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Screening of Cooling Technologies in Europe: Alternatives to Vapour Compression and Possible Market Developments

Simon Pezzutto [1,*], Giulio Quaglini [1], Philippe Riviere [2,3], Lukas Kranzl [4], Antonio Novelli [5], Andrea Zambito [1] and Eric Wilczynski [1]

1 Institute for Renewable Energy, European Academy of Bolzano (EURAC Research), Viale Druso 1, 39100 Bolzano, Italy; giulio.quaglini@eurac.edu (G.Q.); andrea.zambito@eurac.edu (A.Z.); eric.wilczynski@eurac.edu (E.W.)
2 Directorate-General for Energy (DG Energy), European Commission, Unit B3: Buildings and Products, 1049 Brussel, Belgium; philippe.riviere@ec.europa.eu
3 Center for Energy Efficient Systems (CES), Department of Energy and Processes (DEP), Mines ParisTech, PSL University, 60 Boulevard Saint-Michel, CEDEX 06, 75272 Paris, France
4 Energy Economics Group, Institute of Energy Systems and Electric Drives, TU Wien, Gusshausstrasse 25-29/370-3, 1040 Vienna, Austria; kranzl@eeg.tuwien.ac.at
5 Planetek Italia, Via Massaua 12, 70132 Bari, Italy; novelli@planetek.it
* Correspondence: simon.pezzutto@eurac.edu; Tel.: +39-0471-055-622

Abstract: The aim of this study is to investigate, review, and assess the recent advances of alternative cooling technologies using traditional vapor compression (VC) systems as a baseline. Around 99% of the final energy consumption used for cooling in the current European market (European Union plus the United Kingdom (EU27 + UK) is supplied by VC technologies. In comparison, the remaining 1% is produced by thermally driven heat pumps (TDHPs). This study focuses on providing a complete taxonomy of cooling technologies. While the EU heating sector is broadly explored in scientific literature, a significant lack of data and information is present in the cooling sector. This study highlights technologies that can potentially compete and eventually replace VC systems within the decade (2030). Among others, the most promising of these are membrane heat pump, transcritical cycle, Reverse Brayton (Bell Coleman cycle), and absorption cooling. However, the latter mentioned technologies still need further research and development (R&D) to become fully competitive with VC technologies. Notably, there are no alternative cooling technologies characterized by higher efficiency and less cost than VC technologies in the EU market.

Keywords: alternative cooling technologies; Europe; potential; market; outlook

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1. Introduction

The European Union (EU) radically revised its climate and energy policy framework to ease the challenging transition from fossil fuels to renewable energy sources (RES). The EU mainly focused its efforts on reaching ambitious goals by 2020, such as a 20% greenhouse gas emissions (GHG) reduction, a 20% improvement in energy efficiency, and a 20% increase of RES share throughout the EU zone with 1990 as a baseline. Initially, these targets were set by the EU member states (MS) in 2007 and put in legislation in the Renewable Energy Directive (RES-Directive) in 2009 [1].

Different tools were put in the act, such as the Emissions Trading System (ETS), which contributes to cutting GHG emissions cost-effectively from large-scale installations in the industry and energy sector. The emissions trading system works on the "cap and trade" principle and covers 45% of the EU's GHG emissions. The remaining 55% of total EU emissions are covered by the national emission reduction targets, including housing, agriculture, waste and transport [2]. In 2018, GHG emissions were reduced by 23% from 1990 levels. Moreover, the EU aims to reduce its emissions by 40% by 2030, aiming to be the first continent to achieve carbon-neutrality by 2050, with at least a reduction of 80%–95% of GHG emissions [3].

European Union MS set national targets to increase the share in RES by 2020 under the RES-Directive, as the energy sector is responsible for more than 75% of GHG emissions. In 2018, the RES-Directive was revised, becoming the RED II, with a mandatory target for the EU of at least 32% of RES share in energy consumption by 2030 [4,5]. Moreover, the EU aims to produce more than 80% of the electricity from RES by 2050. To accomplish this, RES production needs to be increased by up to 2.5 times above the current level [6].

The EU has made a significant effort in using energy more efficiently, leading to lower energy bills, climate change resilience, and reducing the EU's dependence on external oil and gas suppliers. Each EU MS needed to set its own indicative national energy efficiency targets [5]. In 2018, the Energy Efficiency Directive, initially established in 2002, was revised. The EU energy efficiency was updated by resulting in the Energy Efficiency Directive II (EED II), and its targets were updated to a 32.5% increase by 2030 with a possible revision by 2023 [7].

In 2018, the EU's primary energy consumption (PEC) was approximately 1600 Mtoe/y, which was 5% above the 2020 target set as no more than 1483 Mtoe/y and 22% above the 2030 mark. The final energy consumption (FEC), which is considered the total energy consumed by end-users, was about 1124 Mtoe/y, which was 3% above the 2020 target and 22% above the 2030 target [5,8,9]. At this point, it is worth distinguishing between FEC and useful energy demand (UED). The latter, particularly in the cooling sector, is defined as the net heat removed from the process or space that needs to be cooled compared with the FEC for cooling, which is the cooling device's energy input [10].

The heating and cooling (H&C) sector is the single largest contributor to the PEC [11,12]. This sector includes space heating (SH) and space cooling (SC) for building comfort, domestic hot water (DHW), and industrial heat, accounting for around 800 Mtoe/y. It is followed by the transportation sector with approximately 490 Mtoe/y and the electricity sector with about 310 Mtoe/y [13]. Approximately 85% of H&C is produced from oil and gas sources, and only 15% is generated from RES [14].

Recently, the EU MS aimed to quantify energy consumption throughout different sectors properly. The MS encountered data availability issues and reliability during the H&C sector collection phase, among the SH, SC, and DHW sectors [11,15].

The effort of removing heat against the second law of thermodynamics is referred to as "cooling". Currently, cooling accounts for a relatively small share of the EU's FEC. According to the Joint Research Center (JRC), SC accounts for around 2% of the EU's FEC. If SC and PC were summed up together, the result accounts for 4% of the FEC [16]. Space cooling (SC) is defined as an amount of heat that needs to be removed from indoor air to cool the space and ensure healthy and thermal comfort conditions of the enclosed area's occupants [17]. Space cooling applications can be found in different sectors, mainly in the tertiary (offices, trade, education, health, restaurants, hotels, and other non-residential buildings) and residential (single-dwelling, multi-dwelling houses, and apartment) sectors [18]. The action of removing heat from processes, products or a confined space that contains heat to maintain the required set temperature is defined as process cooling (PC) [19]. Process cooling can be found in a large variety of sectors, such as industrial sites, commercial buildings (e.g., chest freezers in supermarkets), data centers, transport (e.g., refrigerated containers), cold storage, hospitals, greenhouses, agriculture applications, etc.

Notably, in the present text, the term "cooling" includes both SC and PC, and it is worth mentioning that the specific term is used when it needs to differentiate between them.

It has been observed that there is a constant increment in the EU specific and total FEC for SC during the past thirty years. Both the sales volume of SC equipment as well as the cooled floor area had a significant increase since 1990 [20,21]. However, its need is expected to increase significantly until 2030 and 2050 [22]. Different factors lead to the increase in cooling needs. The most relevant factors are indicated to be global warming, population growth, extreme weather events, urbanization, modern building architecture with larger glazing areas (especially in offices), and transformations in data centers [2,15,22,23].

Almost 99% of the cooling technologies market is dominated by vapor compression (VC) air-conditioning and refrigerators driven by electricity [11,24]. The remaining 1% is supplied by the thermally driven heat pumps (TDHPs), sorption cooling technology [25]. The VC technology's leading position in the market is mainly due to its low cost and excellent efficiency. Nonetheless, the halogenated alkanes, which are the most commonly used refrigerants in VC technologies, have been appointed as GHG emission contributors and, therefore, contributors to climate change. The elimination of chlorofluorocarbons (CFCs) and hydrofluorocarbons (HCFCs) refrigerants has been the object of investigation by scientists in the past three decades [26]. The evaluation of alternative cooling technologies became an impending necessity [24].

Implementing refrigerants with zero ozone depletion potential (ODP) was the industry objective almost three decades ago. Simultaneously, in recent years following the aforementioned EU legislation, attention turned to implementing system efficiency and refrigerant fluids with a low global warming potential (GWP) [27]. Moreover, alternative technologies that could have replaced the VC equipment were assessed. The need for alternative cooling technologies from the traditional VC system is emphasized because its efficiency cannot be infinitely improved, and their electrical energy source mainly comes from fossil fuels [26].

In light of what has been stated above, it is worth periodically reviewing the current state-of-the-art of alternative cooling technologies and investigating whether or not these technologies have reached a certain level of readiness to compete with and eventually replace the traditional VC. Their readiness level is commonly defined by the technology readiness level (TRL), a ranking scale from zero to nine [28]. It is also essential to present their technical advancement as it can be considered a useful indicator of their competitive status.

Remarkable attention to the topic was observed in the past thirty years, starting with research from Fisher et al. (1991), which, for the first time, extensively assessed the "not-in-kind" technology alternatives to VC technologies [26].

Brown et al. (2014) revised this research, and their work can be regarded as a "marker" for this paper. Brown et al. have already reviewed several technologies, including an assessment regarding their technological development, market viability and competitiveness with VC technology [24].

The studies of Goetzler et al. (2014) focused on researching, developing, and deploying (RD&D) essential recommendations regarding the withdrawal of support by the U.S Department of Energy (DOE) to the VC systems by identifying alternatives in heating, ventilation and air-conditioning (HVAC) sectors.

Moreso, Goetzler et al. (2017) review the previous publication by enlarging the presented range of technologies on development, which could reduce commercial HVAC energy consumption, giving high-priority to specific technology options, and enforcing recommendations to DOE and other stakeholders on potential research [29].

Lastly, Goetzler et al. (2019) ultimately reviewed their previous studies on HVAC and expanded them by including the most recent technologies.

Moreover, attention turned to the thermally activated cooling technologies from combined cooling, heating and power (CCHP) systems. Deng et al. (2011) presented their working principles in detail, such as desiccant cooling and absorption, adsorption refrigeration, and demonstrating that the CCHP are attractive technologies [30]. Summary suggestions for the proper usage of CCHP systems are provided and are a demonstration that these technologies can meet the air-conditioning, dehumidification and refrigeration needs and meet energy efficiency improvements and climate change resilience.

An interesting study was made for cooling applications, where the cold is stored in phase change materials (PCMs). Osterman et al. (2012) observed that this could keep a large amount of cold where a phase change occurs at a constant temperature with application into the building sector by increasing the thermal comfort [31]. Brown et al. (2014), Goetzler et al. (2014, 2017, 2019), and Osterman et al. (2012) review different cooling systems with particular attention to free cooling applications, encapsulated PCM systems, sorption cooling, and air-conditioning integrated with PCMs. The study demonstrated that PCMs improved energy building performances but encountered losses, heat transfer and storage issues.

Montagnino et al. (2017) focused their study on solar cooling [32]. The work is conducted by discussing the main solar cooling technology options, pointing out that innovation trends were identified both for small-scale and settlement-scale, with more than 1200 installations recorded worldwide, mainly as absorption chillers and non-tracking solar thermal panels. Unfortunately, even though some systems have been considered successful in efficiency and design, VC was identified as the most cost-effective and reliable cooling technology. Montagnino et al. (2017) state that integrated modules, adsorption of desiccant cycles, are optimal solutions for small-scale solar cooling applications. Concentrating solar power (CSP) is integrated with multi-stage adsorption chillers and could be very cost-effective for mid-large installations. The study suggests that the photovoltaic (PV) system will assist the VC cooling machine with a stable position in the market as the PV process is expected to drop in the upcoming years [32].

Moreso, De Negri et al. (2020), in their study, stated that PV is expected to contribute towards the achievement of energy and climate goals as a zero-emission electricity producer adaptable for both commercial and residential usage [33].

Exciting research was done by Liu et al. (2015) on solar thermoelectric cooling technologies, which can be powered directly by the PV without harming the environment and be used in zero energy buildings [34]. Liu et al. (2015) state that, with the advent of new materials, solar thermoelectric cooling technologies are a market promise with a coefficient of performance (COP) of 1.9, more efficient than the conventional thermoelectric cooling system, with an average COP of 0.3–0.4. The study concludes that more effort should be made in research and development (R&D) to compete with VC systems.

The energy demand of data centers has increased in recent years. Therefore, free cooling and thermal energy storage (TES) strategies research have bloomed. Orò et al. (2015) evaluate TES systems' combination with the free cooling strategy and chillers, especially during periods with a high energy efficiency ratio (EER) [35]. However, the study results show that storing the ambient air cold, chilled water by implementing TES is not recommended due to high costs.

It is worth mentioning that the present study encountered different limits since little research regarding the cooling sector can be found compared with the heating sector, which is broadly investigated in the scientific literature [12]. Although several studies are mentioned above, little information can be found regarding cooling technologies, mainly on VC systems alternatives.

In line with the studies mentioned above, the present work aims to screen the existing cooling technologies in the current market and enlarge possible alternatives. It is worth differentiating between active cooling technologies, which require external energy input to meet the cooling need, and passive cooling technologies, referred to as actions, aiming to reduce the cooling need (stores, building insulations, green roofs and blinds). In this paper, only active cooling technologies are screened and are categorized by energy input, working principle and components, physical process, active or passive solution, and purpose application, such as SC or PC. Moreover, to suggest which system could be promising and competitive in the market, relevant technical parameters (such as energy efficiency levels), market maturity, (TRLs) costs, and utilization indications per sector are provided, if available.

The study's core can be identified by creating a complete and exhaustive list of the existing cooling technologies alternative to the VC system. Moreover, to reach the study's scope, the present work aims to assess these technologies' current market, describe their development status, indicate their future potential throughout the EU, and detail their state-of-the-art most promising alternatives to VC.

The central paper's sections include Section 1 by introducing the work, locating it in a broad context, and presenting its aim. Section 2 includes assessing the main scientific paper regarding the topic, the information-gathering process, and the methodology that supported the study. Section 3 specifies the primary outcomes in findings and figures. Section 4 provides the discussion as a critical evaluation of the main results. Finally, Section 5 indicates the conclusions with the identification of potential future implications and studies.

2. Materials and Methods

2.1. Materials

For this work, an extensive bibliographical review has been carried out on alternative cooling technologies.

Notably, during the 1990s, Fischer et al. (1991) observed that CFCs, as working fluids and refrigerating equipment, grew tremendously during the 1960s and 1970s. Eventually, in the 1980s, it was confirmed that these chemicals contributed to the destruction of stratospheric ozone as the primary cause of the Antarctic ozone hole [26]. Fischer et al. (1991) conducted a study to identify chemical and technology alternatives that could replace CFCs before the 2000s. Moreover, the analysis was extended to the potential impact of these alternatives on global warming, with particular attention to hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) as alternatives to CFCs by leading to a substantial reduction in lifetime equivalent CO_2 emissions (TEWI) and global warming effects. Although Fisher et al. in the 1991 report mainly involved sustainable alternatives to working fluids and refrigerants, the point of introducing "not-in-kind" technologies that could have potentially replaced the VC equipment, was raised.

In 2014, Brown et al. provided a review of alternative cooling technologies in the context of the report by Fischer et al. [24]. In this case, Brown et al. (2014) discussed several technologies by presenting their physical working principle, state-of-the-art, and market potential, extending the study not only at the working fluids and refrigerants. The study's core was to create a taxonomy of cooling technology regarding their primary energy input, such as mechanical, electrical, acoustic, magnetic, chemical, potential, thermal, and "natural", and subdivide them by the basic working principle and the refrigerant fluid. The selection of technologies was based on their higher performance potentials and higher market promises.

Another critical research was conducted in 2014 when Goetzler et al. focused their study on the HVAC sector. The study stated that VC technology had been the dominant technology for almost a century, contributing to global climate change by releasing conventional refrigerant emissions into the atmosphere [36]. They stated that identifying sustainable alternatives to VC technologies and HVAC applications extended to the residential and commercial sectors as an objective of the study. The alternative technologies were categorized by their energy savings potential to support the U.S. DOE in further developing these technologies. The report's presented technology options were evaluated as stand-alone space conditioning systems and not as components of space conditioning systems since some were currently used. The development status and performances of the viable technology options were investigated. An estimation for unit energy savings was conducted. A scorecard analysis was created using the VC system as a baseline. Eventually, each technology rank was presented with technical energy savings potential, non-energy benefits, costs and market promises [36].

In 2017, Goetzler et al. conducted research that resulted in updates and progressions in the R&D of alternative cooling technologies considered in the same study from 2014 [29]. Through this process, the study identified 18 high-priority technologies for further development. The identification was divided into technology groups. Particularly, these groups involved topics, such as enhancing performances and energy efficiency of the present generation of HVAC systems. Goetzler et al. (2017), like in the 2014 study, listed the high-priority options and final ranking by their technical maturity. Several technologies were discovered at their initial stage of commercialization.

Further discussion of the presented technologies involved their state and complexity, non-energy benefits, and peak load demand reduction. Furthermore, Goetzler et al. (2017) provided recommendations on pursuing R&D activities on the high-priority options technologies.

Lastly, Goetzler et al. (2019) reviewed their previous study by enlarging the number of technology groups and including new systems [37].

A crucial study was made by ARMINES et al. (2016) under the EU's request. The study investigated the previous, current, and "best cooling technologies available and non-available" on the market [38]. The study mainly focused on freezers and wine coolers regarding the best available technologies, especially regarding their insulation systems, high-efficiency compressors, and variable speed drive compressors. The non-available technologies have been screened and presented their technical aspects, recent research and the TRL.

This sub-section mentions the primary sources and their respective materials, which account for a significant investigation. In more detail, the useful data and information are retrieved in the studies as follows:

- While in the report of Fischer et al. (1991), technologies, such as Stirling cycle refrigeration, Malone cycle refrigeration, evaporative cooling and thermo-elastic heat pumps were discussed and assessed, Brown et al. (2014) excluded further study investigation, stating that these technologies would not be competitive with the traditional VC market. In contrast, in this paper, discussing the technologies mentioned above has been resumed to update potential developments that were not promising in 2014 [24,26].
- The Brown et al. (2014) study focused on selecting six technologies, resulting in sorption cooling, magnetic cooling, thermo-acoustic cooling, desiccant cooling, thermoelectric cooling and transcritical CO_2 cycle technologies. Their physical principles are presented by advancements, the state of technology and the overall assessment. Moreover, Brown et al. (2014) assessed other cooling technologies based on efficiency criteria, such as the Ranque–Hilsh tube or vortex tube, and various gas cycles, e.g., Brayton cycle or Eric(c)son cycle, pulse tube refrigerator, Einstein absorption cycle, and the ejector cycle refrigeration, stating that, for the foreseeable future, they were not able to compete with the VC technology [24].
- In 2014, Goetzler et al. reported in detail the assessment of the Bernoulli heat pump, critical-flow refrigeration cycle, and electrocaloric technologies by identifying them as in the early stage of research and development (R&D). Besides, the absorption heat pump, adsorption heat pump, Brayton heat pump, duplex Stirling cycle, ejector heat pump, evaporative cooling, evaporative liquid desiccant A/C, ground-coupled solid desiccant A/C, magnetocaloric, membrane heat pump (HP), stand-alone liquid desiccant A/C, stand-alone solid desiccant A/C, thermo-acoustic, thermo-elastic, thermoelectric, thermotunneling, and Vuilleumier heat pump were assumed as the remaining viable technology options and further investigated. Lastly, the pulse-tube refrigeration and the vortex-tube cooling were excluded from the research [36]. Previous studies stated that they were not suitable for space conditioning applications [39].
- ARMINES et al. (2016) screened multiple cooling technologies still under development by describing their working principles, recent research and TRL level. The screened technologies are Insulation Improved Thermal Resistance: gas-filled panels and aerogel panels, Lorenz–Meutzner cycle refrigeration, ejector cycle refrigeration for combined refrigerator/freezer, Stirling cycle refrigeration, thermo-acoustic refrigeration, thermo-elastic refrigeration, and magnetic refrigeration. Remarkably, these are appointed as promising non-available cooling technologies [38].
- In 2017, Goetzler et al. identified eighteen technologies and divided them into four groups. The first group is named Technology Enhancements for Current Systems. It involves HVAC sensors, panels, filtration and coatings beyond the study's scope. The second group is called the Alternative Gas-Fired Heat Pumps Technologies, and

includes the Vuilleumier heat pump, ejector heat pump, and fuel cell combined cooling, heating and power system. This technology group mainly uses natural gas and a thermally activated heat pump cycle to provide heating and cool more efficiently. The third group, named Alternative Electrically Driven Heat Pump Technologies, involves membrane cooling system, metastable critical-flow cycle, thermo-elastic cooling system, Sanderson-Rocker Arm Mechanism (S-RAM), turbo-compressor-condenser-expander heat pump, electrocaloric cooling system, electrochemical heat pump and magnetocaloric cooling system. This group aims to provide a more efficient heating and cooling deployment using advanced VC or NVC technologies, with electricity as the primary energy source. The last group of technologies is named Alternative System Architecture, which involves robotic devices, dynamic clothing technologies and wearable devices for personal comfort, aiming to reduce HVAC systems' operating requirements by providing comfort to buildings. It is beyond the study's scope [29].

- Goetzler et al. (2019) analyzed different technologies in HVAC, appliances, refrigeration and water heating and assembled them into five different groups. The first group included HVAC systems, such as thermostats, control devices for space cooling and dehumidification, and hardware and software solutions for HVAC equipment. The second group, named Water Heating, focused on water heaters with smart-connected controls. The third group, named Appliances, Refrigeration, and Relevant Miscellaneous Electric Loads (MELs), focused on general appliances. The fourth group, called Related Natural Gas Technologies, included combined heat and power (CHP) systems for buildings, smart thermostats, water heaters and innovative clothes dryers. The fifth group, which included the most relevant material for the present study, is called Cross-Cutting, and groups thermal energy storage, modulating capacity vapor compression, and non-vapor compression (NVC) material and systems. Significantly, regarding the NVC technologies, Goetzler et al. (2019) stated that researchers estimate energy savings of 20% and are more significant compared to the traditional VC technologies, which may have a high potential in buildings application. Moreover, it mentioned that NVC technologies might offer energy storage that can shift grid-tied energy usage to an off-peak period and offer separate sensible and latent cooling, allowing buildings to operate at a lower energy consumption [37].

2.2. Methods

First, to produce a broad taxonomy of the current cooling technologies, an effective method was set up by starting with a comprehensive analysis of many different sources. The desk research was carried out by excluding references older than ten years and by only including the most recent sources. This is mainly due to better data and information reliability since the work aims to produce a state-of-the-art cooling technology state.

As mentioned in Section 2.1, Fischer et al. (1991), Brown et al. (2014), ARMINES et al. (2016), and Goetzler et al. (2014, 2017, 2019) were significant for the technology scouting phase [24,26,29,36,37]. Notably, to produce the cooling technologies' taxonomy, once necessary data and information for each technology were retrieved from the studies mentioned above, it was worthy of classifying them into groups and eventually deepen their technical and economic viability knowledge.

Although Brown et al. (2014) produced a division based on the primary energy input, it is worthy of mentioning that this is not the only taxonomy that could be developed. For instance, another taxonomy could be produced by operating temperature range, such as cryogenic, low, medium, or high temperatures. Another classification can be made by considering the operational fluid phases, such as gas, liquid, solid, or multiphase. Moreover, one could be based on the primary energy input type, such as thermal energy or mechanical work.

The present work aimed to produce the taxonomy by classifying each technology by dividing them into their physical form of energy input. The latter was the most accessible information, particularly by considering the electrical, mechanical, acoustic, magnetic, chemical, potential, thermal and natural energy inputs.

To complete the state-of-the-art of cooling technologies', their economic viability is considered in the study. Different parameters are investigated in the study for each cooling technology, such as market share, sector applicability, efficiency, energy input and the option to use more renewable energy than VC, costs and the TRL. Significantly TRL is individualized as the best method to evaluate the individual technology maturity grade [28]. The TRL method is based on a marker scale from one to nine, whereas nine is considered the highest level, identifying the technology as an operating system already competitive and commercialized. In contrast, one is the lowest grade, which determines the technology as non-developed, whereas only the working principle is observed.

The complete TRL rank list is presented with the Horizon 2020 (H2020) EU research program definition as follows:

- TRL 1—Basic principles observed;
- TRL 2—Technology concept formulated;
- TRL 3—Experimental proof of concept;
- TRL 4—Technology validated in lab;
- TRL 5—Technology validated in a relevant environment (industrially relevant environment in the case of key enabling technologies);
- TRL 6—Technology demonstrated in a relevant environment (industrially relevant environment in the case of critical enabling technologies);
- TRL 7—System prototype demonstration in an operational environment;
- TRL 8—System complete qualified;
- TRL 9—Actual system is proven in operation environment (competitive manufacturing in the case of key enabling technologies; or space).

Since TRL 5 means that the selected technology is validated in a suitable environment and is not only validated in the lab, as remarked in TRL 4, in this study, the cooling technologies to reach the market need TRL levels of 5 to 9. Besides, a TRL rank of 8 to 9 would be best for systems already available and commercialized.

Moreso, for a more precise allocation of the present study in a time context, a period, such as the ten years between 2020 and 2030 is identified, following the EU's GHG emissions reduction, renewable energy and energy efficiency goals mentioned at the beginning of Section 1 [2,4,6].

Regarding 2030–2050, although the EU has set different goals, as mentioned in the RED II and EED II, the projections are too distant from the present and might change over time. Therefore, 2020–2030 is set as a more realistic time for this study. From 2020 to 2030, the previous TRL classes, such as 5 to 9, regarding reaching the market, and 8 to 9 for a system already commercialized, are referred to as the closest to a realistic scenario. Generally, suppose one of these technologies reaches the market in five years. In that case, the sales could increase from 2025 to 2030 without significantly increasing the stock of cooling systems.

Lastly, it is worth mentioning that RED II aims to support the alternative technologies development, possibly in cost reduction and privileged distribution channels, and could impact the legislations of the cooling market, and with a lifetime of 10 to 25 years, the traditional VC technology's need could decrease over time starting from 2020 [4].

The main methods of the presented study are summarized as follows:

1. Analyze different sources with desk research;
2. Identify the most relevant and recent references for the study;
3. Comprehensively assess the data and pieces of information of the selected sources;
4. List and classify into categorizes the cooling technologies;
5. Deepen the investigation of the technical, economic and viability aspects of the cooling technologies;

6. Produce an exhaustive TRL classification for each cooling technology regarding their current advancement, viability status, applicability sector, efficiency and costs if available;
7. Select the most suitable alternative cooling technology based on the criteria;
8. Detail the selected alternative cooling technologies;
9. Discuss the most promising among the selected technologies.

2.3. Limits of the Study

While the heating sector is broadly investigated in scientific literature, there is comparatively little research on the cooling sector [12]. Therefore, little information can be found regarding cooling technologies, mainly on alternatives to VC systems. A great effort has been made to analyze the sources and assess the reliability of the collected data. The information and the data were not considered for the database if there were uncertainties and a lack of documentation.

Issues, such as missing data and information, were encountered during the desk research technologies scouting phase, especially regarding the technology costs. Since the alternatives to VC technology do not share any market percentage, apart from the TDHPs, it was almost impossible to retrieve a system price with VC technology as a baseline. Nonetheless, each technology is marked with a TRL level, based on reference, even in very early technology development stages. Most of the technical efficiency is assigned, while not for the cost.

In more detail, the electrocaloric cost is unknown, since this technology will use advanced materials that likely have incremental cost over time [29]. The Lorenz–Meutzner cycle (blends only) costs were not identified [36]. The transcritical cycle efficiency is still unknown since it depends on its refrigerant leak rate [24]. The S-RAM encountered efficiency and cost identification issues, although it has been said that it could provide 30%–50% energy savings for commercial rooftop units thanks to variable capacity capabilities [29]. The turbo-compressor-condenser-expander HPs have an unknown cost due to limited information [29]. The pulse tube cost is not identified. The Stirling/Eric(c)son cycles: reverse Stirling has an unknown cost and duplex Stirling, although it has been observed that installation and O&M could be simpler than VC [36]. The reverse Eric(c)son cycles cost is not identified [36,40]. The Reverse Brayton (Bell Coleman cycle) cost is unknown [36]. The elastomeric effect cost is not identified, and no applications are identified [36]. The (metastable) critical-flow cycle cost is unknown so far [29]. The magnetocaloric technology cost is unknown for air-conditioning applications, but regarding supermarkets, from 1 to 5 years of payback period has been identified [29]. However, the cost of magnets can be an issue [36]. The heat of reaction technology efficiency is unknown, and the cost is not identified [41,42]. In the natural convection (heat exchanger mixing), both the efficiency and the costs are not identified, although its technical maturity is high with given market availability. This lack of information is mostly due to its very low market penetration. However, significant R&D efforts have been made regarding this technology [43–46]. Moreso, for the natural conduction (heat exchanger), the efficiency and cost are not identified with the same reasons for the natural convection technology. The evaporative cooling (water evaporation) technology efficiency is not identified [36]. The enthalpy recovery (heat exchanger) efficiency and cost are not individualized [29]. Lastly, the sky radiative cooling technology efficiency and cost are not identified due to its early development stages [45].

3. Results

3.1. Taxonomy of the Cooling Technologies and Main Features

In the list, the technologies are categorized by the physical form of energy input, basic working principle, phase of the working fluid, refrigerant or heat transfer medium, specific physical process or device, active or passive solution, and SC or PC application. While Brown et al. (2014) categorized the cooling technologies based on their primary energy input, basic working principles, the phase of the working fluid, and the refrigerant or heat transfer medium, the present study extends the work by including the specific physical process or device, active or passive solution, and SC or PC application.

Figure 1 provides the resulting taxonomy of cooling technologies.

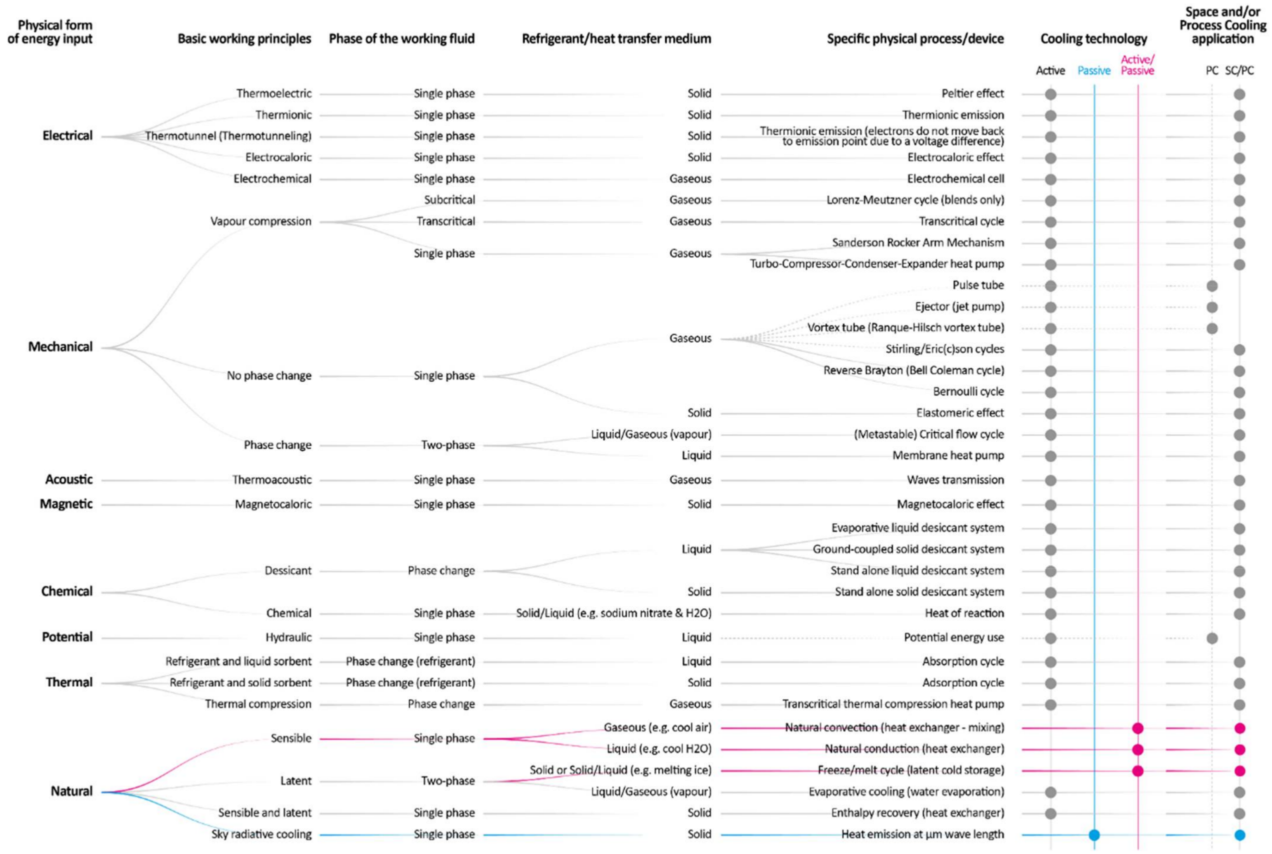

Figure 1. Taxonomy of cooling technologies.

Figure 2 better visually identifies the selected cooling technologies options for the study. Compared with Figure 1, Figure 2 grouped Lorenz–Meutzner cycle (blends only), transcritical cycle, Sanderson-Rocker Arm Mechanism, and turbo-compressor-expander under the vapor compression technology. Besides, reverse Stirling, duplex Stirling, Vuilleumier HP, and reverse Eric(c)son devices are entailed under the Sterling/Eric(c)son cycles. Lastly, the evaporative liquid desiccant systems, ground-coupled solid desiccant systems, stand-alone liquid desiccant systems, and stand-alone solid desiccant systems are included under the desiccant cooling devices.

The phase of the working fluid, refrigerant or heat transfer medium, specific physical process or device, active or passive and SC or PC application categories are excluded from Figure 2 to present only the physical form of energy input and their working principle.

3.2. Selection of Alternative Cooling Technologies

The current section aims to present, in detail, alternative cooling technology to VC at their state-of-the-art. The description of each identified technology indicates, whenever possible, vital technical parameters, such as energy efficiency, market maturity by using the TRL classification, stock and sales costs regarding installation, operation and maintenance (O&M), reparation and dismantling, and sector utilization recommendations.

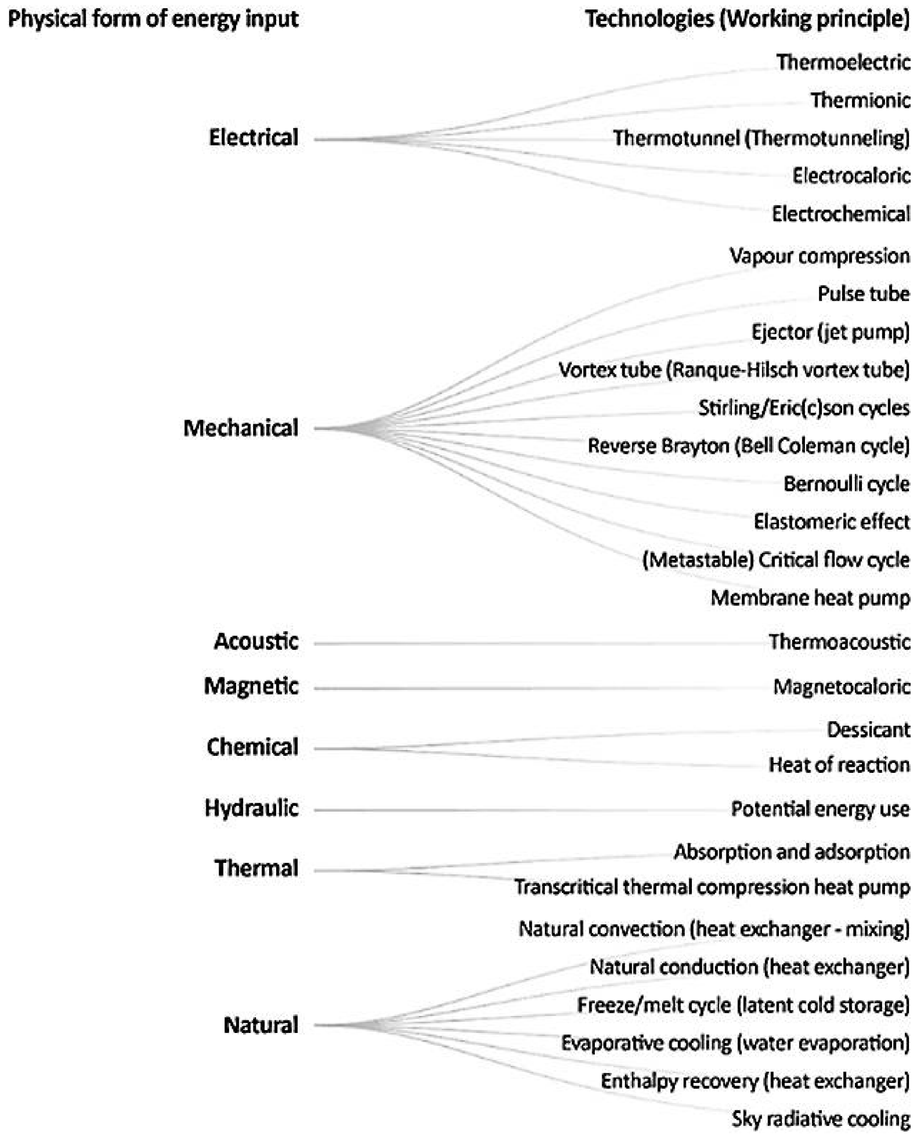

Figure 2. List of the identified cooling technologies.

Regarding the TRL methods, it is worth mentioning that the assigned levels are established either by evaluating the most recent information obtained or by collecting the most recent sources throughout the literature review. Notably, 2019 is designated as the most recent year as a baseline for the information evaluation. Moreover, only the technologies reaching a TRL level of 8 or 9 are available on the market. Table A1 summarizes the central technical and market-related economic features of the taxonomy of cooling technologies.

As specified in Section 2.2, identifying the present study in a specific time context is necessary to select the promising alternative cooling technologies. These technologies entering the cooling market have to compete with the VC's reference cooling technology. Different parameters are considered to identify the best alternative technology options, such as the TRL, the energy efficiency and the cost. The details of the parameters are discussed in the bullets below:

- TRL: a mark from 5 to 9 is set as the most promising baseline for the cooling technologies to reach the market in the upcoming future. Consequently, only the technologies presented in Table A1 that have reached these certain levels are selected.

- Energy Efficiency: the technologies' energy efficiency is indicated in Table A1 with VC efficiency as a baseline. Only the technologies with equal or higher efficiencies are considered.
- Costs: the technology costs are presented in Table A1, with the VC costs as a baseline. Consequently, only the technologies with equal or lower costs are considered being competitive with VC.

In the application of the aforementioned criteria, the reader should consider that an exhaustive technological description of the proposed technologies is beyond the scope of this manuscript.

As a result of the selection process, no cooling technology with a TRL level between 5 to 9, higher efficiency, and lower cost than VC is identified in Table A1. However, the membrane HP technology meets the requirements, since it presents a TRL from 5 to 6, a higher efficiency (assumed), and an equal cost (assumed). Therefore, there is a need for this technology to be further detailed.

To present more technologies, apart from the membrane HP, it is necessary to further scout Table A1 by considering technologies with lower efficiency and higher cost but again with a TRL from 5 to 9. The research results are transcritical cycle, with up to 9 levels of TRL, unknown efficiency, and a higher cost than VC; the pulse tube, with 6 of the TRL levels, but lower efficiency is not an identified cost compared to VC. Moreover, the Reverse Brayton (Bell Coleman cycle) marks 5 to 9 on the TRL level, with lower efficiency and an unknown cost than VC. The potential energy use was marked at a TRL level from 6 to 9 without identifying both efficiency and cost. Additionally, natural convection (heat exchanger–mixing), natural conduction (heat exchanger), and the freeze/melt cycle (latent cold storage) marked up to 9 on the TRL level, with efficiency and cost not identified. Moreover, in evaporative cooling (water evaporation), the efficiency is not identified with the TRL level up to 9. The cost is marked as equal whenever the technology is used as an independent system. Lastly, with a TRL from 7 to 8, the enthalpy recovery (heat exchanger) efficiency and cost are not identified. The aforementioned technologies are summarized in presented below (Table 1).

Table 1. Shortlist of the alternative cooling technologies presented in Table A1 (Appendix A).

Technology	TRL (Year)	Efficiency (Compared to VC)	Costs (Compared to VC)
Transcritical Cycle	Up to 9 (2016)	Higher (depending on climate, refrigerant mixture, and energy-efficient solutions) [46]	Higher [36]
Pulse Tube	6 (2014)	Lower [36]	Not identified
Reverse Brayton (Bell Coleman Cycle)	5–9 (2011)	Lower [47]	Not identified
Potential Energy Use	6–9 (2019)	Not identified	Not identified
Electrochemical	3–4 (2017)	Higher (Assumption) [36]	Unknown
Natural Convection (Heat Exchanger–Mixing)	Up to 9 (2019)	Not identified	Not identified
Natural Conduction (Heat Exchanger)	Up to 9 (2019)	Not identified	Not identified
Freeze/Melt Cycle (Latent Cold Storage)	Up to 9 (2019)	Not identified	Not identified
Evaporative Cooling (Water Evaporation)	Up to 9 (2019)	Not identified	Equal (When used as an independent system) [36]
Enthalpy Recovery (Heat Exchanger)	7–8 (2017)	Not identified	Not identified

As evident from the above, several technologies present high TRL levels and do not identify information concerning system efficiency and cost parameters. In Table A1, absorption and adsorption technology (also referred to as TDHPs) is marked with a TRL from 3 to 9, lower efficiency, and higher cost than VC. Although the TRL level does not match the set criteria mentioned above, starting with a rate of 3 and reaching the level of 9, as mentioned in Section 1, TDHPs are commercialized and supply 1% of the cooling market share. It is worth further investigating and presenting of this technology.

Overall, the following technologies are identified to have at least two out of three parameters identified, and therefore are chosen to be further investigated and presented:

- Transcritical cycle;
- Pulse tube;
- Reverse Brayton (Bell Coleman cycle);
- Membrane HP;
- Evaporative cooling (water evaporation);
- Absorption and adsorption.

3.3. Presentation of Alternative Cooling Technologies

3.3.1. Transcritical Cycle

In the current study, the transcritical cycle is grouped under the mechanical form of energy input and VC technology. It is necessary to distinguish among different working fluid phases, such as single-phase, subcritical, and transcritical. In this technology, the working fluid phase, which is a heat transfer medium that is gaseous, is transcritical.

Working principle

The technology refers to its working principle as a thermodynamic cycle, in which the working fluid passes through both supercritical and subcritical states. Notably, the transcritical cycle is a VC refrigeration cycle, and heat rejections happen above the refrigerant's critical temperature, CO_2, because of its low critical temperature, approximately 31° [48]. Transcritical cycle presents the same processes as the traditional VC technology, such as heat addition, compression and expansion. During the heat rejection process, the working fluid does not change its phase. Instead, its pressure, temperature and density change continuously during the process [49–51].

Status quo

Over the past twenty years, especially from the mid-1990s, R&D has been very active concerning the topic [52,53]. It was first proposed in the early 1990s, with regards to the global warming reduction due to the impact of HFC-based air-conditioners and refrigerators systems. The focus was that the system efficiency, the refrigerant's GWP and the leak rate impact the climate. Several technology applications have been investigated, predominantly residential air-conditioners, HP and automotive air-conditioners [51]. Remarkably, the sector which gave much attention to the transcritical cycle CO_2 is automotive air-conditioning. The latter can be applied to SC and PC.

Brown et al. (2014) marked this technology with high-performance potentials and thus, high market promise [24]. Recently, there have been debates on whether transcritical cycle CO_2 instead of traditional HFC VC equipment could significantly reduce climate impact for individual applications. It should be noted that climate impact strongly depends on system efficiency, the refrigerant's global warming potential (GWP), and particularly its leak rate [24].

Regulations aim to steadily phase down the deployment of high GWP refrigerants. Therefore, the application of the transcritical cycle CO_2 interest has been increased. This technology could probably be an area of interest with a possible larger-scale commercial introduction, which could lead to a cost system reduction for more competitiveness. For instance, if large-scale commercialization is realized, the small-scale installation benefits from the large volumetric cooling capacity of CO_2.

TRL

With reference, the TRL for this cooling technology has been assessed with a mark of up to 9 [52].

Evaluation

In the rising concern of climate change, utilizing natural refrigerants has become a necessity. CO_2 has a low GWP, and it is non-flammable and non-toxic. Hence, a transcritical CO_2 refrigeration system becomes an alternative solution to the conventional systems, mostly based on harmful synthetic refrigerants. In the applications requiring strict compliance with safety regulations, it is the chief solution. In cold ambient temperature regions, it is more energy-efficient compared to the most conventional VC systems. For applications in high ambient temperature regions, it becomes competitive with the implementation of energy-efficient solutions (ejectors, parallel compression, thermal energy storage, etc.) and integrating heat recovery options for space heating, domestic hot water and air-conditioning (AC). The CO_2′s unique thermodynamic and transport properties make it possible to extract heat more effectively for heating purposes. Integrated transcritical CO_2 refrigeration systems supported with energy-efficient solutions have less power consumption, compared to the power consumption of the conventional systems separately meeting different demands [53–55]. By integrating renewable energy sources, the performance of the system can be enhanced. It is worth mentioning that the solar-assisted transcritical CO_2 could reach a COP of 13.5 and decrease the electricity intake by 53.6% compared to traditional transcritical CO_2 machinery [46]. Additionally, by integrating CO_2 in refrigerant blends, H&C performances can be improved. It has been observed that a 60% CO_2-propane combination could grant comparable performances to R134a, which is mostly applied in traditional VC systems. It is important to state that CO_2 is non-flammable and non-toxic and has no controls obligation due to its low GWP [56]. Lastly, through effective control measures, these types of machinery operate safely over a long time by controlling the high side pressure and gas cooler outlet temperature. However, an issue that needs to be pointed out, that could make this technology less attractive than the traditional VC could be the cost [24]. Overall, the transcritical CO_2 technology could suit as a feasible acceptable choice worldwide for numerous purposes with high performances, competitive costs, and a positive environmental impact.

3.3.2. Pulse Tube

This technology has been categorized under the mechanical form of energy input in the present study, with a single-phase change in the working fluid. Its heat transfer medium is gaseous.

Working principle

The pulse tube is a tube with an open- and closed-end. This technology involves different components, such as a regenerator, pulse tube, pressure wave generator, and two heat exchangers. This device's working process is called surface heat pumping by transporting heat against a gradient of temperature. The tube's hot end is the closed-end, capped with a heat exchanger, cooled by the ambient temperature. In contrast, the open end is the cold end, connected to the regenerator by the second heat exchanger. A pressure wave generator is connected to the hot end and provides the pressure gradient oscillations which drive the refrigeration [57]. The working fluid is manly helium. The reference sink temperature of the pulse tube can vary between 20° and 45°.

Status quo

Research activity has been carried out in the past decades regarding this technology. Notably, Brown et al. (2014) marked this technology as not competitive with VC systems due to the applicability limitations, mainly involving the PC sector [24]. Moreso, Goetzler et al. (2014) screened out the pulse tube technology throughout their research, since it was not considered suitable for space conditioning [24]. This technology's applicability is mainly for cryocooling, since it can reach significantly low temperatures, such as −170° to −270°. Regarding its efficiency, COP levels in cryocooling have reached values from 0.01 to 0.10. Several applications include the cooling of sensors, gas liquefaction, medical specimens and superconductors. In terms of capacity, especially for low temperatures and cryocooling applications, most systems have ranged from 0.5 to 100 W [29]. Moreso, this technology can reach approximately 33,000 h of operation [29]. Although some methods mitigate it, they are characterized by a relatively noisy operation [57–59].

TRL

With reference, the TRL for this cooling technology has been assessed with a mark of 6 [60].

Evaluation

The pulse tube's technical maturity has not been reached yet. It has not been developed for SC yet, mainly due to its cooling efficiency, which is still low compared to VC [36]. Moreover, regarding its environmental footprint, the pulse tube does not offer energy savings compared to VC technology and R&D, concerning its SC applications is too little yet [29]. Overall, according to the previous studies mentioned above, this technology cannot be marked as promising to be very competitive with the VC in both SC and PC sectors. It is more likely that the pulse tube will find and capture its market share as a niche in cryocooling applications in the PC sector.

3.3.3. Reverse Brayton (Bell Coleman Cycle)

In the current study, this technology is grouped under the mechanical form of energy input, with a single-phase change in the working fluid. Its heat transfer medium is gaseous.

Working principle

Generally speaking, the Brayton cycle works as a constant-pressure heat engine and, set in a reverse mode, is named Reverse Brayton. To achieve the cooling effect, gas is compressed, cooled, and expanded inside the system. At the end of the expansion process, the gas temperature is low and can be used to cool and enclose directly or indirectly. Mainly the utilized gas inside the cycle is air.

Status quo

The Reverse Brayton has achieved market success in an application where traditional VC systems encounter significant issues. Thanks to its simple design, high reliability, low O&M requirements, and ability to reach significant low temperatures, this technology has already conquered transportation SC in aircraft, trains, ships, commercial and industrial refrigeration, and freezing, such as cold storage, blast freezing, and cryocooling. Moreover, the Reverse Brayton can be commonly found in the Liquefied Natural Gas (LNG) industry for sub-cooling applications. Although it has broad applicability, Reverse Brayton has limited potential due to its low COP levels. On average, COP ranges are around 0.5 to 0.8, below conventional VC system efficiencies. Therefore, Reverse Brayton is not expected to provide more energy savings than VC [36,57]. The possibility of cooling a permanently inhabited lunar base with this technology has even been explored [61].

TRL

This technology is evaluated with a TRL level from 5 to 9.

Evaluation

As an overall assessment, it can be said that Reverse Brayton technology is mostly preferable in SC applications in aircraft, trains and ships, detaining a significant amount of market in the transport SC. A large market share is detained by the commercial and industrial refrigeration sector and freezing. Lastly, it has applications in the LNG sector. With further R&D, this technology could also lead to building SC, which is not available yet; and eventually, this will be competitive with VC technology in all market sectors.

3.3.4. Membrane HP

In the present study, the membrane HP is classified under the mechanical and physical forms of energy input groups. The phase change of the working fluid, which its heat transfer medium is liquid, is two-phase.

Working principle

The membrane HP can provide sensible cooling with the same principles used in the evaporative chiller. It provides cooling and dehumidification by transferring moisture across several membranes using a vacuum pump. Virtually, when the working fluid, which is the outside air, has dew points higher than the coil temperature, the membrane HP system can continue to provide sensible cooling by water vapor transfer membrane. Moreover, these systems can dehumidify the supply air [62].

Status quo

Regarding its applicability, it can be said that it is technically applicable to all residential and commercial buildings. Moreover, it is technically viable for all climate regions and building types. The membrane HP is viable for both SC and PC applications [29].

Regarding recent developments, the membrane HP is in the second generation prototype stage. These prototypes are designed approximately with the same size as the VC systems, with the same capacity. The membrane HP has moderate cooling capacity ranges, such as from 4 to 30 kW [29,60]. Although it uses a membrane that is already commercialized for energy recovery ventilators, the membrane HP is not commercialized yet. Regarding energy efficiency, the energy efficiency ratio (EER) is set by researchers as twice as much as the VC technology, resulting in energy savings of 50% [36]. Concerning the cost, it is assumed that this technology has approximately the same price as the VC technology [29]. Technically, the installation and the O&M procedures are comfortable and can be compared with the VC. Moreover, it is still unclear whether this technology can produce less noise for the VC. Lastly, regarding the environmental footprint, the zero-GWP working fluid, such as the air utilized in the system, can reduce direct GHG emissions [63].

TRL

With reference, the TRL for this cooling technology has been assessed at a level of 5 to 6 [29].

Evaluation

As an overall assessment, it can be said that this technology can positively help to reduce peak energy demands due to its better efficiency compared with VC. As mentioned in Goetzler et al. (2019), a certain amount of R&D still needs to be carried out, such as developing and testing prototypes and validating performances to compete with the VC technology market [37]. Following Goetzler et al. (2014), this work marks the membrane HP as a promising technology [36]. Mainly regarding SC in commercial buildings, it can increase comfort and efficiency.

3.3.5. Evaporative Cooling (Water Evaporation)

In this work, this technology is categorized under the natural physical form of energy input, with latent cooling as a working principle, with a two-phase change as liquid and gaseous (vapor) heat transfer medium.

Working principle

The evaporative cooling (water evaporation) technology uses the effect of evaporation as a natural heat sink. The air provides sensible heat, which is absorbed and used as latent heat to evaporate the water. The amount of water that can evaporate regulates the amount of sensible heat that can be absorbed [64,65].

Status quo

Regarding the evaporative cooling (water evaporation) technology, it was already discussed as state-of-the-art in the report by Fischer et al. (1991) and at the time, was evaluated as not competitive with VC for comfort cooling and near-room temperature refrigeration [26]. Brown et al. (2014) reviewed the technology and revealed that no significant progress was made, and therefore, in this study, it has been excluded from a further investigation [24,48]. This technology reached a far low market penetration since it has specific inabilities to meet moisture removal requirements at all times, even in hot-dry climates. Moreover, it has a high water consumption level and complexities in supplying water installation equipment and O&M concerns [36]. In the SC sector, this technology can be found in applications both for residential and commercial buildings. It can be installed in all the building types, but only in hot-dry climate regions [36]. Moreover, it can also be found in PC applications. These devices' typical water utilization efficiency is 50%, consuming nearly 4 L of water per 3.5 kW of capacity installed in one operating hour [36].

TRL

This technology reaches a TRL level of up to 9.

Evaluation

It can be said that the evaporative cooling (water evaporation) technology has advantages, such as the cost, which is around as much as the equivalent VC systems [36]. The disadvantages are that the system is not well designed; these issues include excessiveness of humidity in the air and energy waste. Overall, because this technology has some geographical applicability restrictions, as well as installation complexity, high dependence on water supply, and O&M concerns, this technology cannot be marked as promising, since it is clear that it has no possibility for competing throughout the EU with the VC, but only in certain areas with hot-dry air climate.

3.3.6. Absorption and Adsorption

In this work, this technology is categorized under the thermal physical form of energy input, with refrigerant and liquid sorbent as a working principle for absorption and with refrigerant and solid sorbent as a working principle for adsorption. Respectively, the heat transfer medium of the working fluid is liquid for absorption and solid for adsorption.

Working principle

Mainly sorption cooling devices (also named TDHPs) use the same principle as VC. The heat is moved due to the evaporation and condensation of a refrigerant. The ab-/adsorption chillers are powered by natural gas or other heat sources, such as process steam, solar thermal and waste heat instead of electricity. Moreover, these technologies do not need a compressor for generating the pressure differences needed, but they use an ab-/adsorber, a pump and a generator [23].

Status quo

In the EU, sorption cooling technology covers around 1% of the market share. In contrast, in countries, such as Japan or China, sorption chillers' installed capacity represents a large fraction of the sold cooling types of machinery. The triple effect chillers and the generator absorber heat exchanger (GAX) technology have been introduced in the past twenty years. These technologies have been applied in residential and small commercial sectors by developing smaller, single effect, gas-fired ammonia/water absorption systems [66]. The GAX technology can improve the COP by 10%–40% compared to traditional ammonia/water absorption systems. For large commercial applications, several manufacturers offer lithium bromide (LiBr) absorption chillers. Sorption cooling received great R&D efforts for applications involving waste heat recovery (e.g., industrial processes, fuel cells and gas turbines), low-temperature sources (e.g., solar and geothermal), and tri-generation (cooling, heating and power). Mainly, the most extensive applications can be found in absorption instead of adsorption cooling. This is related to the fact that the refrigerant is liquid in absorption cooling, and adsorption is solid. Brown et al. (2014) presented in their study, absorption cooling as one of the six promising alternatives to VC technologies [24]. This technology has SC and PC applications [36].

TRL

With reference, this technology has been assessed with a TRL level from 3 to 9 [67].

Evaluation

As an overall assessment, it can be said that absorption cooling technology detains positive potential since it has applications in both residential and commercial sectors. Moreover, it can be deployed for district cooling (DC) systems. Issues concern efficiency and cost. The COP values range between 0.5 and 0.7 without offering any savings in residential and light commercial sectors compared to VC systems [36]. Moreover, the costs are around 300% more than traditional VC systems [36,63]. However, solar thermal absorption cooling marks higher electrical efficiency and a TRL from 7 to 8, and waste thermal absorption cooling marks higher electrical efficiency with significant potential applicability for DC. Overall, since this technology's energy input involves RES, and regulations and incentives significantly support this technology, absorption cooling can be a promising alternative to VC [15,24,25,64–66].

4. Discussion

In this study, two TRL ranges have been considered, such as the first starting from 1 to 4 and the second starting from 5 to 9. The first range of technologies is excluded from any further investigation since they are declared not competitive over 2020–2030. The technologies which reach a TRL from 5 to 9, such as the transcritical cycle (up to 9), pulse tube (6), Reverse Brayton (Bell Coleman cycle) (5–9), membrane HP (5–9), potential energy use (6–9), natural convection (heat exchanger mixing) (up to 9), natural conduction (heat exchanger) (up to 9), freeze/melt cycle (latent cold storage) (up to 9), evaporative cooling (water evaporation) (up to 9), and enthalpy recovery (heat exchanger) (7–8), can be further investigated in terms of efficiency and cost.

Having a higher efficiency and lower cost than VC systems could make one of these alternative cooling technologies competitive to VC and the preferable option. However, after further scouting, it can be concluded that, as visible in Table A1, there are no cooling technologies that can be considered competitive to the VC devices so far. However, with an equal cost (assumed), only the membrane HP from the previous list marks higher (assumed) efficiency. Its TRL level, from 5 to 9, makes this technology promising in SC applications, especially for commercial buildings, with higher (assumed) efficiency compared to VC that can reduce peak loads during high energy demands. It is the only technology in Table A1, which has all three parameters identified and meets all the requirements.

To present more technologies, attention turned to other systems that have two out of three parameters identified, with even lower or equal efficiency or lower or equal price than VC technologies. The identified systems are transcritical cycle (higher cost), pulse tube (lower efficiency), Reverse Brayton (Bell Coleman cycle), and evaporative cooling (water evaporation).

Particularly, Brown et al. (2014), already paid attention to the transcritical cycle. Its state-of-the-art is reviewed by stating that CO_2 can be an adequate substitute to high GWP refrigerants, with the potential to be sponsored with easy regulations and laws, with VC's competitiveness in cost (higher), O&M, and installation, especially for large capacities. Its system works with the same principle as the VC, which is already commercialized, and it can be more comfortable for the transcritical cycle to create its own space on the market once the R&D phase is complete [24]. As VC, this technology can find applications in both SC and PC, which can be remarked as promising. In contrast, the pulse tube is marked with lower efficiency than VC and is restricted only in PC applications, although too little information can be found, and more R&D is required. Brown et al. (2014) and Goetzler et al. (2014) already screened out this technology in their study. Therefore, based on previous research, this technology is not considered a promising alternative to compete with VC [24,36]. Besides, the Reverse Brayton (Bell Coleman Cycle), although marked with lower efficiency than VC, has found several applications in SC, including aircraft, trains, ships and PC, such as the refrigeration and freezing LNG sectors. Although this technology did not find any SC in building applications yet and requires further R&D, it can be considered a promising alternative thanks to its simple design, high reliability, low O&M requirements, and ability to reach significant low temperatures. Lastly, the costs of evaporative cooling (water evaporation) have been assessed as equal to the VC system used as an independent system. However, there are issues regarding its design and applicability, especially related to geographical location. Therefore, it has not been assessed as a promising solution that can compete with VC technology [68].

Although absorption and adsorption technology shows a TRL range starting from 3 instead of 5, all three parameters were identified during desk research, as set in the criteria.

Therefore, it has been decided to further scout and present this technology [69]. Overall, according to previous studies, absorption and adsorption are considered to be a promising solution, with significant R&D activity, RES as an energy input, and a generous incentives scheme, especially for solar thermal absorption cooling in several EU MS, as remarked by Rowe et al., and waste thermal absorption cooling for DC [70].

In the bullets below, the alternative cooling technologies, which are marked as promising in this study, are listed:

- Membrane HP;
- Transcritical cycle;
- Reverse Brayton (Bell Coleman cycle);
- Absorption cooling.

It is worth mentioning, that not only the technologies included in Table A1 are considered sustainable solutions. The combination of VC and PV can be a sustainable solution by obtaining the sun's electricity input required by VC. Depending on climate and global irradiation, it has higher efficiency, but there are also limitations, such as higher installation and O&M costs associated with space constraints with rooftop installation [71]. Another promising solution is the cold recovery in building panels, ranked with a TRL from 7 to 8, with a higher efficiency and lower price than VC. Besides, it has some limitations, such as that it can be designed and installed in brand new buildings that have limitations with the older ones. Additionally, also worth mentioning are the cold recovery in air handling unit (AHU) or rooftop, direct ambient air free cooling, which both require AHU. Furthermore, the indirect ambient air free cooling, use of liquid with natural or waste cold source, evaporative cooling, direct, indirect, direct + indirect, and cold storage (centralized) have higher efficiency than VC technology.

5. Conclusions

The present study constructs a complete taxonomy of the cooling technologies, including their main features, with an overlook of the European market from 2020 to 2030. The main discovery of the current work has been that, currently, there are no cooling technologies ready to compete with vapor compression technology in the European Union market.

Overall, it has been observed that the vapor compression technology shares around 99% of the European market with a technology readiness level of up to 9 (2019). While the remaining 1% of the European fair is detained by the thermally driven heat pump machinery, which is a sorption cooling technology with a readiness level of 3 to 9 (2014).

As aforementioned, Figure 1 visually presents the taxonomy of cooling technologies, while Table A1 presents their main features. As can be understood from Figure 1, and Table A1, currently there are technologies with a readiness range from 5 to 9. Notably, such technologies are characterized by a transcritical cycle (up to 9), pulse tube (6), Reverse Brayton (Bell Coleman cycle) (5–9), membrane heat pump (5–9), potential energy use (6–9), natural convection (heat exchanger mixing) (up to 9), natural conduction (heat exchanger) (up to 9), freeze/melt cycle (latent cold storage) (up to 9), evaporative cooling (water evaporation) (up to 9), and enthalpy recovery (heat exchanger) (7–8), which mark an appropriate level of readiness. Moreover, Table A1 details the main features, essential for this study, such as efficiency and costs, by which, the following threshold equal or higher (compared to vapor compression), has been considered as competitive in the European market.

In the list of the cooling technologies, only the membrane heat pump (5–9) meets all the requirements in terms of the readiness level, efficiency and cost. To present more solutions, technologies with two out of three parameters identified have also been assessed, such as the transcritical cycle (up to 9), pulse tube (6), Reverse Brayton (Bell Coleman cycle) (5–9), and evaporative cooling (water evaporation). Moreso, absorption and adsorption (3–9) have been included in the presentation since it contributes to 1% of the European market share.

After the evaluation phase, the membrane heat pump, transcritical cycle, Reverse Brayton (Bell Coleman cycle), and absorption cooling have been appointed as promising solutions that can compete with the vapor compression technology. Although the remaining technologies present readiness levels from 5 to 9, there is a significant lack of information regarding cost and efficiency. Therefore, the efficiency cannot be further assessed and compared to vapor compression since they have only one out of three parameters identified. It has been stated that the remaining technologies on the list, with a readiness between 1 and 4, need more research and development. In addition, some solutions and recommendations were presented in Section 4, such as combining the vapor compression technology with renewable energy sources.

In conclusion, it is worth highlighting the fact that there is a significant lack of information regarding the technical and economic aspects of alternative technology to vapor compression. By scouting the sources of information for this study, it was difficult to retrieve a large amount of data, and most of them are not available or are outdated, fragmented, or not accessible.

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Conflicts of Interest: The information and views set out in this article are those of the author and do not necessarily reflect the official opinion of the European Commission.

Appendix A

Table A1. Main feature of cooling technologies.

Technology	TRL (Year)	Sector	Efficiency	Costs
Thermoelectric	4 (2016)	SC/PC	Lower [36]	Equal (Assumption) [34]
Thermionic	2 (2014)	SC/PC	Higher (Assumption) [36]	Equal (Assumption) [36]
Thermotunnel	2 (2019)	SC/PC	Higher (Assumption) [36]	Equal (Assumption) [47]
Electrocaloric	2 (2019)	SC/PC	Higher (Assumption) [36]	Unknown
Electrochemical	3–4 (2017)	SC/PC	Higher (Assumption) [34]	Unknown
Vapour Compression: RACs and CACs	Up to 9 (2019)	SC/PC	-	-
Lorenz-Meutzner Cycle (blend only)	4 (2019)	SC/PC	Higher (Assumption) [47]	Not identified
Transcritical Cycle	Up to 9 (2016)	SC/PC	Unknown	Higher [36]
Sanderson Rocker Arm Mechanism	3–4 (2017)	SC/PC	Unknown	Unknown
Turbo-Compressor-Condenser-Expander HPs	3–4 (2017)	SC/PC	Higher (Assumption) [36]	Unknown
Pulse Tube	6 (2014)	PC	Lower [36]	Not Identified

Table A1. *Cont.*

Technology	TRL (Year)	Sector	Efficiency	Costs
Ejector (Jet Pump)	3 (2014)	PC	Lower [36]	Lower (Assumption) [47]
Vortex Tube (Raque–Hilsch Vortex Tube)	4 (2014)	PC	Lower [36]	Lower [36]
Stirling/Eric(c)son Cycles: Reverse Stirling	4 (2017)	SC/PC	Lower [36]	Unknown
Duplex Stirling	3–4 (2017)	SC/PC	Lower [47]	Unknown
Transcritical Cycle HP	3–4 (2017)	SC/PC	Lower [36]	Lower (Assumption) [36]
Reverse Eric(c)son Cycles	4 (2019)	SC/PC	Lower [47]	Not identified
Reverse Brayton (Bell Coleman Cycle)	5–9 (2011)	SC/PC	Lower [36]	Not identified
Bernoulli Cycle	3–4 (2017)	SC/PC	Lower [47]	Equal (Assumption) [47]
Elastomeric Effect	2 (2016)	SC/PC	Higher (Assumption) [47]	Not Identified
(Metastable) Critical Flow Cycle	3–4 (2017)	SC/PC	Lower [47]	Unknown
Membrane HP	5–6 (2017)	SC/PC	Higher (Assumption) [36]	Equal (Assumption) [47]
Thermoacoustic	4 (2016)	SC/PC	Lower [36]	Equal (Assumption) [47]
Magnetocaloric	3–4 (2016)	SC/PC	Higher (Assumption) [47]	Unknown
Desiccant: Evaporative Liquid Dessiccant System	3–4 (2019)	SC/PC	Higher (Assumption) [36]	Equal (Assumption) [36]
Ground-Coupled Solid Desiccant System	3–4 (2017)	SC/PC	Higher [47]	Higher (Assumption) [36]
Stand-Alone Liquid Desiccant System	3–4 (2017)	SC/PC	Lower [36]	Higher (Assumption) [36]
Stand-Alone Solid Desiccant System	3–4 (2017)	SC/PC	Lower [47]	Higher [36]
Heat of Reaction	2 (2019)	PC	Unknown	Not identified
Potential Energy Use	6–9 (2019)	SC/PC	Not identified	Not identified
Absorption and Adsorption	3–9 (2014)	SC/PC	Lower [47]	Higher [47]
Transcritical Thermal Compression HP	4 (2019)	SC/PC	Lower [36]	Higher [47]
Natural Convection (Heat Exchanger–Mixing)	Up to 9 (2019)	SC/PC	Not identified	Not identified
Natural Conduction (Heat Exchanger)	Up to 9 (2019)	SC/PC	Not identified	Not identified
Freeze/Melt Cycle (Latent Cold Storage)	Up to 9 (2019)	SC/PC	Not identified	Not identified
Evaporative Cooling (Water Evaporation)	Up to 9 (2019)	SC/PC	Not identified	Equal (When used as independent system) [36]
Enthalpy Recovery (Heat Exchanger)	7–8 (2017)	SC/PC	Not identified	Not identified
Sky Radiative Cooling	3–4 (2019)	SC/PC	Not identified	Unknown

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