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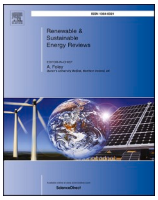

A comprehensive scouting of space cooling technologies in Europe: Key characteristics and development trends

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ABSTRACT

This paper presents a comprehensive taxonomy and assessment of existing and emerging space cooling technologies in Europe. The study aims to categorize 32 alternative space cooling technologies based on eight scouting parameters (physical energy form, basic working/operating principle, refrigerant or heat transfer medium, phase of the working fluid, specific physical process/device, type of space cooling technology, fuel type and technology readiness level) and evaluate their key characteristics and development trends. The increasing demand for space cooling in Europe necessitates a thorough understanding of these technologies and their potential for energy efficiency. The majority of space cooling demand in Europe is currently met by conventional vapour compression systems, while a small portion is covered by thermally-driven heat pumps. The study reveals that several alternative space cooling technologies show promise for energy-efficient cooling but are not yet competitive with vapour compression systems in terms of efficiency and cost in the short-term and medium-term. However, technologies such as membrane heat pumps, thermionic systems, thermotunnel systems, and evaporative liquid desiccant systems demonstrate cost-competitiveness and energy efficiency in specific applications. The findings highlight the need for further research and development to improve the efficiency, costs, and market competitiveness of alternative space cooling technologies. The study also emphasizes the importance of policy support and the urgency to reduce greenhouse gas emissions, which can drive the adoption and advancement of sustainable cooling solutions.

1. Introduction

The need for space cooling (SC) has a significant impact on overall electricity consumption since buildings account for about 40% of Europe's primary energy use [1,2]. It is estimated that air-conditioning systems in residential and commercial buildings account for about 45% of the total electricity consumption [3,4].

The primary energy consumption in the EU in 2018 was 1600 Mtoe/y, which is 5% more than the 2020 objective and 22% more than the 2030 target. The final energy consumption in 2018 was 3% and 22% higher than in 2020 and 2030, respectively [5–7]. The major contributor to primary energy consumption is the heating and cooling sector [8,9]. Space heating, SC, domestic hot water (DHW) and industrial heat and cold account for 50% of the primary energy consumption [10].

SC is defined as the process of cooling indoor air by removing heat from the air and providing buildings' occupants with thermal comfort [11], while process cooling (PC) refers to the removal of unwanted heat from processes (cooling a product, cooling a specific process or cooling a machine) to ensure the continuation of the process safely and reliably. There are various applications for SC in different sectors (tertiary and residential). Currently, SC is the building energy end-use with the highest rate of growth since 1990, with an almost tripled energy demand. This growth in SC consumption is due to different factors such as climate change, extreme heatwaves, urbanization and new building constructions with increased glazing surfaces [12–14].

Vapour compression (VC) air-conditioning systems account for about 99% of the market for SC technologies [8,15]. The thermally-driven heat pumps (TDHPs) supply the remaining 1% of the SC need in the EU market [16]. Therefore, the potential for significant energy savings is

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Abbreviations:

Centralized Air-Conditioners	CACs
Chlorofluorocarbon	CFC
Coefficient of Performance	COP
Domestic hot water	DHW
Energy Efficiency Ratio	EER
Global Warming Potential	GWP
Greenhouse gas	GHG
Heating, ventilation, and air-conditioning	HVAC
Hydrochlorofluorocarbon	HCFC
Hydrofluorocarbon	HFC
Ozone Depletion Potential	ODP
Photovoltaic	PV
Process cooling	PC
Room-Air Conditioners	RACs
Seasonal Energy Efficiency Ratio	SEER
Seasonal Performance Factor	SPF
Space cooling	SC
Technology Readiness Level	TRL
Thermally-driven heat pumps	TDHPs
Variable Refrigerant Flow	VRF
Vapour compression	VC

made attractive by performance upgrades to conventional VC systems [17]. Due to their low operating costs, low investment costs, and high efficiency, VC systems have taken the lead in the market. It has become vital to assess potential alternative SC technologies since halogenated alkanes, the most extensively utilized refrigerants in VC systems, contribute to climate change and Greenhouse Gas (GHG) emissions.

Following EU regulations, the main focus recently has been on increasing the efficiency of the systems and using refrigerants with low Global Warming Potential (GWP) to lessen the impact of air-conditioning systems on climate change. It is worthwhile to assess the most recent developments in alternative SC technologies and determine whether or not they are at a point where they can compete with the conventional VC systems, which are ranked by their Technology Readiness Level (TRL) [18,19]. The performance and physical principle of VC systems have been the subject of a very large number of studies on SC technologies (see, for instance [20–23]). On the other hand, several studies [23–26] have concentrated on alternatives (e.g. TDHPs).

The goal of the industry was to utilize refrigerants with no Ozone Depletion Potential (ODP) already about 30 years ago [27]. Therefore, Chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerant use was eliminated through the investigation of alternative cooling (SC and PC) systems in a study by Fischer et al. [28] in which they investigated ten alternative cooling systems. Due to this, another study by Brown et al. [15] used Fischer et al. [28] findings as the main "marker" to assess alternative cooling technologies. Goetzler et al. [29] evaluated the alternatives in the heating, ventilation, and air-conditioning (HVAC) industry in order to provide critical suggestions in response to the U.S. Department of Energy's (DOE) decision to reduce support for VC systems. In addition to that, Goetzler et al. [30] recommendations to the stakeholders and DOE on future research broadened the range of alternative technologies that potentially minimize commercial HVAC energy demand. A recent study by Goetzler et al. [31] assessed earlier HVAC research studies to take into account new and developing technologies.

The thermally-driven SC technologies from combined cooling, heating & power (CCHP) systems were also evaluated in previous studies. Deng et al. [32] described the CCHP's operating principles in depth, highlighting the benefits of desiccant cooling, adsorption, absorption refrigeration systems, and other technologies. Additionally, another study by Montagnino et al. [33] discussed solar cooling technologies, including small-scale and large-scale systems. According to the study, the photovoltaic (PV) system will help the VC systems maintain its lead in the market share due to the decrease in the cost of PV nowadays and also in the coming years. Another recent study by Elnagar et al. [23] found that thermally-driven cooling technologies have a unique advantage over conventional electricity-driven cooling systems. These technologies can be powered by different thermal energy sources, providing greater flexibility in terms of energy sources. Additionally, thermally-driven cooling systems typically require less electrical input, making them more resilient against power outages. This can be particularly advantageous in areas with unstable electricity grids or during times of widespread power outages. The low electrical input also makes thermally-driven cooling systems more sustainable and environmentally friendly.

According to a recent study by Pezzutto et al. [27], there will not be any alternative cooling technologies available between 2020 and 2030 in the EU market that can compete with VC systems. The study also presented a taxonomy of cooling systems (SC and PC).

1.1. Literature review

Various SC technologies that are already on the market as well as emerging technologies, are evaluated for this study through a comprehensive analysis of the literature. Additionally, a patent search over the previous ten years is included to find the most promising SC technologies, taking into account the International Patent Classification (IPC) codes "F24F (Air-conditioning, Air-humidification, Ventilation, Use of air currents for screening)", and "F25 (Refrigeration or cooling; combined heating and refrigeration systems; heat pump systems; manufacture or storage of ice; liquefaction or solidification of gases)" [34,35].

This paper investigates SC technologies using a number of studies as the main sources. In the 1990s, a study by Fischer et al. [28] discussed the chemical and technological alternatives to CFCs by 2000. Additionally, the analysis was expanded to consider how these substitutes might affect global warming, with a focus on HCFCs and hydrofluorocarbons (HFCs) as CFC alternatives. Technologies including thermoelastic heat pumps, evaporative cooling, Stirling cycle refrigerators, and Malone cycle refrigerators were covered by Fischer et al. [27].

Within the framework of the study by Fischer et al. [28], another study by Brown et al. [15] reviewed alternative cooling systems in 2014. The study discussed a number of technologies by outlining their physical working principles, present technological state, and market potential. The main goal of the study was to categorize cooling technologies according to their main source of energy, such as electrical, mechanical, chemical, magnetic acoustic, thermal, potential and "natural". Due to their high market maturity and expected high-performance potential, six technologies—thermoelectric, sorption, desiccant, magnetic, thermoacoustic, and transcritical CO_2 cycle—were discussed in this study. The study also evaluated various competing SC technologies and came to the conclusion that they would not be able to compete with VC technologies in the near future.

In 2014, Goetzler et al. [36] conducted another important study with the HVAC industry as the primary focus. The study identified sustainable alternatives to HVAC and VC technologies. The study gave an in-depth analysis of the different technologies and noted that the electrocaloric, critical-flow refrigeration and Bernoulli heat pump technologies were still in the early stages of research and development. The final technology list included magnetocaloric, thermoacoustic, thermoelastic, thermoelectric, thermotunneling, Vuilleumier heat pumps, sorption heat pumps, Brayton heat pumps, ejector heat pumps, duplex Stirling cycle, desiccant cooling systems, and membrane heat pumps, among others. The vortex-tube and pulse-tube cooling systems, which are more suited for PC applications [37], were not included in this study, which primarily focused on SC applications. The amount of energy saved per unit was estimated. Using the VC system as a baseline, a scorecard analysis was made.

Another study by Goetzler et al. [30] in 2017 led to updates and advancements in the Research and Development (R&D) of alternative cooling methods taken into account in the same study from 2014 [36]. The study investigated four categories of eighteen technologies, the first of which is "Technology Enhancements for Current Systems". The second category is referred to as "Alternative Gas-Fired Heat Pumps Technologies", and it more efficiently offers heating and cooling by mostly making use of natural gas and thermally activated heat pump cycles. The third group, known as "Alternative Electrically Driven Heat Pump Technologies," uses electricity as its primary energy source through the use of VC and non-VC systems to provide more efficient heating and cooling. The fourth category, "Alternative System Architecture," includes robotic devices, wearable comfort gadgets, and dynamic cooling garment technologies. This category intends to reduce HVAC system operating costs by enhancing building comfort.

Recently, Goetzler et al. [31] included recent HVAC technologies, appliances, refrigeration and water heating. The study divided the investigated technologies into five groups. The most relevant data for the current study was in the fifth group, named "Cross-Cutting", which includes materials and systems for thermal energy storage, VC with modulating capability, and non-vapour compression (NVC). It has been found that previous studies predict energy savings of 20% regarding the NVC technologies compared to the current VC technologies, which may offer more possibilities for use in the building sector.

VHK et al. [38] conducted a significant study in 2016. The study compared the market-available "best cooling technologies" with others that are non-available in the market. The study identified a number of non-commercial cooling technologies as being particularly promising, including magnetic refrigeration, Lorenz-Meutzner cycle refrigeration, Stirling cycle refrigeration, ejector cycle refrigeration, thermoacoustic refrigeration, and thermoelastic refrigeration.

Lastly, Pezzutto et al. [11,27] focused on the European market from 2020 to 2030. The study developed a taxonomy for cooling technologies (SC and PC). It has been found that membrane heat pumps, Reverse Brayton (Bell Coleman cycle), transcritical cycle, and absorption cooling are promising technologies and might compete with VC systems.

In terms of methodology, the literature review heavily relies on existing studies and patent searches to gather information about the different cooling technologies. However, a thorough review study is still required that focuses on the key characteristics of SC technologies. This paper focuses on technologies that are applicable to SC applications. However, there are a few parts of the text which refer both to space and process cooling.

First, the present study gives an overview of the conventional VC systems and their classification based on the generation and distribution systems as well as the major characteristics and costs. Secondly, the main focus of the study is to provide a taxonomy for all existing and emerging SC technologies following the previous research while taking into account new emerging technologies that have not been evaluated in previous studies. The SC technologies are grouped in this taxonomy according to the physical energy form, basic working/operating principle, refrigerant/heat transfer medium, phase of the working fluid, particular physical process/device, type of SC technology (active, passive, or both), fuel type and TRL. The study investigates 32 alternative SC technologies by describing their major technical characteristics, costs and development trends, as shown in Fig. 2.

The paper is organized as follows. The paper is organized as follows. The methodology for this review, including the primary scientific sources, is presented in Section 2. The results are presented in section 3, (section 3.1) presents the complete SC taxonomy, (section 3.2) presents the conventional VC systems and (section 3.3) presents the alternative SC technologies. Section 4 discusses the key findings and recommendations of the study, the strength and limitations, as well as the implication on practice and future research. Finally, section 5 concludes the recommendations and the implications on the practice of the study.

2. Review methodology

A thorough analysis of multiple sources was the base of an effective methodology that was used to create a comprehensive taxonomy of alternative SC technologies. The studies stated above [13,15,28,30,31,36,38] are the main resources for the technologies scouting phase. Only the most recent sources were used in this study. Since the effort intends to provide a state-of-the-art cooling technology, this is mostly owing to enhanced information and data reliability. The study aims to evaluate the current status of alternative SC technologies and their development trends.

The primary energy input was the key parameter used to categorize cooling technologies in an earlier study by Brown et al. [15]. Additionally, other taxonomies could be developed by incorporating additional parameters, such as the operating temperature range (low, medium, or high) and operational fluid phases (gaseous, liquid, solid or multiphase). To develop the cooling taxonomy, a recent study by Pezzutto et al. [27] categorized each cooling technology according to the physical form of energy input (electrical, mechanical, chemical, magnetic acoustic, thermal, potential and "natural"). The study also included system efficiency, applications and TRL.

In this paper, the scouting parameters used to categorize the alternative SC technologies are shown in Fig. 1. This study focuses only on SC technologies and categorizes them based on eight parameters as follows: physical energy form, basic working/operating principle, refrigerant or heat transfer medium, phase of the working fluid, specific physical process/device, type of SC technology (active, passive or both), fuel (fuel type used to drive the SC technology, the possibility to be driven by renewable energy source) and TRL.

The eight parameters are explained as follows: there are seven types

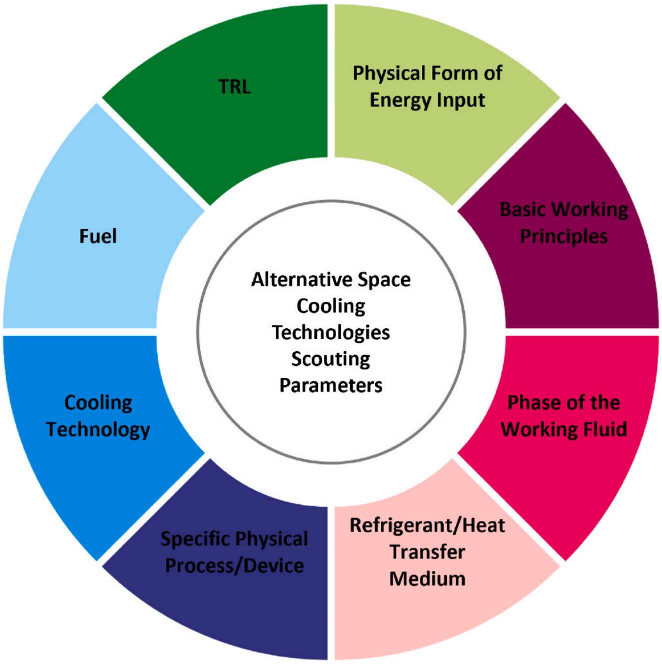

Fig. 1. Alternative space cooling technologies scouting parameters.

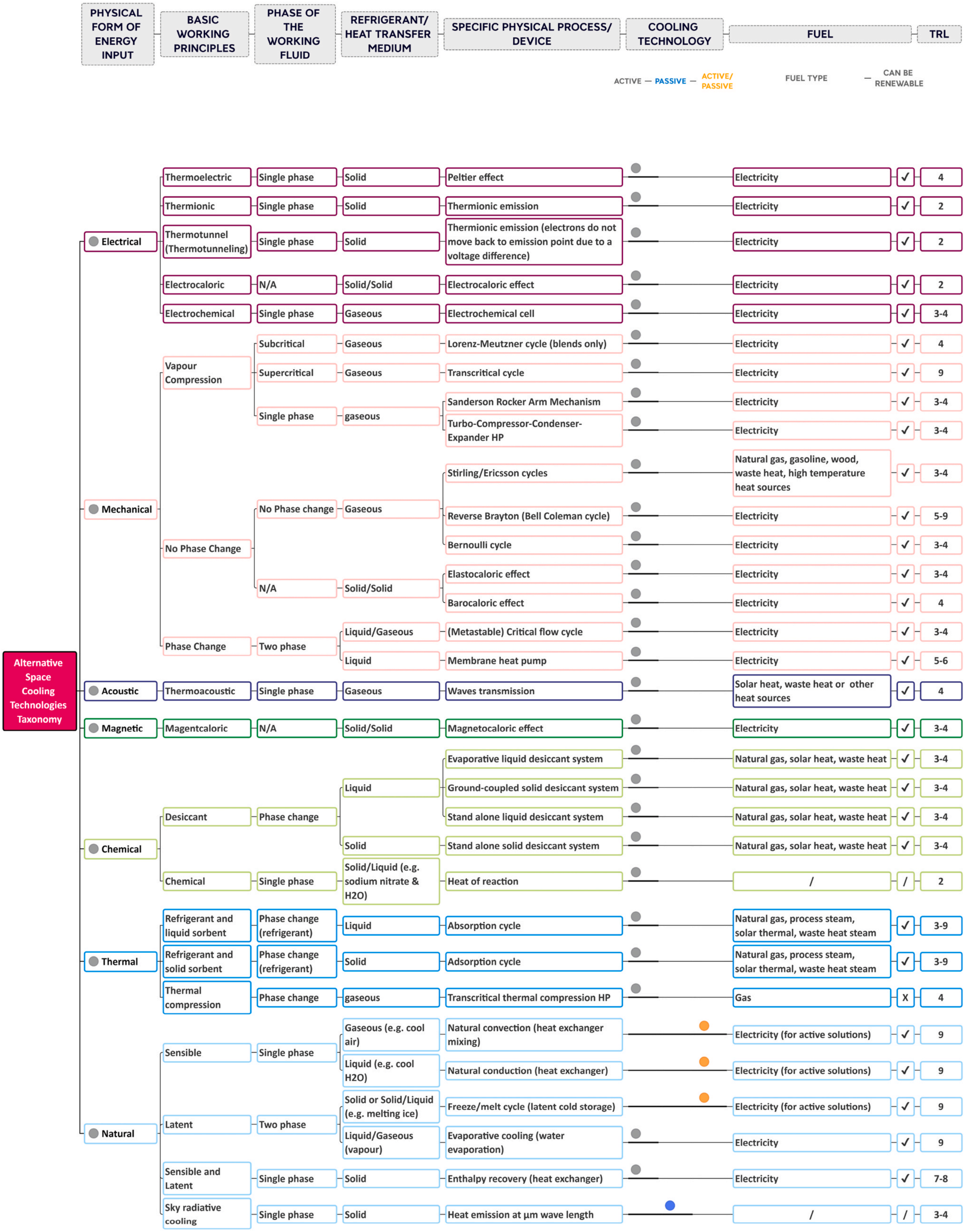

Fig. 2. Cooling technologies taxonomy.

Table 1
Space cooling technologies list.

The physical form of energy input	SC Technologies
Electrical	Peltier effect, Thermionic effect, thermotunneling, electrocaloric effect, electrochemical effect
Mechanical	Reverse Rankine, Transcritical cycle, Turbo-Compressor-Condenser-Expander heat pump, Lorenz-Meutzner Cycle, Sanderson Rocker Arm, Stirling/Ericsson cycles, reverse Brayton (Bell Coleman cycle), Bernoulli cycle, elastocaloric effect, barocaloric effect, (Metastable) critical flow cycle, membrane heat pump
Acoustic	Thermoacoustic (waves transmission)
Magnetic	Magnetocaloric
Chemical	Desiccant systems, heat of reaction (endothermic)
Thermal	Absorption and adsorption cycles, transcritical thermal compression heat pump
“Natural”	Natural conduction (heat exchanger), natural convection (heat exchanger mixing), evaporative cooling (water evaporation), sky radiative cooling, freeze/melt cycle (latent cold storage) and enthalpy recovery (heat exchanger)

of energy in the physical form of energy input (electrical, mechanical, chemical, magnetic acoustic, thermal, potential and “natural”). The state of the working fluid determines whether it is in a single-phase, two-phase, no-phase change, subcritical, or supercritical condition. The working fluid’s phase is irrelevant for caloric systems since there is not a working fluid in the vast majority of them; instead, the fluid just acts as a heat carrier and doesn’t undergo any phase change. The refrigerant/heat transfer medium explains the medium’s phase (solid, gaseous liquid, or multiphase). The specific physical process/device refers to the used device in the cooling technology, which is specifically designed to remove heat from an object, material or environment to achieve a desired cooling effect. According to the area of intervention, the type of SC technology parameter shows the type of SC technology (active, passive, or both). Additionally, the parameter “fuel” is used to denote the sort of fuel utilized to power SC appliances (in particular, renewable or not). TRL, the final parameter in the taxonomy, is used to describe the life stages of technologies in the development process, from the initial concept through the existing application in the market.

TRL is a system for assessing technology maturity, *“TRL is based on a scale from 1 to 9, with 9 being the most advanced technology”*, according to the Guide for Technology Readiness Assessment of the U.S. Department of Energy [19].

The TRL is defined by the H2020 EU research program, resulting in the list below [18].

- *“TRL 1: Observing and reporting of basic principles.*
- *TRL 2: Formulation of technology concept and/or application.*
- *TRL 3: Proof-of-concept through critical function and/or characteristic analysis and experimentation.*
- *TRL 4: Validation of component and/or breadboard in a laboratory environment.*
- *TRL 5: Validation of component and/or breadboard in a relevant environment.*
- *TRL 6: Demonstration of system/subsystem model or prototype in a relevant environment.*
- *TRL 7: Demonstration of system prototype in an operational environment.*
- *TRL 8: Completion and qualification of the actual system through testing and demonstration.*
- *TRL 9: Proven success of actual system through mission operations.”*

The cooling technologies in this study require TRL levels of 5–9 to be commercially viable. A TRL level of 8–9 would also be ideal for systems that are already on the market.

Furthermore, the study describes the major characteristics of the SC technologies – among others: on-site and/or off-site sources, cold sources and reference sink temperatures, resource usage type, such as water consumption or refrigerant leaks, efficiency levels, costs and development trends.

3. Space cooling technologies

3.1. Taxonomy of space cooling technologies

This study only focuses on SC technologies and extends the previous studies by adding various parameters to categorize the technologies in Fig. 2, which shows the final taxonomy of the alternative SC technologies. In addition to that, the study provides a comparison between the alternative SC technologies based on their TRL level to show their willingness to compete in the market with the conventional VC systems. Therefore, section 3.2 gives an overview of the conventional VC systems, including their major characteristics, costs and development trends. Section 3.3 explains the alternative SC systems by including new technologies that have not been studied before by Brown et al. [15] and Pezzutto et al. [27], such as the elastocaloric effect and barocaloric effect. Finally, the taxonomy results in the technologies introduced in Table 1.

Section 3.3 also represents the major characteristics of the alternative SC technologies, which include fuel type used, cold source, reference sink temperature, resource usage, range of available size per type of the system, and efficiency level (Energy Efficiency Ratio – EER, Seasonal Energy Efficiency Ratio – SEER, Coefficient of performance – COP, Seasonal Performance Factor – SPF, etc.). For VC systems, the efficiency is typically measured according to industry standards such as AHRI 210/240 or ISO 5151 [39,40]. For alternative SC technologies, the efficiency can be measured efficiency based on the boundary condition of each system or anticipated efficiency based on the heat input required to drive the cooling cycle. In addition to that, development trends, including the TRL, are also discussed for each technology.

3.2. Conventional vapour compression systems

Among various SC technologies, conventional VC systems are now dominating the market for a number of reasons as follows: their scalability, low cost, relatively compact size, use of non-flammable and non-toxic refrigerants and high efficiency [41]. Nearly 99% of Europe’s SC demands are met by VC systems [8,15]. VC technologies have a TRL level of up to 9 since they are already actual systems in the different sectors of the market. It must be stressed that flammable fluids are more and more used, among others, due to efforts to limit the refrigerant charge.

As shown in Fig. 3, conventional VC air-conditioning systems are split into two categories according to the generation of systems that produce cold air and chilled water, as well as the distribution to centralized systems and decentralized systems. Centralized air-conditioners (CACs) and decentralized systems, which are known as room-air-conditioners (RACs), are the two main types of VC air-conditioning systems. CACs refer to systems with a single base location which is used to cool the whole building, while RACs are used to cool a single space. RACs come in four different types (split systems, multi-split systems, single duct systems, and packaged units), while there are three different types of CACs (Variable Refrigerant Flow - VRF systems, rooftop systems, and chillers).

The physical principle of the different types of conventional VC systems is explained in this section. Although they are also used in the tertiary, particularly in offices, RACs are most frequently used in the residential sector. CACs are also used in households but mostly in the tertiary sector [42].

3.2.1. Split systems

Split air-conditioning refers to a reversible air source heat pump with one indoor unit and one outdoor unit. The indoor unit is located inside

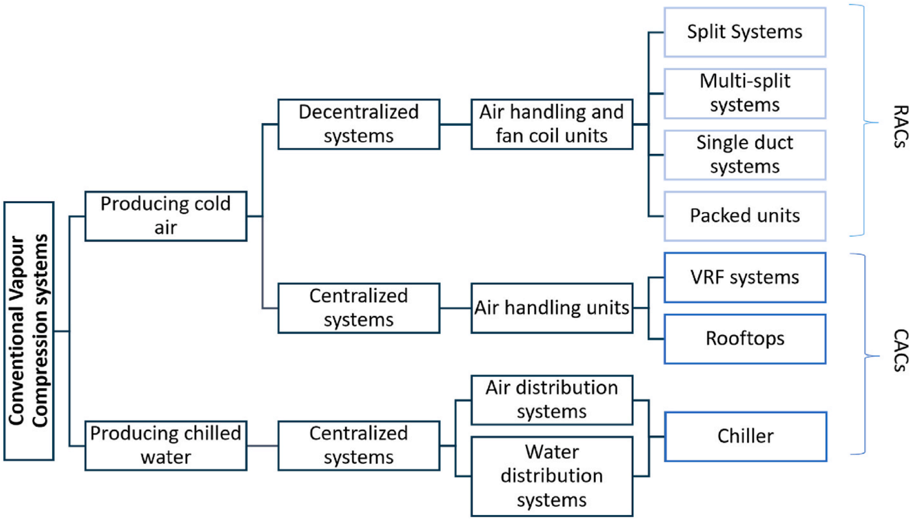

Fig. 3. Classification of conventional vapour compression systems.

the building and has an air filter and evaporator coil. The condensing unit (outdoor unit) is located outside the building and has a compressor and condenser coils [43].

3.2.2. Multi-split systems

Multi-split systems are air-conditioning systems that have several indoor units as well as one outdoor unit. The total number of indoor units determines the maximum cooling capacity of a multi-split system.

3.2.3. Packaged units

A packaged air-conditioning unit is also known as a unitary air-conditioning system. A standard packaged air-conditioning system's components are all housed in a single casing and include a condenser, an evaporator, a compressor and an expansion valve. Packaged units are also referred to as "through-the-wall-air conditioners" because of the way they are mounted in residential structures [42,44].

3.2.4. Portable unit systems

Portable unit systems are also known as moveable unit systems, where all the system's parts are contained in the same cabinet and designed to be easily carried inside the building. There is relatively little installation needed for the system. The condenser, which circulates the refrigerant (the cooling medium), draws in the indoor air to be cooled. The refrigerant is then rejected outside through a duct.

3.2.5. Rooftop units

Rooftop units, often referred to as outdoor packed units, are typically available in large capacities located on the building's roof and use ducts to cool the buildings. In order to fulfil the requirements of medium-to-large-sized buildings, rooftop systems are offered in a variety of capacities.

3.2.6. Chillers

Chillers are large air-conditioning systems that produce chilled water and distribute it to cooling coils in air handling units that cool the indoor air and terminal units through a cooling network of heat exchangers and pipes. Three distinct types of chillers are available (air-cooled, water-cooled and evaporative-cooled).

3.2.7. Variable Refrigerant Flow (VRF) systems

VRF system, sometimes referred to as a VRV (variable refrigerant volume) system, consists of a single outdoor condensing unit that distributes refrigerant to several indoor units. VRF systems typically have more cooling capacity than conventional split systems.

The major characteristics (fuel type used, cold source, reference sink temperature, resource usage, range of available size per type of the system, and efficiency level), costs and development trends of the conventional VC systems are explained as follows.

- **Fuel type used**: Electricity
- **Cold source**: air or water
- **Reference sink temperature**: an inlet temperature of 27–35 °C for air-to-air systems, 35 °C for air-to-water systems, and 30 °C for water-to-water [45].
- **Resource usage**: refrigerant
- **Range of capacity installed**: for conventional VC technologies, the range of capacity installed varies mainly between RACs and CACs. The range goes from about 3 to more than 150 kW [13].
- **Energy efficiency**: energy efficiency (SEER) of VC technologies varies among 2–5 (for currently installed technologies in Europe). The mean SEER of VC technologies is estimated to be 2.7 for portable appliances and 5.7 for split systems [46], and around 4–4.5 on average in the EU [47].
- **Costs (investment, installation, operation and maintenance):** Purchasing prices for RACs and CACs are shown in Table 2 [42]. As a result, the average cost of purchasing RAC units is approximately 1050€/unit, while the average cost of purchasing a CAC system is approximately 43283€/unit. The mean installation costs and the Operation and Maintenance (O&M) costs for RACs and CACs are shown in Table 3 and Table 4, respectively. The results show that the average installation cost for RACs is 230€/kW, and for CACs is approximately 300 €/kW. The average O&M cost for split systems is 55€/unit/year, while the average O&M cost for CACs is approximately 1850 55€/unit/year. The indicated O&M costs don't include energy costs.
- **Typical applications**: VC is the dominant cooling technology for SC as well as PC applications. Nearly 99% of Europe's cooling demand is covered by VC technologies [13,29,49,48].
- **Development trends**: there are a number of R&D efforts for VC technologies carried out by public and private institutions: among others, a number of the most important ones are: energy efficiency increase, deployment of environmentally friendly refrigerants, miniaturized mechanical VC refrigeration systems, small-scale cooling devices, etc. [13,29,42,49,48].

Table 2

Purchasing prices for room air-conditioners (RACs) and centralized air-conditioners (CACs) [€/unit] for the reference year 2016 [11,48].

System type	Mean purchasing costs [€/unit]
RACs	
Movable systems	409
Split systems (capacity <5 kW)	1051
Multi-split systems (capacity >5 kW, including single ducted systems)	1692
CACs	
Rooftop + packaged units	18135
Chiller (air-to-water) (capacity <400 kW)	20768
Chiller (water-to-water) (capacity <400 kW)	1676
Chiller (air-to-water) (capacity >400 kW)	111370
Chiller (water-to-water) (capacity >400 kW)	88033
VRF systems	19720

Table 3

Installation costs for room air-conditioners (RACs) and centralized air-conditioners (CACs) [€/kW] for the reference year 2016 [11,41].

System type	Mean installation costs [€/kW]
RACs	
Movable systems	164
Split systems (capacity <5 kW)	300
Multi-split systems (capacity >5 kW, including single ducted systems)	226
CACs	
Rooftop + packaged units	279
Chiller (air-to-water) (capacity <400 kW)	260
Chiller (water-to-water) (capacity <400 kW)	173
Chiller (air-to-water) (capacity >400 kW)	181
Chiller (water-to-water) (capacity >400 kW)	117
VRF systems	789

Table 4

Operation and Maintenance (O&M) costs for room air-conditioners (RACs) and centralized air-conditioners (CACs) [€/kW] for the reference year 2016 [11,48].

System type	Mean (O&M) costs [€/unit/year]
RACs	
Movable systems	/
Split systems (capacity <5 kW)	42
Multi-split systems (capacity >5 kW, including single ducted systems)	68
CACs	
Rooftop + packaged units	725
Chiller (air-to-water) (capacity <400 kW)	830
Chiller (water-to-water) (capacity <400 kW)	787
Chiller (air-to-water) (capacity >400 kW)	4455
Chiller (water-to-water) (capacity >400 kW)	3521
VRF systems	789

3.3. Alternative space cooling systems

This section is thoroughly describing the major characteristics of the alternative SC systems by explaining shortly the physical principle of each technology and the technical parameters such as fuel type used, cold source, reference sink temperature, resource usage, range of available size per type of the system, and efficiency level (COP, EER, SEER, SPF, etc.). The efficiency levels of VC systems are typically assessed and rated under specific regulations and standards. These regulations and standards provide a framework for measuring and comparing the performance of VC systems, and they often include requirements for testing procedures, equipment specifications, and energy efficiency metrics. However, this is not yet the case for alternative SC technologies, which may not have established regulations or standards for assessing their efficiency levels.

Table 5 shows the energy efficiency of the various technologies using conventional VC's efficiency as a benchmark. It can be seen that only 11 technologies have higher foreseen efficiencies than conventional VC systems' actual efficiency as follows: thermionic, thermotunnel, electrocaloric, electrochemical, Lorenz-Meutzner cycle (blends only), Turbo-Compressor-Condenser-Expander HP, elastocaloric effect, membrane HP, magnetocaloric effect, ground-coupled solid desiccant system

Table 5

Efficiency and costs of alternative space cooling technologies (unknown is when a source mentions that efficiency and costs are not known, while not identified is when the information is not found in any source).

Technology	Efficiency	Costs
Thermoelectric	Lower [30]	Equal (Assumption) [50]
Thermionic	Higher (Assumption) [30]	Equal (Assumption) [30]
Thermotunnel	Higher (Assumption) [30]	Equal (Assumption) [29]
Electrocaloric	Higher (Assumption) [30]	Unknown
Electrochemical	Higher (Assumption) [50]	Unknown
Lorenz-Meutzner cycle (blends only)	Higher (Assumption) [51]	Not identified
Transcritical cycle	Unknown	Higher [30]
Sanderson Rocker Arm Mechanism	Unknown	Unknown
Turbo-Compressor-Condenser-Expander HP	Higher (Assumption) [30]	Unknown
Stirling/Ericsson cycles (Reverse Stirling, Duplex Stirling, Reverse Ericsson)	Lower [29,30]	Unknown
Reverse Brayton (Bell Coleman cycle)	Lower [30]	Not identified
Bernoulli cycle	Lower [36]	Equal (Assumption) [29]
Elastocaloric effect	Higher [29,52]	Not identified
Barocaloric effect	Higher [52]	Not identified
(Metastable) Critical flow cycle	Lower [36]	Unknown
Membrane HP	Higher (Assumption) [30]	Equal (Assumption) [29]
Thermoacoustic	Lower [36]	Equal (Assumption) [29]
Magnetocaloric effect	Higher [29,52]	Unknown
Evaporative liquid desiccant system	Higher (Assumption) [30]	Equal (Assumption) [30]
Ground-coupled solid desiccant system	Higher [29]	Higher (Assumption) [30]
Stand-alone liquid desiccant system	Lower [30]	Higher (Assumption) [30]
Stand-alone solid desiccant system	Lower [29]	Higher [30]
Heat of reaction	Unknown	Not identified
Absorption and Adsorption cycles	Lower [29]	Higher [29]
Transcritical Thermal Compression HP	Lower [30]	Higher [29]
Natural Convection (Heat Exchanger–Mixing)	Not identified	Not identified
Natural Conduction (Heat Exchanger)	Not identified	Not identified
Freeze/Melt Cycle (Latent Cold Storage)	Not identified	Not identified
Evaporative Cooling (Water Evaporation)	Not identified	Equal (when used as an independent system) [30]
Enthalpy Recovery (Heat Exchanger)	Not identified	Not identified
Sky Radiative Cooling	Not identified	Unknown

Concept	Formulation	Lab Test	Lab Prototype	Lab-scale plant	Pilot plant	Demonstration	Commercial refinement required	Commercial
TRL1	TRL2	TRL3	TRL4	TRL5	TRL6	TRL7	TRL8	TRL9

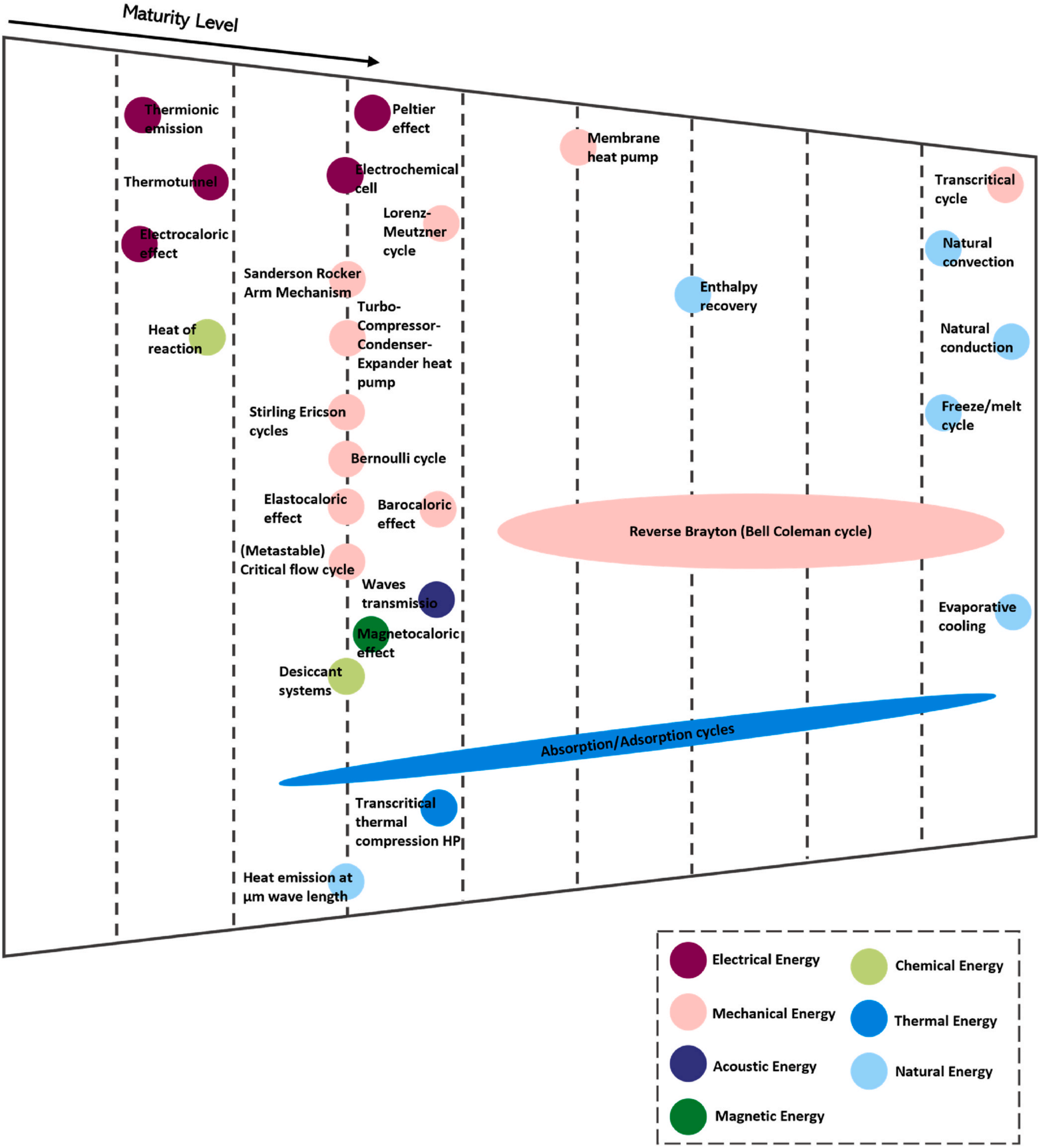

Fig. 4. TRL of alternative space cooling technologies.

and evaporative liquid desiccant system.

In addition to the efficiency level, this section investigates the TRL for the alternative SC technologies, as shown in Fig. 4, which indicates only the TRL of the alternative systems to be compared with the conventional VC systems that have TRL up to 9. In order for cooling technology to compete in the market in the near future, a TRL between 5 and 9 is defined as the most promising baseline. Only ten technologies have a TRL level between 5 and 9 as follows: absorption cycles, adsorption cycles, reverse Brayton cycle, membrane HP, enthalpy recovery, transcritical cycle, natural convection, natural conduction, freeze/melt cycle and evaporative cooling. Most of the other technologies have a TRL level between 3 and 4 as they are in the state of the lab test or either lab prototype. Few technologies have a TRL level of 2 in the formulation phase for the technology concept, such as thermionic emission, thermotunnel, electrocaloric effect and heat of reaction.

The technology costs are also presented in Table 5, using the conventional VC systems' costs as a baseline. It can be seen that there are no technologies with lower costs than conventional VC systems. The costs for most of the technologies are either not identified or equal to VC costs by assumption based on the previous references. Transcritical cycle, stand-alone solid desiccant system, stand-alone liquid desiccant system, ground-coupled solid desiccant system, absorption/adsorption cycles, and transcritical Thermal Compression HP have higher costs than VC systems.

In the present taxonomy, thermoelectric, thermionic, thermotunnel, electrocaloric, and electrochemical technologies are grouped under the electrical form of energy input, so all these cooling devices are powered by electricity. In addition to that, they use air as a cold source.

3.3.1. *Thermoelectric*

Thermoelectric cooling is based on the Peltier effect. A Peltier cooler is composed of semiconductor materials, typically made from bismuth telluride or other similar compounds. When an electric current is passed through the junction of two different semiconductors, a temperature differential arises. As one junction warms up, the other one gets cooler. The cool side drops below room temperature while the warm side is kept at ambient temperature by being connected to a heat sink. The heat sink can also be a coolant fluid which is cooled down by the ambient temperature. During the cooling process, the heat transfer medium of thermoelectric cooling devices does not change phases (single phase (solid)).

- **Reference sink temperature**: for most thermoelectric applications, Normal heat sink temperature rise above ambient (or cooling fluid) is between 5 and 15 °C.
- **Resource usage**: no liquid refrigerant.
- **Energy efficiency**: the maximum theoretical second law efficiency of current status quo materials of thermoelectric cooling systems is around 0.18, which is considerably lower than the second law efficiency of 0.50 achieved by today's VC technologies [15,53].
- **Range of capacity installed**: small-size applications and installed capacities of up to a few hundred watts [36].
- **Typical applications**: portable refrigerators, car seat air-conditioning, wine cabinets, and spot cooling for electronics are a few examples of typical applications for such technology [36].
- **Development trends**: research will likely make the efficiency of thermoelectric cooling devices and VC close in local comfort applications such as cooled seats [36].

3.3.2. *Thermionic*

In thermionic cooling, energetic electrons emit from the surface of the cathode to remove heat and allow the cathode to cool. Thermionic cooling devices' heat transfer medium doesn't change phases during the cooling operation (single phase (solid)).

- **Reference sink temperature**: moderate heat sink temperatures, around 20 °C, are typical of thermionic devices.
- **Resource usage**: no liquid refrigerant.
- **Energy efficiency**: ideally, it is possible for a thermionic technology efficiency to approach the Carnot efficiency [54]. Moreover, assumptions indicate that thermionic cooling modules could achieve 50–55% of the Carnot efficiency [36].
- **Range of capacity installed**: very low capacities, for instance, between 50 and 500 W.
- **Typical applications**: this technology can be applied to all cooling applications in residential and commercial buildings in different climate regions.
- **Development trends**: although research continues to focus on this technology, particularly on new materials for embedded applications [55], it remains subject to numerous challenges that limit the development of thermionic cooling.

3.3.3. *Thermotunnel (thermotunneling)*

Thermotunnel cooling is comparable to thermionic emission cooling (also known as thermotunneling). The difference is that in thermotunnel cooling, electrons do not move back to the emission point due to voltage difference. The heat transfer medium of thermotunnel cooling devices does not undergo a phase change during the cooling process too (single phase (solid)).

- **Reference sink temperature**: the same sink temperature of thermionic cooling [assumed].
- **Resource usage**: no liquid refrigerant (same as thermoelectric).
- **Energy efficiency**: the expected efficiency is 55% of Carnot, the same as thermionic systems, as opposed to 40–45% of Carnot for typical VC systems in HVAC applications [36].
- **Range of capacity installed**: very low capacities [30].
- **Typical applications**: same as thermoelectric, technically, it can be applied to all cooling applications for residential and commercial buildings. Thermotunneling cooling devices are currently being developed for small electronics cooling applications.
- **Development trends**: there are still numerous challenging issues that need to be overcome, as seen by the limited prototype development. Technology's future development trends are average.

3.3.4. *Electrocaloric*

According to the electrocaloric refrigeration theory, materials are imposed on an electric field. By modifying the dipolar state of the material, which in turn leads to a change in entropy and a consequent increase in temperature, the material is made to release heat in response to the applied electrical field [52]. There is no working fluid in the electrocaloric systems. The fluid is only a heat carrier but does not undergo any phase change during the cooling process. It is the solid refrigerant (caloric material) that undergoes a solid-solid phase change.

- **Reference sink temperature**: relatively low sink temperatures, such as around 20 °C.
- **Resource usage**: no liquid refrigerant.
- **Energy efficiency**: electrocaloric cooling instruments are characterized by relatively high (projected) energy efficiency values, such as projected COPs ranging from 3.7 to 4.9. These projected COPs are 16–53% higher than the overall system COP of baseline air-conditioners [36].
- **Range of capacity installed**: the capacities of electrocaloric cooling systems are too small for cooling and refrigeration applications, with few watts of up to 2 kW [52].
- **Typical applications**: it can be applied to all cooling applications
- **Development trends**: R&D is currently focusing on manufacturing electrocaloric materials and electrodes. However, the technology is still being developed for HVAC and other cooling applications in buildings.

3.3.5. *Electrochemical*

An electrochemical cell, for cooling purposes, compresses a hydrogen working fluid using a proton exchange membrane to drive a VC or metal hydride HP cycle. During the cooling process, the heat transfer medium in electrochemical cooling devices does not change phase (single phase (gaseous)).

- **Reference sink temperature**: electrochemical cooling devices are characterized by moderate sink temperatures, such as 35 °C [56].
- **Resource usage**: hydrogen/refrigerant [30].
- **Energy efficiency**: current efforts focus on developing room air-conditioners with a COP higher than 4 [30].
- **Range of capacity installed**: small power applications, such as 1 kW [57].
- **Typical applications**: development of a new product has initially prioritized packaged air-conditioning systems.
- **Development trends**: for the technology to be commercialized, extensive R&D is required to better understand its potential energy savings and cost-effectiveness.

The alternative VC systems (Lorenz-Meutzner cycle, transcritical cycle, S-RAM, Turbo-Compressor-Condenser-Expander HP), no phase change (Stirling/Ericsson cycles, reverse Brayton, Bernoulli cycle, elastocaloric effect, barocaloric effect), and phase change ((Metastable) critical flow cycle, Membrane HP) technologies comprise the second group of cooling technologies (mechanical energy) as shown in Fig. 2. These technologies are driven by electricity except for Stirling/Ericsson cycles which are driven by thermal energy sources such as natural gas, gasoline, wood, waste heat or high-temperature heat sources. Additionally, they use air as a cold source.

3.3.6. *Lorenz-Meutzner cycle (blends only)*

The working fluid for the Lorenz-Meutzner cycle is a zeotropic mixture that has a gliding temperature differential during the evaporation and condensation phases [58]. These devices are electrically driven. There is very little data or information available on this technology since it is not currently on the market. Therefore, not much information regarding capacities, applications and development trends.

- **Reference sink temperature**: the condenser air inlet temperature in the cycle is about 32 °C [59].
- **Resource usage**: refrigerant.
- **Energy efficiency**: the Lorenz-Meutzner cycle has shown advantages and achieved 20% energy savings compared to standard refrigerators. Therefore the efficiency is projected to be higher than traditional VC systems [51].
- **Range of capacity installed**: large capacity [60].
- **Typical applications**: large systems such as domestic refrigerator-freezer [60].
- **Development trends**: this technology is only studied in the laboratory, but prototypes are in the development stages [60].

3.3.7. *Transcritical cycle*

The CO_2 transcritical cycle was proposed to reduce the global warming impact of HFC-based air-conditioning and refrigeration systems. Transcritical systems maintain CO_2 above the critical temperature by cooling it at the gas cooler's inlet without allowing it to condense.

- **Reference sink temperature**: a heat sink temperature of up to 90 °C.
- **Resource usage**: refrigerant.
- **Energy efficiency**: the efficiency in unknown at this time.
- **Range of capacity installed**: 6–12 kW for optimal working conditions [61].
- **Typical applications**: centralized commercial systems [62].
- **Development trends**: for the next 20 years, it is anticipated that research interest in the transcritical CO_2 cycle will remain high, with a potential for large-scale commercial applications.

3.3.8. *Sanderson rocker arm mechanism*

This cooling technology uses a unique rocker arm design to transfer heat from the engine to the cooling system, allowing for more efficient cooling and improved performance. It works by using a rocker arm to connect two or more pipes. When the temperature in the space increases, the rocker arm expands, allowing the air to flow freely through the pipes. When the temperature in the space decreases, the rocker arm contracts, restricting the flow of air. By controlling the flow of air in this way, the space can be cooled when necessary. The heat transfer medium of the system does not change phases (single phase (gaseous)).

- **Reference sink temperature**: the temperature of the cooling airflow intake is 48.9 °C [63].
- **Resource usage**: refrigerant.
- **Energy efficiency**: **the** efficiency in unknown at this time.
- **Range of capacity installed**: in heat pump and cooling applications with capacities ranging from 25 to 300 kW [64].
- **Typical applications**: this technology is intended for use in packed rooftop units for commercial buildings [30].
- **Development trends**: S-RAM cooling technology has seen a number of advancements in recent years. Many of these advancements have focused on improvements in the cooling efficiency of the mechanism. At the moment, the core S-RAM compressor is being tested with heat exchangers, and new designs are being developed to increase the efficiency and reduce the size of the heat exchangers [30,65].

3.3.9. *Turbo-compressor-condenser-expander heat pump*

Turbo-compressor-condenser-expander HP uses a turbine-compressor to compress the refrigerant, a condenser to reject heat to the environment, and an expander to expand the refrigerant and absorb heat from a low-temperature source. The heat transfer medium of the system does not change phases (single phase (gaseous)).

- **Reference sink temperature**: the reference sink temperatures range from 55 to 65 °C [66].
- **Resource usage**: refrigerant.
- **Energy efficiency**: the performance of the current design is estimated at a SEER of 20 in residential buildings compared to a SEER of 14 as a baseline [30].
- **Range of capacity installed**: in heat pump and cooling applications with capacities ranging above 150 kW [66].
- **Typical applications**: air-cooled packaged units in commercial buildings.
- **Development trends**: it is expected that this technique will continue to be uncompetitive with vapour compression in the near future since prototypes are still in the development stage and further research and development have to be done.

3.3.10. *Stirling/Ericsson cycles*

The following technologies have been assigned to Stirling/Ericsson cycles since they have the same principles. The technical characteristics of the cycles are described below in Table 6. The heat transfer medium of the system does not change phases (no-phase change (gaseous)).

Table 6
Stirling/Ericsson cycles characteristics.

System	Reference sink temperature	Range of capacity installed
Reverse Stirling	20–50 °C [67,68]	40–100 W [69]
Duplex Stirling	approximately 17 °C [70]	50 W–20 kW [71]
Vuilleumier HP	500 °C and higher [36]	7.5–20 kW [36]
Reverse Ericsson	about 30 °C [72]	Around 700 W [73]

3.3.10.1. Reverse stirling. The reverse Stirling cycle is a thermodynamic cycle involving a heat engine that is based on the Stirling cycle but operates in reverse [74].

3.3.10.2. Duplex Stirling. The duplex Stirling machine (or duplex Stirling HP) utilizes a gas-fired Stirling engine's mechanical energy to compress and expand a gaseous refrigerant while transferring it between two chambers [75].

3.3.10.3. Vuilleumier HP. A Vuilleumier HP produces a warm and a cold side by cyclically compressing and expanding a gaseous working fluid (typically high-pressure helium) using a gas-fired heat engine [36].

3.3.10.4. Reverse Ericsson. The Ericsson engine is based on the Ericsson cycle (reversible cycle).

- **Resource usage**: refrigerant.
- **Energy efficiency**: reverse Stirling and duplex Stirling cycles are characterized by low energy efficiency levels – the estimated COP is approximately 1 [11,36]. Vuilleumier HP has an estimated COP of 0.8 [36]. Reverse Ericsson cycle has a second-law efficiency of approximately 3% [73].
- **Typical applications**: reverse Stirling devices are used for cooling electronic sensors and microprocessors. Duplex Stirling devices are available for applications for cryocooling, low-temperature and niche refrigeration. Vuilleumier HP would be appropriate for most of the applications in residential and commercial buildings. Reverse Ericsson devices are used for refrigeration and air-conditioning.
- **Development trends**: the different Stirling/Ericsson cycles are currently under development for the different HVAC applications.

3.3.11. Reverse Brayton (Bell Coleman cycle)

Reverse Brayton (Bell Coleman cycle) is a modified version of the Brayton cycle, which is an ideal thermodynamic cycle used to describe the operation of a gas turbine engine. The reverse Brayton cycle allows for heat rejection at a lower temperature than in a traditional Brayton cycle, improving the system's efficiency. The heat transfer medium of the system does not change phases (no-phase change (gaseous)).

- **Reference sink temperature**: moderate inlet temperatures such as around 20 °C [76].
- **Resource usage**: refrigerant.
- **Energy efficiency**: reverse Brayton cycles have a COP range between 0.5 and 0.8 [36].
- **Range of capacity installed**: can reach large capacities such as nearly 90 MW.
- **Typical applications**: transportation space condition, commercial and industrial refrigeration.
- **Development trends**: recent trends in the development of the reverse Brayton cycle have focused on increasing its efficiency and reducing its cost in different applications, such as food freezing applications [77].

3.3.12. Bernoulli cycle

The Bernoulli cycle cooling system uses the principles of the Bernoulli equation to transfer heat. The cycle produces cooling across the nozzle throat by accelerating a working fluid through a converging-diverging nozzle. The heat transfer medium of the system does not change phases (no-phase change (gaseous)).

- **Reference sink temperature**: relatively low temperature, cooler than the indoor temperature
- **Resource usage**: **refrigerant**.
- **Energy efficiency**: current prototypes have very low COPs (around 0.1) but are expected to improve in the near future (COPs of 2–3) [36].
- **Range of capacity installed**: relatively small capacities (e.g. 5 W) [36].
- **Typical applications**: for the majority of vapour compression cooling applications, the Bernoulli HP would be appropriate (split systems and packaged units).
- **Development trends**: Bernoulli HP is a developing technology. Although the COP of the current prototypes is quite low, it is anticipated to increase.

3.3.13. Elastocaloric effect

In elastocaloric refrigeration, pressure is exposed to the elastocaloric materials, which may be done by compression, tension, bending, or torsion [52]. The elastocaloric effect is a cooling technology that utilizes the change in temperature of a material when it is subjected to mechanical stress. When an elastocaloric material is stretched, it absorbs heat and cools down, while when it is released from the stress, it releases heat and heats up [78]. The same as electrocaloric systems, there is no working fluid in the elastocaloric systems. The fluid is only a heat carrier but does not undergo any phase change during the cooling process.

- **Reference sink temperature**: near the room temperature [79].
- **Resource usage**: water [52,79].
- **Energy efficiency**: elastocaloric effect has high COPs that could be higher than 9 [52].
- **Range of capacity installed**: small capacities below 1 kW [52,80].
- **Typical applications**: domestic cooling devices since the effect can be applied to various cooling applications in residential and commercial buildings.
- **Development trends**: several laboratory prototypes are currently being developed [30].

3.3.14. Barocaloric effect

Adiabatic compression, heat transfer (from a cold to a hot heat exchanger), decompression, and heat transfer (from a hot to cold heat exchanger) are the four key processes of the barocaloric refrigeration cycle. The barocaloric effect utilizes the change in temperature of a material when it is subjected to pressure. When a barocaloric material is compressed, it heats up and releases heat, while when it is released from the pressure, it cools down and absorbs heat [81]. The same as electrocaloric systems and elastocaloric systems, there is no working fluid in the barocaloric systems. The fluid is only a heat carrier but does not undergo any phase change during the cooling process.

- **Reference sink temperature**: near the room temperature [79].
- **Resource usage: water** [52,79].
- **Energy efficiency**: barocaloric effect has a high COP value of 6 [52].
- **Range of capacity installed**: few watts for modelling [52].
- **Typical applications**: cryocoolers
- **Development trends**: early stage for developing materials and cycles [52].

3.3.15. (Metastable) critical flow cycle

Using a converging-diverging nozzle, the critical-flow refrigeration cycle provides SC by expanding a liquid refrigerant and absorbing heat from a secondary fluid. The working fluid of critical flow cycle cooling devices undergoes a phase change during the cooling process (two-phase). The mediums used are liquid/gaseous.

- **Reference sink temperature**: critical flow cycle devices are characterized by moderate sink temperatures, such as 35 °C [82].
- **Resource usage**: refrigerant.

- **Energy efficiency**: laboratory prototypes have an estimated COP of 1.7. Additionally, researchers found that the COP of the system can be improved up to 15 [30,36].
- **Range of capacity installed**: such technologies have a moderate installed capacity of up to 15 kW [83].
- **Typical applications:** due to the need for a secondary working fluid in order for the nozzle assembly to transfer heat, large commercial chillers are one of the most promising applications.
- **Development trends**: recent advancements show promising developments for commercial HVAC applications.

3.3.16. *Membrane heat pump*

A membrane HP uses a vacuum pump to transfer moisture across a number of membranes to provide cooling and dehumidification. The working fluid of membrane HPs undergoes a phase change during the cooling process (two-phase). The mediums used are liquid.

- **Reference sink temperature**: an inlet temperature of 35 °C [84].
- **Resource usage**: water.
- **Energy efficiency**: researchers claim that EER could be twice that of VC systems, resulting in energy savings of 50%, with an estimated SEER of 30 [30].
- **Range of capacity installed**: moderate cooling capacities, such as from 4 to 30 kW [85].
- **Typical applications**: a promising technology for improving the comfort and efficiency of commercial buildings through the separation of the air-conditioning process into sensible heat cooling and dehumidification [86].
- **Development trends**: in comparison to VC systems for SC, membrane-based heat pump systems have caught the interest of several research teams as a possibly more environmentally friendly technology with the development of several prototypes [87].

3.3.17. *Thermoacoustic*

Thermoacoustic cooling works by transforming acoustic energy into thermal energy. The presence of acoustic waves (standing or travelling) expands, and they can be either standing waves or travelling waves. The technology is driven by waste heat, solar heat or other heat. The working fluid of thermoacoustic cooling devices also does not undergo a phase change during the cooling process (single phase). The mediums utilized (e.g. helium, argon, air) are gaseous.

- **Reference sink temperature**: relatively low inlet temperatures, for example, 25–35 °C [88].
- **Resource usage**: refrigerant.
- **Energy efficiency**: the maximum theoretical efficiency of VC technology is higher than that of thermoacoustic technology [36].
- **Range of capacity installed**: relatively low capacities, about 3.5 kW [36].
- **Typical applications**: applications like portable air-conditioners.
- **Development trends**: development of commercial supermarket chillers [36].

3.3.18. *Magnetocaloric effect*

The magnetocaloric effect, which exposes paramagnetic materials to a magnetic field, is the basis for magnetic cooling. For the vast majority of magnetocaloric materials, heating and cooling are caused by magnetization and demagnetization, respectively [52,89]. There is no working fluid in the magnetocaloric systems. The fluid is only a heat carrier but does not undergo any phase change during the cooling process. The mediums utilized (e.g. gadolinium) are solid.

- **Reference sink temperature**: relatively moderate sink temperatures, such as 25 °C [36].
- **Resource usage**: refrigerant.
- **Energy efficiency**: depending on the conditions, the COP varied from 0.2 to 9.4 during the test [52].
- **Range of capacity installed**: relatively low capacities such as 500 W to 3.5 kW [30].
- **Typical applications**: mobile refrigerators, medical and commercial [30,52].
- **Development trends**: R&D focuses on magnetocaloric materials and system design optimization [52].

3.3.19. *Desiccant cooling systems*

In desiccant cooling systems, desiccants remove water from entering airstreams, which are then cooled by air-conditioners or evaporative coolers. The working fluid of desiccant cooling instruments undergoes a phase change during the cooling process. The mediums utilized are liquid or solid (according to the different systems as described below). Desiccant cooling systems are driven by natural gas, solar heat or waste heat.

3.3.19.1. Evaporative liquid desiccant system. The combination of evaporative cooling with liquid desiccants is known as evaporative liquid desiccant technology. The system typically consists of a liquid desiccant solution that is circulated through a regenerator, where it is heated and regenerated, and a dehumidifier, where it removes moisture from the air [90]. The mediums utilized are liquid.

3.3.19.2. Ground-coupled solid desiccant system. Ground-coupled fluid systems and solid desiccants are combined in the ground-coupled solid desiccant technology. They utilize the principle of desiccant dehumidification to remove moisture from the air, followed by heat exchange with the ground to cool the air. The mediums utilized are liquid.

3.3.19.3. Stand-alone liquid desiccant system. In stand-alone liquid desiccant systems, moisture from the air is absorbed using liquid desiccant materials having a strong affinity for water [23]. The mediums utilized are liquid. Compared to solid desiccants, liquid desiccants provide a number of benefits. Since liquid desiccants often have fewer pressure drops, they can be used with low-temperature regeneration [23,91].

3.3.19.4. Stand-alone solid desiccant system. Stand-alone solid desiccant systems also absorb moisture from the air using solid desiccant materials with a high affinity for water. The mediums utilized are solid.

The technical characteristics of the different desiccant cooling systems are described below in Table 7.

Table 7
Desiccant cooling systems characteristics.

System	Reference sink temperature	Range of capacity installed	Energy efficiency values
Evaporative liquid desiccant	20–50 °C [93]	moderate capacities of about 35 kW [36]	COPs range from approximately 0.2–1.3 [93]
Ground-coupled solid desiccant	16–21 °C [94]	small capacities about 1 kW [36]	a COP ranging between 9.6 and 16.3 [95]
Stand-alone liquid desiccant	regeneration temperature of 60–75 °C [96]	small capacities of about 1.7–5.5 kW [96]	a COP ranging between 4.8 and 5.5 [97]
Stand-alone solid desiccant	high regeneration temperature (up to 170 °C) [98]	moderate capacities of about 10 kW [99]	COPs less than 1 [100]

Table 8
Natural cooling systems characteristics.

System	Resource usage	Typical applications
Natural Convection (heat exchanger – mixing)	air	residential and tertiary sectors
Natural conduction (heat exchanger)	water	residential and tertiary sectors (water loops cooling the ambient via an air-to-water heat exchanger)
Freeze/melt cycle (latent cold storage)	air	residential and tertiary sectors
Evaporative cooling (water evaporation)	water	residential and commercial buildings in hot-dry climate regions
Enthalpy recovery (heat exchanger)	air	offices and education buildings
Sky radiative cooling	air	residential and tertiary sectors

- **Resource usage**: water.
- **Typical applications**: with the exception of ground-coupled solid desiccant systems and stand-alone liquid desiccant systems, which are only applicable in hot-humid climate zones, all desiccant cooling systems are applicable to all applications for all building types and climate areas [36].
- **Development trends**: for the next two decades, desiccant cooling systems will not have a high market penetration [15]. Even if evaporative liquid desiccant systems have developed, they have not yet been commercialized, while several institutions are working to develop advanced products for stand-alone liquid desiccant systems [36]. Conventional solid desiccants are still struggling to achieve acceptable cooling performance [92]. The ground-coupled solid desiccant system has been considered a “moderately promising” technology by the DOE and has not yet achieved market penetration [36].

3.3.20. *Heat of reaction*

Cooling through a chemical process occurs through an endothermic reaction at which heat (energy) is taken in, followed by a drop in temperature. In this case, a reaction (e.g. of two chemical substances) takes in energy from the starting point until the end. The working fluid at chemical cooling does not undergo a phase change during the cooling process (single phase). The mediums utilized are solid/liquid.

- **Reference sink temperature**: moderate inlet temperature levels such as about 30 °C [101].
- **Resource usage**: refrigerant (e.g. sodium nitrate or H2O).
- **Energy efficiency**: the efficiency in unknown at this time.
- **Range of capacity installed**: low capacities of up to a few hundred watts.
- **Typical applications**: very small applications such as portable electronic device heat management [9].
- **Development trends**: even though this technology has interested some industries [102], its development trend appears to be limited.

3.3.21. *Absorption and adsorption cycles*

Similar in operation to the VC refrigeration cycle, the key distinction between absorption and adsorption cooling systems is that thermal energy, rather than mechanical work, drives the cycle. Water/ammonia and lithium bromide/water are typical working fluids (sorbent/refrigerant) for absorption systems, and metal chlorides/ammonia, zeolite/water, activated carbon/methanol, zeolite/water, activated carbon/ammonia, silica gel/water, or composite adsorbents for adsorption systems. Sorption cooling systems are driven by natural gas, solar thermal, process steam or waste heat steam.

- **Reference source temperature**: inlet temperatures between 70 and 100 °C and higher [36].
- **Resource usage**: refrigerant.
- **Energy efficiency**: COPs range from approximately 0.4–1.2 depending on the cycle configuration [103,104].
- **Range of capacity installed**: available in a range of capacities ranging from 4.5 kW to 30 MW [23,105,106].
- **Typical applications**: applicable for SC solutions for both residential and commercial buildings.
- **Development trends**: the use of such technology is being expanded through a number of initiatives, including the development of environmentally benign refrigerant pairs, improved energy efficiency, decreased cost, and scaled-down size [36].

3.3.22. *Transcritical thermal compression heat pump*

Transcritical thermal compression HP is a new technology developed by boostHEAT company driven by gas. It includes a thermal compressor that uses the heat produced by the combustion of gas not to heat water directly (for example) but to activate a heat pump cycle. It operates using an external point heat source to compress CO2.

- **Reference sink temperature**: high temperature of 700 °C [107, 108].
- **Resource usage**: refrigerant.
- **Energy efficiency**: the COP is approximately 2 [107].
- **Range of capacity installed**: relatively moderate capacities such as about 17–50 kW [107].
- **Typical applications**: can be used in SC applications in residential and commercial sectors [108].
- **Development trends**: average development trend for a wider range of applications, including residential and commercial buildings.

3.3.23. *Natural cooling*

Natural cooling systems that utilize sensible heat refer to certain building designs that make an effort to include physical concepts (such as reflection) into the building’s envelope in order to reduce the rate of heat transfer into buildings (particularly from the sun). In contrast, natural cooling systems working with latent heat refer to certain building designs which attempt to integrate physical principles (e.g. evaporation) into the building’s envelope to remove heat from buildings. Natural cooling solutions can be passive or active cooling technologies.

3.3.23.1 Natural convection (heat exchanger – mixing). Natural convection occurs in natural cooling systems that use gaseous refrigerants (e.g. cold air) and working fluid that does not undergo a phase transition (single phase). The technology can be an active/passive system.

3.3.23.2 Natural conduction (heat exchanger). Natural conduction occurs in natural cooling systems that use liquid refrigerants (e.g. cold water) and working fluid that does not undergo a phase transition (single phase). The technology can be an active/passive system.

3.3.23.3 Freeze/melt cycle (latent cold storage). The freeze/melt cycle occurs in natural cooling systems that use solid/liquid refrigerants (e.g. melting ice) and working fluid that undergoes a phase change (two-phase). In a typical freeze/melt cycle system, water or another suitable phase change material (PCM) is used as the storage medium. The technology can be an active/passive system.

3.3.23.4 Evaporative cooling (water evaporation). At natural cooling systems where the working fluid undergoes a phase change (two-phase) and liquid/vapour refrigerants (e.g. water/water vapour) are used, the process uses large heat sorption due to evaporation of water. The technology is an active system.

3.3.23.5 Enthalpy recovery (heat exchanger). The integrated heat and moisture exchange panels are used in this technique. A modular energy recovery ventilator panel is used to provide preconditioned outside air directly to a room by installing it in the building envelope. The working fluid does not undergo any phase change during the cooling process. This technology is an active system.

3.3.23.6 Sky radiative cooling. According to the SC taxonomy, sky radiative cooling is the only completely passive solution identified, as shown in Fig. 2. Sky radiative cooling results from the longwave infrared radiation heat transfer between a surface on earth and molecules (primarily water vapour, CO_2 and ozone) at a reduced altitude over the surface [109]. Through the atmospheric window, thermal infrared radiation from an item on earth is sent into the cold universe to cool it by sky radiative cooling.

Additionally, the resource usage and typical applications are shown in Table 8.

- **Reference sink temperature**: N/A
- **Energy efficiency**: N/A
- **Range of capacity installed**: N/A
- **Development trends**: due to natural cooling systems being available for decades on the market but having achieved quite a low market penetration so far as well as R&D efforts are still needed.

4. Discussion

4.1. Findings and recommendations

SC technologies have become increasingly important as the world looks for different ways to reduce energy consumption and decrease the effects of climate change and global warming. The aforementioned technologies have the potential to significantly improve energy efficiency and reduce environmental impact. Additionally, the study also identified a trend towards dependence on non-renewable energy sources in SC technologies and reducing greenhouse gas emissions.

The parameters used to categorize the alternative SC technologies in this study were chosen to provide a comprehensive understanding of the characteristics and potential of each technology. This information can be used to identify the most promising technologies for further development and implementation. These parameters include the physical form of energy input, basic working/operating principle, refrigerant or heat transfer medium, phase of the working fluid, specific physical process or device, type of SC technology (active or passive solution), fuel type, and TRL. The physical form of energy input, for example, indicates the type of energy required to drive the technology, while the basic working principle and phase of the working fluid provide insight into the underlying physics of the technology and how it functions. Similarly, the refrigerant or heat transfer medium used in the technology is an important factor in determining its performance and characteristics. The specific physical process or device refers to the technology-specific process or device that is used to cool the air. The type of SC technology refers to whether the solution is active or passive. Finally, the fuel type, in particular, whether it is renewable or not, refers to the type of energy used to drive the technology. Lastly, the TRL was used to indicate the level of maturity of each technology. This parameter provides insight into the potential for each technology to be developed and implemented in the near future.

While alternative SC technologies such as absorption systems, adsorption systems and desiccant systems have the potential to provide energy-efficient cooling, they often cannot compete with conventional VC systems in terms of efficiency and cost in the short-term and medium-term [110]. However, some alternatives such as thermionic, thermotunnel, membrane heat pump and evaporative liquid desiccant systems have been shown to be cost-competitive and energy-efficient options in certain applications. Additionally, the development of new technologies such as electrocaloric, electrochemical, Lorenz-Meutzner Cycle (blend only), turbo-compressor-condenser-expander HP, elastocaloric, barocaloric and magnetocaloric is also promising and assumed to be more efficient than traditional VC systems, but still under development and testing phase and have either unknown or not-identified costs as shown in Table 5.

The long-term competitiveness of alternative SC technologies depends on several factors. First, policy support plays a crucial role in promoting the adoption of sustainable cooling solutions [111]. Governments can implement policies that incentivize the use of energy-efficient and environmentally friendly SC technologies. For example, policies could include financial incentives, regulations, and standards that encourage the deployment of alternative SC systems. These policies can create a favourable market environment, driving investment and research into improving the long-term viability of alternative SC technologies. Second, the urgency to address climate change and reduce greenhouse gas emissions is increasing. Conventional VC systems contribute to CO_2 emissions, and the environmental impact of cooling is a growing concern [112]. As countries strive to achieve their climate goals and transition to more sustainable energy systems, the demand for energy-efficient and low-carbon cooling technologies will likely rise. This increased demand could lead to further advancements and cost reductions in alternative SC technologies.

Among the alternative SC technologies that have the potential to be more efficient than conventional VC systems, Membrane HP stands out as having the highest TRL of 5–6. This means that the Membrane HP has been validated and demonstrated in a relevant environment, proving its effectiveness and reliability. It also means that the technology is at a stage where it is ready for commercialization and has been validated by testing in a relevant environment. Additionally, other technologies that also have high TRL, such as absorption/adsorption cooling systems, reverse Brayton, and enthalpy recovery. However, these technologies either have a very low efficiency or their efficiency has not been identified. Absorption/adsorption cooling systems have a TRL range of 3–9, and they use a heat source to drive a cooling process instead of electricity. However, these systems typically have a lower COP compared to VC systems and are, therefore, less efficient. Reverse Brayton systems have a TRL range of 5–9, and enthalpy recovery systems have a TRL of 7, but their efficiencies are not yet identified.

Lastly, other alternative SC technologies are already commercialized in the market with a TRL of 9, but their efficiencies and costs are mostly not identified. These technologies include the transcritical cycle, natural conduction (heat exchanger), natural convection (heat exchanger – mixing), evaporative cooling (water evaporation) and freeze/melt cycle (latent cold storage). More research is needed to identify the efficiencies and costs for such systems, to have a better understanding of their performance and make them more competitive with VC systems in the market.

It is necessary to acknowledge the uncertainties surrounding the results and findings presented. One of the primary sources of uncertainty lies in the complex interplay between technological advancements and market dynamics. While the paper provides recent insights into the current state of these alternative SC technologies, their future development depends on various factors, including regulatory frameworks, investment patterns and consumer preferences. These factors are subject to change over time, and accurately predicting their evolution is challenging. Furthermore, Predicting market acceptance accurately is inherently challenging, as it involves understanding and forecasting the behaviour and preferences of diverse actors within complex socio-technical systems [113]. To enhance the robustness and validity of the findings, future research should consider integrating uncertainty modelling approaches. By incorporating probabilistic or scenario-based analyses, researchers can provide better approaches to the potential future outcomes and highlight the range of possibilities.

4.2. Strength and limitations

The first strength of the paper relies on the comprehensive analysis of a wide range of SC technologies, using multiple well-defined parameters to categorize and evaluate each technology. Another strength of the paper is based on providing a realistic assessment of the potential for each technology to be developed and implemented by using TRL as a parameter to evaluate the maturity of each technology. The third strength of the paper is identifying several alternative SC technologies with the potential to provide energy-efficient cooling, such as membrane heat pumps, thermionic systems, thermotunnel systems, and evaporative liquid desiccant systems. The fourth strength of the study is identifying trends towards reducing greenhouse gas emissions in SC technologies, which is important for addressing climate change and promoting sustainability.

However, the study has some limitations. The scientific literature is rich in research and investigation on both the heating sector and conventional VC cooling technologies but relatively little on alternative SC technologies. There is still a significant gap in the knowledge about these systems compared to the VC and heating technologies, despite the increasing interest in developing alternative SC technologies. The fact that some of these technologies are still in the early stage of development or have not yet attained a large market share is one of the main reasons for the lack of knowledge on alternative SC technologies. This makes it difficult to determine the cost of these systems using VC technology as a baseline.

Furthermore, since a number of these systems are still undergoing research and development, the costs and efficiencies of these systems are not yet known. For instance, the only competing SC technology with a sizable market share is TDHP, although even in this instance, the information is limited. The other alternative SC technologies have limited information available in the scientific literature, as shown in Table 5. To make these systems more competitive in the market, further study is required to more accurately analyze the potential performance and anticipated costs of these systems.

Lastly, it should be acknowledged that the exclusive reliance on a qualitative approach to analyze the performance of different technologies. This limitation arises from the nature of the study, which aimed to synthesize existing literature and provide a comprehensive overview of the topic at hand. The use of a qualitative approach allowed for a deep understanding of the technologies and their impact, but it may not provide a practical understanding or quantitative assessment of their performance.

4.3. Implication on practice and future research

The field of alternative SC technologies offers promising perspectives for reducing energy consumption, minimizing environmental impact, and addressing the challenges posed by climate change and global warming [114]. The findings of this study have significant implications for both practice and future research. The study highlights that more experimental investigations and field experiments should be carried out in order to close the information gap about various SC technologies. The study also emphasizes that there is still a lack of information about alternative SC technologies compared to VC and heating technologies. This is due to the fact that some of these technologies are still under development or have not yet attained a sizable market share. To bridge the knowledge gap in this research area and provide guidance for future investigations, a roadmap outlining approaches for filling these gaps can be proposed.

- Novel materials play a crucial role in the development of alternative SC technologies. Research should focus on exploring and evaluating materials with enhanced cooling capabilities, high emissivity, and low solar absorptivity [115].
- System integration and optimization are key aspects that should be addressed in future research. It is essential to develop innovative approaches for integrating alternative SC technologies into existing building systems or designing new systems that maximize energy efficiency. This includes exploring optimal control strategies, developing smart and adaptive cooling systems, and considering the interaction between cooling technologies and other building systems, such as ventilation and energy storage. Additionally, optimizing the sizing and configuration of cooling systems can help achieve better performance and energy savings.
- Hybrid systems offer significant potential for improving the overall efficiency and performance of alternative SC technologies. By combining multiple cooling technologies, such as membrane heat pumps and evaporative liquid desiccant systems, researchers can leverage the strengths of each technology and achieve higher energy efficiency. Future studies should focus on the design, optimization, and integration of hybrid systems, considering factors such as compatibility, control strategies, and cost-effectiveness.
- To further understand these systems' performance and make them more competitive with VC systems on the market, additional quantitative research is required to determine their costs and efficiency. This includes conducting experimental investigations, field experiments, and quantitative studies to assess the potential benefits, performance, and economic viability of these technologies.
- It is recommended to incorporate scenario analysis as a complementary methodology in future studies. By combining the qualitative approach used in the current study with scenario analysis, researchers can enhance the practical understanding of technology performance and its implications. This methodology could involve developing realistic scenarios that reflect real-world conditions and evaluating the performance of different technologies within those scenarios. The scenarios could consider factors such as user requirements, environmental conditions, and technological constraints.

This study is an integral part of the ongoing LIFE21-CET-COOLING-CoolLIFE project. This project aims to comprehensively address various aspects of SC technologies, including both active and passive SC measures. Furthermore, the project undertakes an in-depth investigation into the economic, policy, social, and cultural dimensions that can significantly impact the market acceptance of these technologies. In addition to these crucial factors, the project also emphasizes the examination of the policy landscape surrounding SC technologies, as well as the social dynamics associated with their adoption. Moreover, the project recognizes the importance of considering the environmental implications and health risks associated with these technologies. By actively incorporating these dimensions into our study, we strive to provide a comprehensive understanding of the factors influencing the market acceptance of SC technologies.

5. Conclusion

The study analyzed a wide range of alternative SC technologies to provide a comprehensive understanding of the characteristics and potential of each technology. In total, the study assessed 32 alternative SC technologies based on eight parameters (the physical form of energy, basic working principle, refrigerant/heat transfer medium, phase of the working fluid, specific physical process/device, type of SC technology (active, passive or both), fuel (fuel type used to drive the SC technology, the possibility to be driven by renewable energy source) and TRL).

The findings of the study found that while a number of alternative SC technologies have the potential to provide energy-efficient SC, they often cannot compete with conventional VC systems in terms of efficiency and cost. However, specific alternatives such as membrane heat pumps, thermionic systems, thermotunnel systems, and evaporative liquid desiccant systems have been shown to be cost-competitive and energy-efficient options in certain applications. The development of new technologies such as electrocaloric, electrochemical, Lorenz-Meutzner Cycle (blend only), turbo-compressor-condenser-expander HP, elastocaloric, barocaloric, and magnetocaloric is also promising and assumed to be more efficient than traditional VC systems, but they are still under development and testing phase, and their costs are either unknown or not identified. The study recommended that more research is needed to identify the efficiencies and costs of these alternative SC technologies to better understand their performance and make them more competitive with VC systems in the market. The findings also indicated a trend towards reducing greenhouse gas emissions and dependence on non-renewable energy sources in SC technologies, which is essential for addressing climate change and promoting sustainability.

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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

No data was used for the research described in the article.

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