustainab*		
Row 3	"circular economy" OR recycl* OR reduc* OR reus* OR redesign* OR "end?of?life" OR 3Rs* OR "waste management" OR sustainab*	cool* OR refrig* OR fridg* OR "air cond*" OR freez* OR cold	"global production network*" OR "value chain*" OR "global commodity chain*" OR "global value chain*" OR "supply chain*"
<b>Criteria of Search</b>			
Date:	03-Nov-21	03-Nov-21	03-Nov-21
Database:	IBSS	Web of Science	Scopus
Language:	English	English	English
Search in:	Anywhere except full text	Topic = Abstract, Title, Keywords	Abstract, Title, Keywords
Document type:	Peer-reviewed	Journal Articles	Article or Review
Years:	All dates	1900-present	All years
<b>Search Results – term combinations</b>			
Databases:	IBSS	Web of Science	Scopus
CE AND cool	198,749	138,021	184,386
CE AND GPN	26,945	18,938	22,277
cool AND GPN	1081	670	896
CE AND cool AND GPN	456	294	389

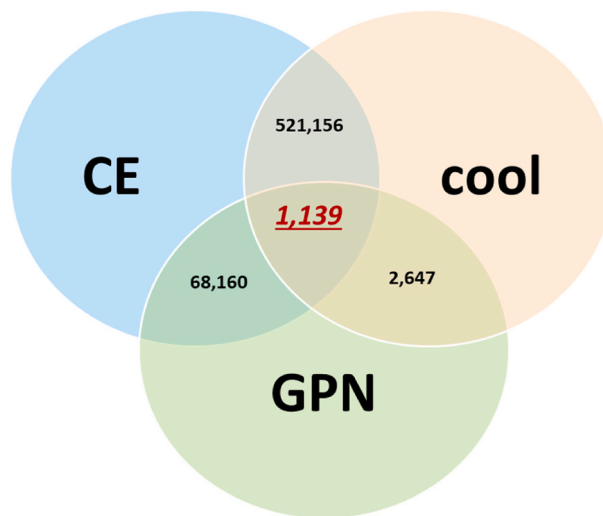


Fig. A1. Publications found for Circular Economy (CE), cooling (cool\*) and Global Production Network (GPN)

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