Report on Cooling Technologies, Market, Best Practices and Planning in Europe

Cooling Down

Deliverable number: D2.1

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Project Full Title:	Unlocking the potential of renewable cooling for a decarbonised cooling sector fit for the climate of the 21st century
Project Acronym:	COOLING DOWN
Grant Agreement No.	101077140
Title:	Report on Cooling Technologies, Market, Best Practices and Planning in Europe
ORCID:	

Approval status			
	Name	Function	Date
Deliverable responsible	**Fh. IEG**	Draft by Task leader	14/04/2024
Review by partners	**all**	Comments by partners	18/04/2024
WP leader	**Fh. IEG**	Validation by WP leader	25/04/2024
Final Version by project coordinator and WP leader	**EGEC**	Validation	30/04/2024

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Table of Contents

TABLE OF CONTENTS 3

LIST OF FIGURES 5

LIST OF TABLES 6

LIST OF ABBREVIATIONS 7

INTRODUCTION 8

MAPPING OF COOLING SYSTEMS AND APPLICATIONS 9

TASK OBJECTIVES 9

THE ROLE AND IMPORTANCE OF COOLING 9

COOLING DEGREE DAYS INDEX 11

KEY ASPECTS - COOLING SYSTEMS AND APPLICATIONS 12

Methodology 12

Technological aspects 13

Operational aspects 14

Sustainability 14

Economical aspects 14

Summary 14

OVERVIEW AND STATE OF DEVELOPMENT FOR COOLING TECHNOLOGIES AND STORAGES 15

Methodology 15

Supply temperatures for cooling 15

Cooling technologies 18

MAPPING OF COOLING TECHNOLOGIES AND STORAGES 25

Methodology 25

Portfolio for cooling technologies 26

Portfolio TES 37

Examples on system integrated cooling technologies 39

CONCLUSION 40

ASSESSMENT OF COOLING DEMAND AND MARKET OVERVIEW 41

TASK OBJECTIVES 41

THE IMPORTANCE OF COOLING DEMAND ASSESSMENT 41

Literature review 41

Future prevision 43

Importance of cooling demand estimation 44

THE ASSESSMENT OF COOLING DEMAND 45

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Methodology ... *45*
Actual saturation of space cooling ... *50*
Electrical energy consumption assessment ... *52*
Results ... *53*
Future projection of 2030 cooling demand ... 60
Methodology ... *60*
Results ... *61*

STATE-OF-THE-ART COOLING SYSTEMS BASED ON RES AND RECOMMENDATIONS ... 68

Task objectives ... 68
The importance of integrated cooling systems ... 69
The role of thermal energy storages within cooling systems ... 69
Potential of TES integration ... *69*
KPIs and barriers ... *71*
Integration of Cooling Systems into Heating Applications ... 73
The importance of integrating cooling systems into heating applications ... *73*
Best Practice Example: Minewater 2.0 Heerlen ... *74*
Integration of Cooling Systems into the Electricity Sector ... 78
The importance of integrating cooling systems into the electricity sector ... *78*
Best practice example: EUREF "Energiewerkstatt" by GASAG Solution Plus ... *80*
Conclusions and recommendations ... 84

REFERENCES ... 86

ANNEXES ... 95

Annex 1: Cooling Degree Day Index ... 95
Annex 2: Survey Results ... 97
Annex 3: Symbology ... 99
Annex 4: Results for the assessment of cooling demand ... 100
Annex 5: Results for the future projection of 2030 cooling demand ... 101

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List of Figures

Figure 1: Cooling Degree Days Index for each country, based on [7,8] 12
Figure 2: Survey participants by sector 13
Figure 3: Temperatures for process and space cooling, based on [9–14] 16
Figure 4: Final energy demand for process and space cooling in the EU27+UK [15] 17
Figure 5: Overview of main cooling technologies assessed within Cooling Down 20
Figure 6. Overview of main thermal energy storages 21
Figure 7: Schematic diagram for vapour compression cooling generator 22
Figure 8: Schematic diagram for vapour-jet cooling generator 22
Figure 9: Schematic diagram for adsorption cooling generator (closed system) 22
Figure 10: Schematic diagram for absorption cooling generator (closed system) 22
Figure 11: Schematic diagram for a solid desiccant and evaporative cooling system (open system) 23
Figure 12: Schematic diagram for liquid desiccant and evaporative cooling system (open system) 23
Figure 13: Schematic diagram for free cooling system (based on air) 24
Figure 14: Schematic diagram for free cooling system (based on water) 24
Figure 15: Schematic diagram for indirect evaporative cooling system 24
Figure 16: Schematic diagram for indirect evaporative cooling system 24
Figure 17: Schematic diagram for sensible and latent storage, based on [21] 25
Figure 18: Schematic diagram for thermochemical storage, based on [22] 25
Figure 19: Residential Building (RB) types: general information 46
Figure 20: Non-Residential Building (NRB) types: general information 47
Figure 21: Process diagram 48
Figure 22: Statistics and correlation for cooling saturation in residential sector 51
Figure 23: Specific cooling demand for each country 54
Figure 24: Specific cooling demand for residential buildings for each country 55
Figure 25: Specific cooling demand for service buildings for each country 55
Figure 26: Total potential cooling demand for each country 56
Figure 27: Comparison of total potential cooling demand for residential and service buildings 57
Figure 28: Potential and actual cooling demand in residential buildings 57
Figure 29: Potential and actual cooling demand in service buildings 58
Figure 30: Comparison of actual cooling demand for residential and service buildings. 59
Figure 31: Potential electricity demand for space cooling. 59
Figure 32: Actual electricity demand for space cooling. 60
Figure 33: Specific cooling demand for residential sector, 2022 and 2030 compared 62
Figure 34: Specific cooling demand for service sector, 2022 and 2030 compared 62
Figure 35: Total potential cooling demand for residential sector, 2022 and 2030 compared. 63
Figure 36: Total potential cooling demand for service sector, 2022 and 2030 compared. 64

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Figure 37: Actual cooling demand for residential sector, 2022 and 2030 compared. 64
Figure 38: Actual cooling demand for service sector, 2022 and 2030 compared................................ 65
Figure 39: Potential and actual cooling demand for Europe 65
Figure 40: Actual electricity demand for space cooling in residential, in 2022 and 2030 66
Figure 41: Actual electricity demand for space cooling in service, in 2022 and 2030 67
Figure 42: Schematic of the hybrid renewable energy system, source: [135] 70
Figure 43: Clustered list of TES specific KPIs, based on [136] 71
Figure 44: Digital illustration of the EUREF "Energiewerkstatt" by GASAG Solution Plus [96]............ 80
Figure 45: Schematic diagram of the EUREF "Energiewerkstatt". Own illustration based on [141]. ... 81
Figure 46: Change of CDD for countries with a predominance of Cfb, based on [7,8] 95
Figure 47: Change of CDD for countries with a predominance of Csa, based on [7,8]........................ 96
Figure 48: Change of CDD for countries with a predominance of Csc, based on [7,8]........................ 96
Figure 49: Change of CDD for countries with a predominance of Dfb, based on [7,8] 96
Figure 50: Change of CDD for countries with a predominance of Dfc, based on [7,8]......................... 96

List of Tables

Table 1: TRL of cooling technologies [10,16]... 19
Table 2: Water evaporative systems (Part I)... 27
Table 3: Water evaporative systems (Part II)... 28
Table 4: Thermal systems (Part I)... 29
Table 5: Thermal systems (Part II)... 30
Table 6: Thermal systems (Part III)... 31
Table 7: Mechanical systems (Part I)... 32
Table 8: Mechanical systems (Part II)... 34
Table 9: Natural flow systems (Part I)... 35
Table 10: Natural flow systems (Part II)... 36
Table 11: Thermal Energy Storage... 38
Table 12: Integration for Thermal Energy Storage (Case studies) 39
Table 13: Integration for Sector Coupling (Case studies).. 39
Table 14: Building stock subdivisions 45
Table 15: Latent load for residential and office buildings.. 49
Table 16: Source of cooling saturation for residential buildings 51
Table 17: SEER in the residential sector, EU27+UK, the reference year 2016 [10] 53
Table 18: SEER in the service sector, EU27+UK, the reference year [10].. 53
Table 19: Actions to contrast barriers to TES, based on [136] 72
Table 20: Main results for the assessment of cooling demand.. 100
Table 21: Main results for 2030 101

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List of Abbreviations

Abbreviations	Definition
5GDHC	5th Generation District Heating and Cooling
CDD	Cooling Degree Days Index
CFC	Chlorofluorocarbon
CCHP	Combined Cold, Heat and Power
CHP	Combined Heat and Power
COP	Coefficient of Performance
CTES	Thermally Energy Storages in Cooling
DEC	Direct Evaporative Cooling
DHC	District Heating and Cooling
DPEC	Dew-Point Evaporative Cooling
ECI	European Cooling Index
EER	Energy Efficiency Ratio
FIC	Fluoroiodocarbon
GNI	Gross National Income
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluorooelifin
HRE4	Heating Roadmap Europe 4
IEC	Indirect Evaporative Cooler
NRB	Non-Residential Building
ODP	Ozone Depletion Potential
PtC	Power-to-Cold
PtH	Power-to-Heat
RB	Residential Building
RES	Renewable Energy Sources
SAC	Solar Assisted Cooling
SEER	Seasonal Energy Efficiency Ratio
TES	Thermally Energy Storages
TRL	Technology Readiness Level
Subscripts	**Definition**
th	thermal[1]
el	electrical

[1] "th" refers to high temperature heat flows that are not related to cooling. Energy units ("kW" or "kWh" in this report refer to energy or capacity values for cooling.

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Introduction

The objective of the COOLING DOWN project is to propose a vision for a renewable cooling sector in Europe in the coming decades, and issue policy recommendations and proposals to achieve it. Beyond the technological, economic, and social trends to be assessed through research, expert consultations and modelling, the COOLING DOWN project will also be seeking to address the contribution of renewable cooling technologies to climate change adaptation with a specific focus on the mitigation of the urban heat island effect. The overall project duration of COOLING DOWN is 30 months.

The Work Package 2 “State of the art on cooling” is structured into the following tasks:

- Mapping of cooling systems and applications (Task 2.1)
- Assessment of cooling demand and market overview (Task 2.2)
- Definition of reference performance assumption and energy efficiency of cooling systems (Task 2.3)
- State of the art cooling systems based on RES and recommendations (Task 2.4)

The results of Task 2.3 can be found within the report “Deliverable D2.2 - Analysis of the energy efficiency and the performance indicators of cooling systems” [1]. Moreover, the works undertaken focus on identifying cooling technologies/storages along their characterization, assessing the space cooling demand for buildings in the residential, commercial and tertiary sector among five selected European countries with the largest cooling demand (IT, ES, FR, GE, GR) and analysing state of art integrated cooling systems.

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Mapping of Cooling Systems and Applications

Task objectives

Within this task a mapping and structuring of the cooling and cold storage technologies with middle to high TRL level is undertaken on the basis of collected and surveyed literature sources among the consortium partners. The focus lies on technologies for the space cooling and cooling in the tertiary sector. Cooling technologies within the industrial sector with lower temperature levels for the supply temperature and/or higher cooling capacities will be addressed indirectly. The collected literature among the partners has been collected within a project database[2].

Further, a mapping along a performance and technology overview on characteristics, such as the performance or efficiency range, main components, used refrigerants, storage capacities, etc., for the selected cooling and cold storage technologies is assessed. For various sectors and applications operating temperatures are identified highlighting which technologies can be introduced in future cooling systems. The technological overview serves moreover as input for other works within the Cooling Down project.

Last of all, key aspects for state-of-the-art cooling systems have been collected and evaluated on the basis of two surveys performed within the project consortiums and participants from a webinar taking place in May 2023. The key aspects are grouped into categories such as technology, operation-, ecological- and economy-related aspects. The assessed key-aspects highlight the various and diverse important factors of cooling systems and provide decision makers a base for further discussion.

The role and importance of cooling

Coping with an increasing demand for cooling is undisputedly one of the biggest challenges for the current century. The main drivers influencing the increased implementation of cooling devices are foremost higher ambient air temperatures due to global and local climate changes, the population increase as well as higher local incomes and GDP resulting in higher comfort demands, increase of building stock with high a fraction of glass facades that elevate the internal thermal loads and a higher demand for digital services as well as highly processed industrial products. The necessity for space cooling either in residential, commercial or tertiary

[2] The database is based on Citavi.

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buildings is commonplace in areas that experience long lasting heat periods lasting at least several weeks or months. However, in recent years even for countries or regions with a cooler climate the demand for space cooling has risen.

While there are different solutions for keeping buildings cool, the most common is active air conditioning system relying mostly on electrical energy for cooling the indoor air mass that can vary extensively in cost and output energy. Other or alternative methods and technical solutions for the supply of cooling in buildings are related to the building architecture, the external use of vegetation on facades or surface areas, thermally driven or passive cooling systems, seasonal and/or subsurface cooling storages and many more. However, the overwhelming bulk of devices installed in the space cooling sector rely on vapour compression systems and are thus powered by electricity [2]. Despite a series of advantages such as operational flexibility, cost effectiveness, standardized planning procedures, these systems rely on the availability of electricity in the grid. With increasing heat wave periods this poses a challenge for any electrical grid as in peak demand times power outages can occur due to an overload. Moreover, for vapour compression systems the majority of the refrigerants used are synthetic fluids with notable high values for the global warming potential and whose partial release and leaking to the environment is unavoidable and depends on aspects like size, quality aspects, etc.

In the context of increasing cooling demands and fluctuating energy sources, the importance of Thermal Energy Storages in Cooling (CTES) within energy-efficient cooling systems grows continuously. Similar to heating systems, where the storage of heat can play a significant role in improving the energy efficiency of a system, integrated CTES going beyond small size cold water storages or buffer tanks can play a key role for optimizing the overall supply of cooling. Furthermore, CTES integration makes the use of waste cold possible and the peak shaving potential of CTES can play a central role in the context of sector coupling.

According to [2] the total installed cooling output for space cooling systems in 2016 accounted worldwide for 11.7 TW that has quadrupled since 1990 and shows further that approx. 50 % of the cooling capacity is installed in residential applications. While the installed capacity in the European Union accounts roughly for 7 %, the share of the installed cooling capacity in the commercial sector is dominating with 654 GW. Intermediate- to large-scale vapour compression chillers are state-of-the-art in the commercial building, whereas mini-split or multi-split air conditioning systems can be found mainly in residential buildings. Moreover, the energy efficiency of these systems has been rising in the recent years due to individually achieved technological developments increasing collectively the efficiency of the cooling

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technology [3]. However, a main influence factor on the overall efficiency of a vapour compression cooling system is thermodynamically given by the required cooling supply temperature and the ambient air conditions. For the same required cooling supply temperature, a cooling system based on mechanical vapour compression will always operate at a reduced efficiency if installed in a region with higher ambient air temperatures as the required temperature lift for the refrigerant is higher [4]. Consequently, common and easy to implement energy efficiency measures can result in higher setpoint temperature for space cooling systems. Not to mention social aspects, human behaviour and various quality standards of the cooled areas with regard to their thermal losses. Furthermore, following the invasion war of Russia to Ukraine several EU member states had introduced measures early 2022 for coping with the electricity demand from cooling applications and during the summer period [5].

With global and local climate changes increasing the ambient air temperature, the number of cooling degree days is consequently rising at different rates across the regions. An increase of the global average temperature from 0.0 to 1.0 K is estimated to increase the number of cooling degree days by 14 % [6]. Along with demographic and economic factors, the future challenges for energy efficient cooling systems and its environmental impacts need to be addressed and tackled early.

Cooling Degree Days Index

The *Cooling degree day* (CDD) *index* is a measure of the need for cooling and is calculated using a base temperature. This base temperature is the highest daily average air temperature for which indoor cooling is not required and can vary depending on the environment and physical infrastructure. Eurostat calculates CDD using a climatological approach and sets the base temperature at a constant value of 24°C [7]. Figure 1 displays the average annual CDD index per country and its corresponding Köppen-Geiger climate classification. Malta and Cyprus are the only countries with CDD greater than 700, whereas Sweden, Norway, and Ireland have CDD less than 1. Cyprus has a warm climate with hot, dry summers, while Norway and Sweden have a boreal climate with no dry seasons and cool summers. Although Ireland has the lowest CDD of any state, its climate is characterized by warm temperatures, no dry seasons, and warm summers. With regard to the development of CDD in each country, a strong increase accounting (around 100% up to 1000%) can be seen for the majority of countries (see Annex 1, Figure 46 to Figure 50).

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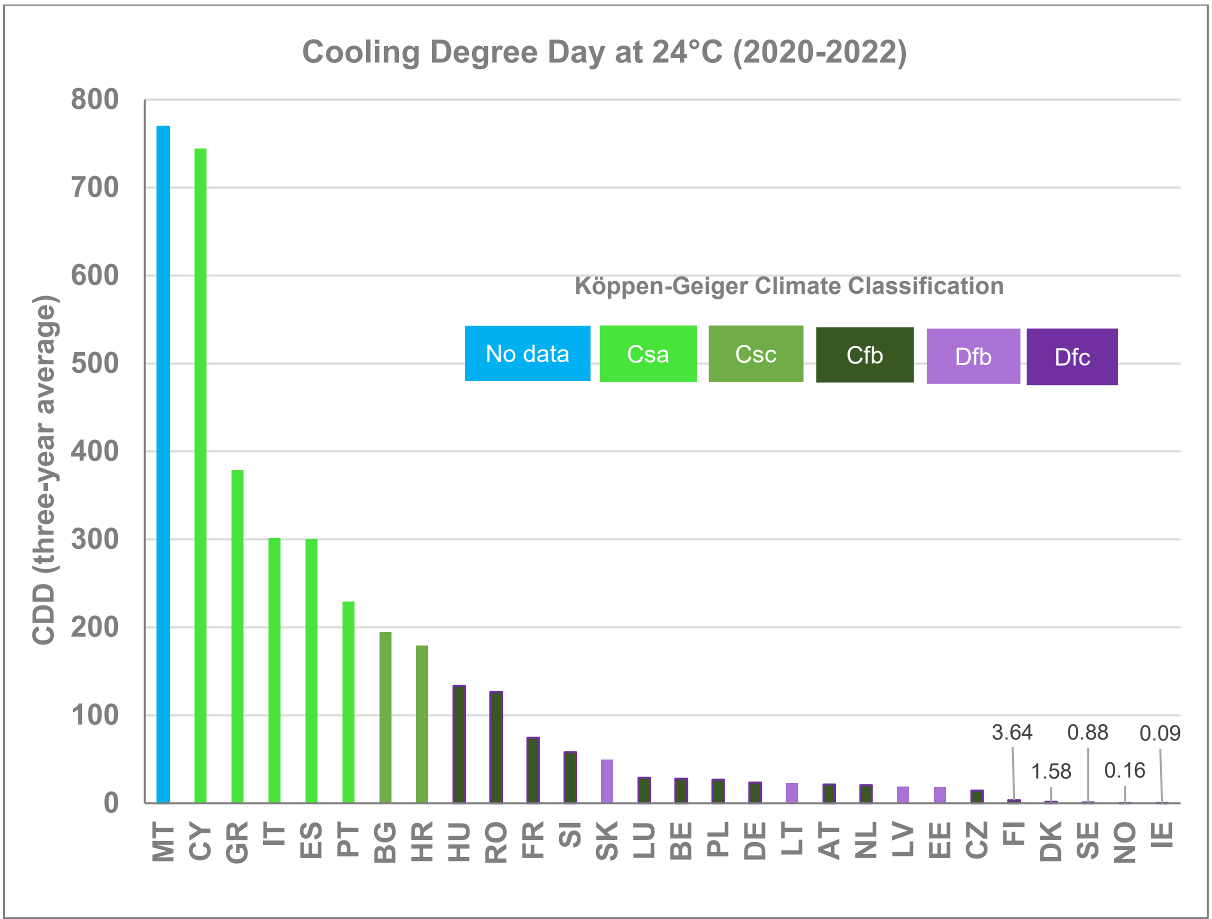

Figure 1: Cooling Degree Days Index for each country, based on [7,8]

Key aspects - Cooling systems and applications

Methodology

The initial stage of mapping cooling and thermal energy storage technologies involved identifying and assessing key aspects of cooling systems. To achieve this, a survey was designed to gather the opinions of various stakeholders in the cooling sector on pre-selected criteria by Fraunhofer IEG. The survey comprised 21 questions categorised into technological (9), operational (5), sustainability (4), and economic (3) aspects. The questions aimed to assess the qualification and relevance of selected technologies and aspects, as well as their estimated level of development.

The survey was conducted in two phases. The first phase involved consortium members, while the second phase involved participants of the May 2023 webinar. A total of 10 consortium members and 17 webinar participants completed the survey. Among the respondents, 41%

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identified themselves as researchers, while 26% identified as consultants and/or advisors (see Figure 2). Annex 2 provides the selected criteria and a summary of the survey results for each phase.

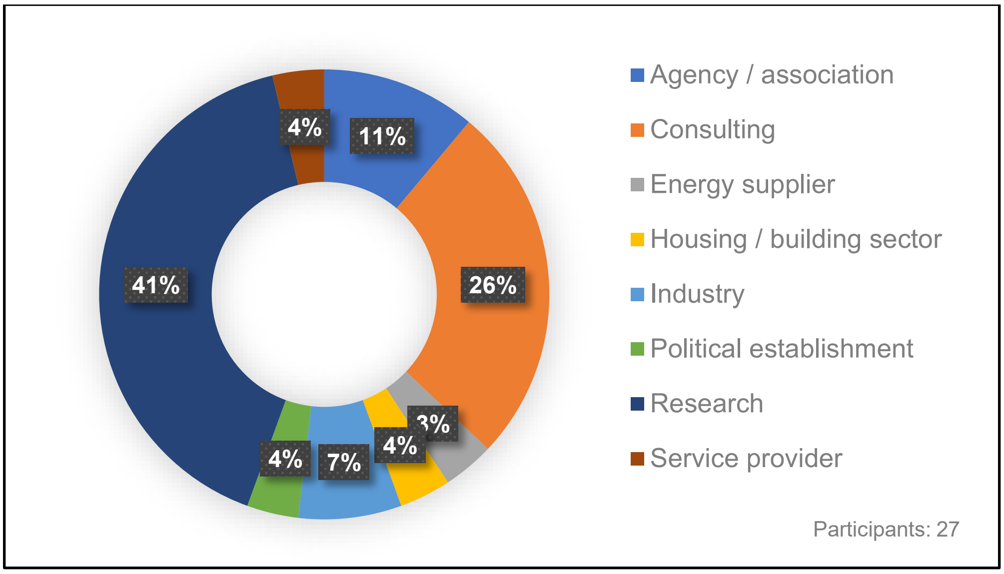

Figure 2: Survey participants by sector

Technological aspects

As far as the technological aspects are concerned, the survey indicated a higher rating (high importance) for the role of electricity-driven systems compared to non-electricity driven cooling systems within the future cooling energy system. For small-scale systems, non-electricity driven systems were found to have lower importance. Depending on local climate conditions, passive cooling systems emerged with a significant importance. Storage systems for cooling garnered a general high rating, with thermochemical storages receiving the highest rating compared to latent and sensible storage types and a stronger emphasis on long-term storage systems. District cooling, particularly 5th generation District Heating and Cooling (DHC) grids, emerged with high importance, while trigeneration systems received a lower importance rating. The survey revealed a preference for electricity from renewable sources over heat from renewable sources in future cooling systems. Regarding development state, most considered technologies were classified as sufficiently developed, with notable potential for further developments in 5th generation DHC systems, district cooling with decentralized generation, and thermal storages.

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Operational aspects

Moving on to operational aspects, parameters such as energy consumption, efficiency, maintenance, and safety were all given high or very high relevance ratings. Efficiency and energy consumption received the highest ratings. Exergy efficiency was considered less important than parameters like total energy consumption, primary energy consumption, low-maintenance, and fail-safe operation. No singularly outstanding aspect or development demand emerged within the operational aspects cluster.

Sustainability

In terms of sustainability, the survey results highlighted the importance of parameters such as refrigerants, hazards, and emissions, with CO2 emissions receiving the highest rating overall. Global warming potential (GWP) and ozone depletion potential (ODP) were equally rated as important for assessing the use of refrigerants and their sustainability. Parameters like resource efficiency, holistic indicators, hazards, and component replacement frequency were all considered as highly relevant.

Economical aspects

Economically, all aspects related to the financial feasibility of cooling systems, including cost of the cooling system, financing, market availability, profitability, and eco-friendliness were rated with high relevance. Market availability, eco-friendliness and overall cost of cooling systems emerged as the most important aspects within the economic cluster, while profitability received a slightly lower rating. Aspects such as capital expense (CAPEX), operating expense (OPEX), funding schemes, and cost-effective design or sizing of components were all deemed highly important. In comparison, exergo-economic evaluations were rated as less important according to the survey.

Summary

As a result, the extensive surveys undertaken show that, according to the expert audience, there is no singular salient aspect or parameter that is particularly relevant for the design of the future sustainable cooling system. Nor does any specific aspect emerge as demanding targeted research and development endeavours. Notably, 5th Generation DHC systems, passive cooling systems, and storage technologies acquire high significance with further development potential. In the area of storage technologies, particular emphasis is placed on

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the evaluation of subsurface structures as a solution for long-term thermal storage of cooling. As sources for renewable cooling supply, both renewable electricity and heat are essential, with electricity driven technologies being assigned a greater relevance especially for small scale applications. In the operation cluster the assessment identifies efficiency and energy consumption as the most important parameters. For the operational aspects disparities in ratings become more pronounced, revealing a greater diversity of opinions among the expert audience. Further, little development is perceived for operational aspects in future cooling systems. CO2-emissions, OPEX, market availability and overall costs were assessed as the dominant evaluation parameters of sustainability and economic efficiency of cooling systems. Nonetheless, these criteria are supplemented by a spectrum of other parameters such as resource efficiency and funding mechanisms, which contribute to a comprehensive assessment.

Overview and state of development for cooling technologies and storages

Methodology

The second stage in mapping the cooling technologies and the thermal energy storages[3] involved identifying the technologies currently available on the market and used in space cooling that will play a significant and relevant role in the future energy system. Two selection criteria were established for the technologies: the input energy source and the Technology Readiness Level (TRL). The selected technologies were then grouped based on their principle of operation. Figure 5 shows the cooling technologies that met the project's criteria, while Figure 6 shows the corresponding thermal energy storage technologies. Furthermore, simplified schematic diagrams illustrating the fundamental components of the cooling generator (i.e. cooling device or system either passive, active or free cooling system) for each technology along energy or mass flows were created (see Figure 10 to Figure 16).

Supply temperatures for cooling

The temperature of the cold supply varies depending on the distribution medium and end use. Figure 3 shows that process cooling requires a wide range of temperatures, some of which

[3] for cooling applications.

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are below -20°C and above 40°C. In contrast, air conditioning and cooling of buildings and production sites require minimum temperatures of 6°C and maximum temperatures of 30°C. This temperature range can be achieved using various technologies, including vapour compression, water evaporation, and natural cooling systems. As a result, these cooling systems can be used in industrial application or in process cooling as well.

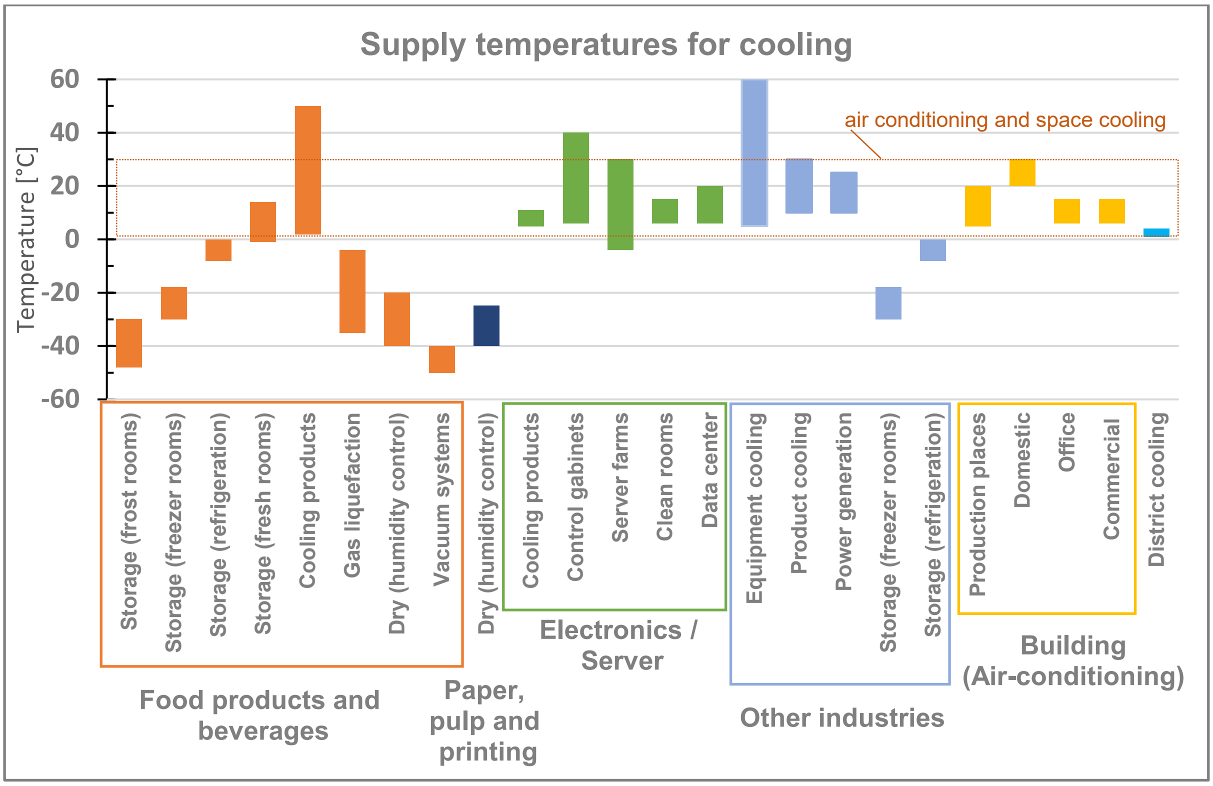

Figure 3: Temperatures for process and space cooling, based on [9–14]

Low temperatures (<0°C) are required for industrial processes (freezing and storage of products, gas liquification, etc.) or for process cooling. However, the cooling demand or the final energy demand (mainly electricity) for industrial cooling or process cooling varies in the EU according to the national industrial needs. Figure 4 highlights the final energy demand for process cooling and space cooling in the EU27+UK according to the required supply temperature levels.

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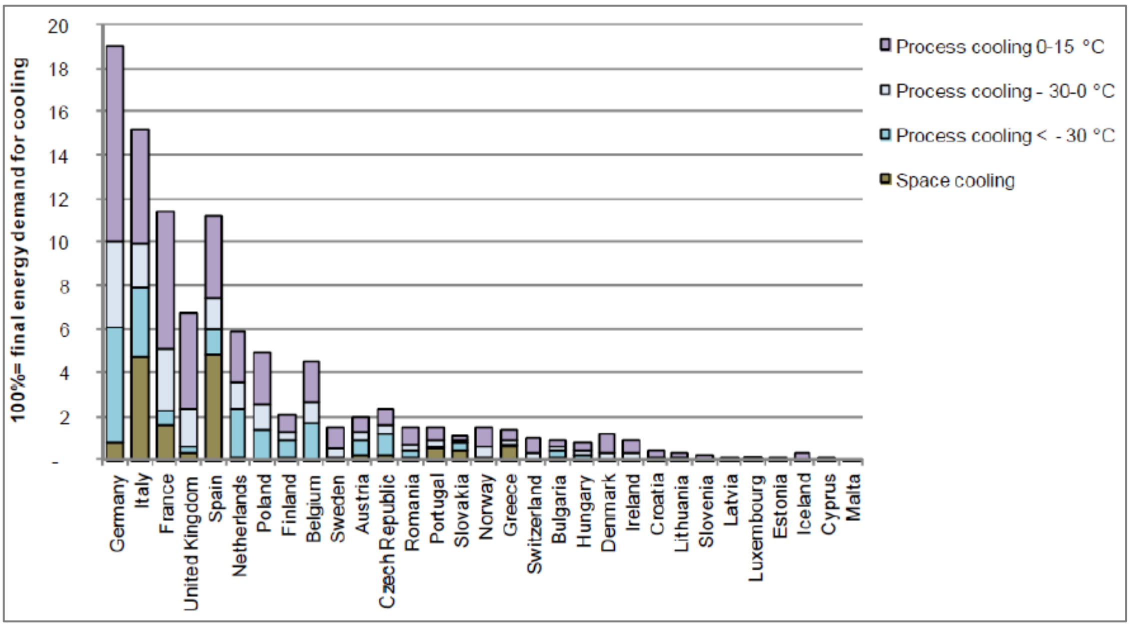

Figure 4: Final energy demand for process and space cooling in the EU27+UK [15]

For space cooling systems (cooling of residential/commercial buildings and production places), minimum supply temperatures of 6°C and maximum supply temperatures of 30°C are required, so the range is narrow compared to the industrial sector. Space cooling systems designed for low supply temperatures (6-10°C) are typically used in cases where air-conditioning systems and dehumidification of the supply air is needed. Lowering the temperature of the ambient air in an air handling unit below the dew-point temperature allows an active control of the relative humidity for the supply air streams. As a result, the air conditions within a building can be controlled effectively, especially when the humidity level of the ambient air is high (>80%). Large scale district cooling networks are operated similarly at low supply temperatures in order for every end-user to be able to provide cooling for its building or application.

Nevertheless, increasing the supply temperature in cooling systems can have several advantages:

- reduction of thermal losses
- increased share of natural cooling
- increased performance / efficiency for mechanical cooling system based on vapour compression
- lower investment costs due to reduced sizing of the cooling system

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Cooling technologies

According to [10], the 2022 EU study identified 28 cooling technologies and grouped them into 8 categories based on the physical form of the input energy: electrical (5), mechanical (10), acoustic (1), magnetic (1), chemical (2), hydraulic (1), thermal (2) and natural (5). However, approximately 50% of these technologies are still at an early stage of development and in an experimental phase, making commercialisation difficult in the short to medium term. Technologies with a Technology Readiness Level (TRL) between 1 and 4 are either in the conceptual phase or have been validated in the laboratory. Those with a TRL between 5 and 7 have been validated and demonstrated in relevant and operational environments, respectively. Only technologies with a TRL of 8 or 9 are currently available on the market [10]. Technologies that have the potential to be more efficient and those that use renewable energy sources could be an alternative to address the increasing demand for space cooling in the coming years.

The selected criteria aimed to narrow down the range of technologies and align the mapping with the project objectives. These criteria include:

1. Input energy types such as electrical, mechanical, thermal, and natural.
2. Evidence of a TRL of 8 or 9 by 2019.

Table 1 lists the cooling technologies that meet the first criterion, the assigned TRL and the year in which this level was assigned. This project did not undertake any assessments on the TRL values, but used information from the 2022 EU study. Cooling technologies with an electricity-based operating principle, such as thermoelectric devices based on semiconductor materials, are still in conceptual or laboratory validation phases (TRL 2-4). While there are a larger number of refrigeration technologies using mechanical energy, only vapour compression and reverse Brayton cycle technologies achieve a TRL of 9. The latter being successfully used in transportation space conditioning and industrial/commercial refrigeration applications for storage/freezing. However, the technology is not expected to provide energy savings (in comparison to conventional vapour compression systems) due to low COP values (0.5-0.9). Cooling technologies with an operating principle based on heat transfer (thermally driven cooling systems) are low in numbers (market share at approx. 1%) with only sorption cooling technology, such as ab-/adsorption chillers (closed or open systems), achieving a TRL higher than 8. On the other hand, technologies that exploit natural cooling have a TRL higher than 7, with the exception of sky radiative cooling which was recently discovered in 2014 (TRL

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3-4). Although 20 technologies are listed in Table 1, only 6 (highlighted in bold) show a TRL higher than 8 by 2019.

Table 1: TRL of cooling technologies [10,16]

Input energy	Technology	TRL	Year of assignment
Electrical	Thermoelectric	4	2016
	Thermionic	2	2014
	Thermotunnel	2	2019
	Electrocaloric	2	2019
	Electrochemical	3 - 4	2017
Thermal	**Absorption and adsorption**	**3 - 9**	**2019**
	Transcritical thermal compression heat pump	4	2019
Mechanical	**Vapour compression**	**Up to 9**	**2019**
	Pulse tube	6	2014
	Ejector	3	2014
	Vortex tube	4	2014
	Stirling/Ericson cycles	4	2017
	Reverse Brayton	5 - 9	2011
	Bernoulli cycle	3 - 4	2017
	Elastomeric effect	2	2016
	Critical flow cycle	3 - 4	2017
	Membrane heat pump	5 - 6	2017
Natural	**Natural convection**	**Up to 9**	**2019**
	Natural conduction	**Up to 9**	**2019**
	Freeze/melt cycle	**Up to 9**	**2019**
	Evaporative cooling	**Up to 9**	**2019**
	Enthalpy recovery	7 - 8	2017
	Sky radiative cooling	3 - 4	2019

The technologies listed above relate to the physical process for the supply of cooling as an end energy. A cooling generator or a cooling system can be a compact device or installation that creates a temperature differential to extract heat from a heat source (e.g. a space or a process requiring cooling) [1]. This “extracted” heat is released together with the energy input (electricity or heat) to a heat sink. For most applications, such as systems with conventional chillers based on vapour compression, heat from the cooling process/generator is rejected to the environment. Utilizing this rejected heat, either directly through heat pumps for heat supply or indirectly through thermal storage systems, can increase the overall efficiency of the energy supply system for the corresponding area, building or region.

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A free or natural cooling system utilises a natural cold source to extract heat from the space or process. This is possible when the temperature level of such a natural source (air, water, ground) is lower than the required temperature level for cooling. Natural cooling systems typically consist of pipes and/or ducts, pumps and/or fans, and a fluid as a distribution medium [1]. The objective of thermal energy storages (TES) integration is the temporal compensation between demand and generation. Depending on the memory type, this function is based on the latent or sensible heat of a storage medium or a thermochemical reaction.

Within this task a categorisation for cooling systems (see Figure 5) and thermal energy storages for cooling (see Figure 6) was undertaken. As previously described, not all available cooling technologies are shown in Figure 5 and Figure 6. The cooling technologies were categorised based on the physical principle of operation of the cooling generator system and/or the medium of distribution of the cooling system. It is important to note that cooling generators may include one or more cooling technologies. Thermal energy storage technologies are classified based on the working principle and the physical state of the storage medium.

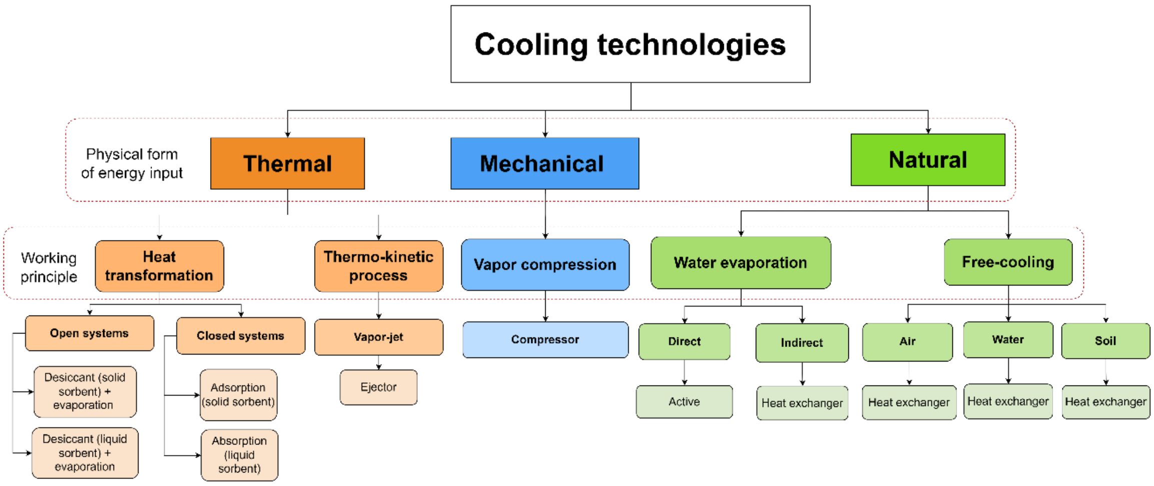

Figure 5: Overview of main cooling technologies assessed within Cooling Down

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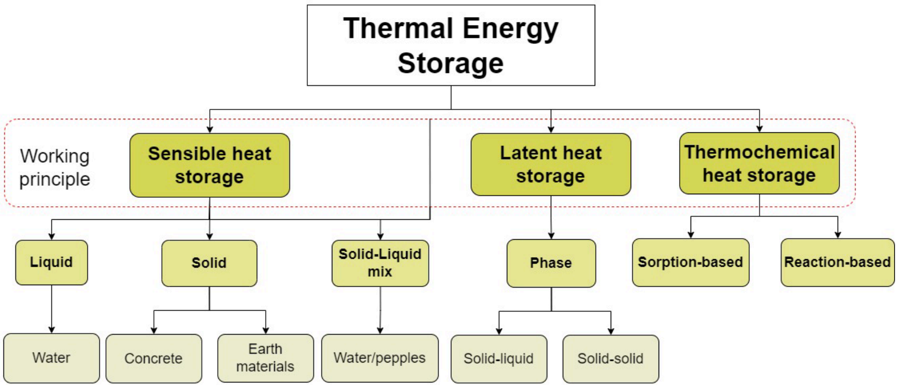

Figure 6. Overview of main thermal energy storages

Cooling generator system

The cooling generator system is a component of the cooling system. Its operation can be continuous or intermittent, depending on the operating principle and technology used. The principle of operation involves mass and energy transfers, with the direction of these flows determining whether the processes are classified as closed or open cycles. Schematic and simplified diagrams of the cooling generator systems for each technology are shown in Figure 7 to Figure 12. Each diagram indicates the direction of mass and energy flow, specifying the type of energy (thermal or electrical). The symbology (legend) used in the diagrams is given in Annex 3.

Cooling generators use vapour compression, sorption or other energy-driven thermodynamic cycles [1]. Some operate under a closed cycle scheme, such as vapour compression, vapour ejector, adsorption and absorption systems (see to Figure 10). Here the working medium (refrigerant or sorbent) is in a closed circuit and has no direct contact with other media such as the distribution medium (water, air, etc). On the other hand, cooling generator systems that combine one or more cooling technologies operate under an open cycle scheme (see Figure 11 and Figure 12). For those systems, typically used in air conditioning applications for space cooling, the distribution medium air.

All cooling generator systems require an energy input to operate, whether thermal or electrical. Both electricity and heat can be supplied from renewable energy sources.

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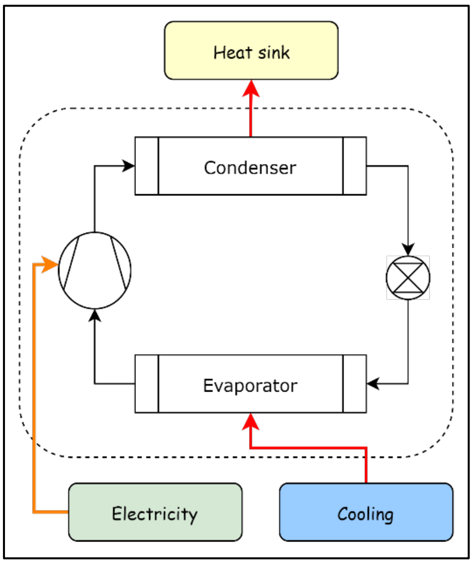

Figure 7: Schematic diagram for vapour compression cooling generator

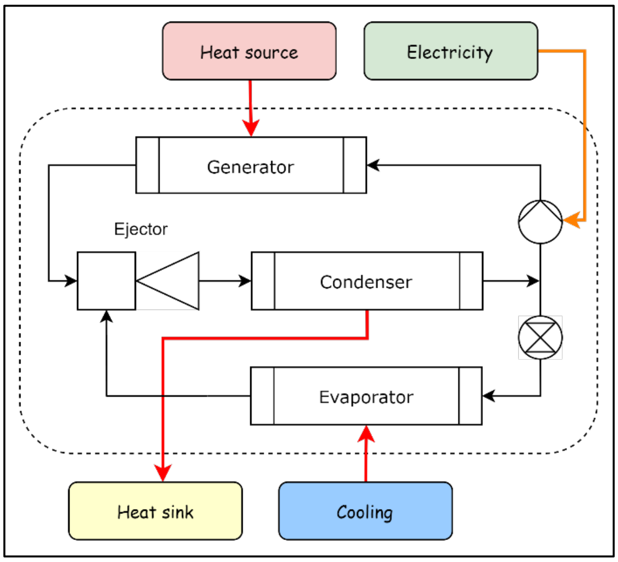

Figure 8: Schematic diagram for vapour-jet cooling generator

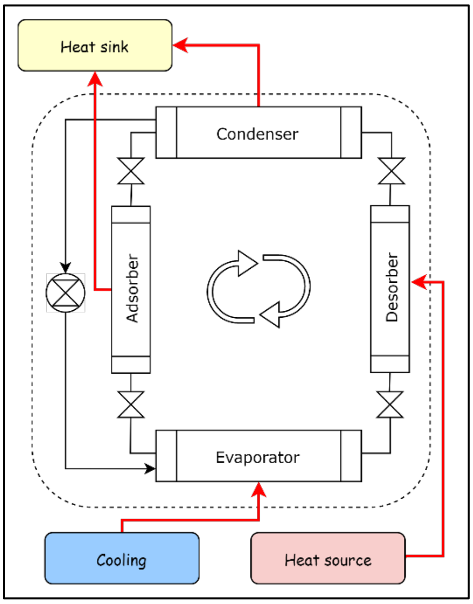

Figure 9: Schematic diagram for adsorption cooling generator (closed system)

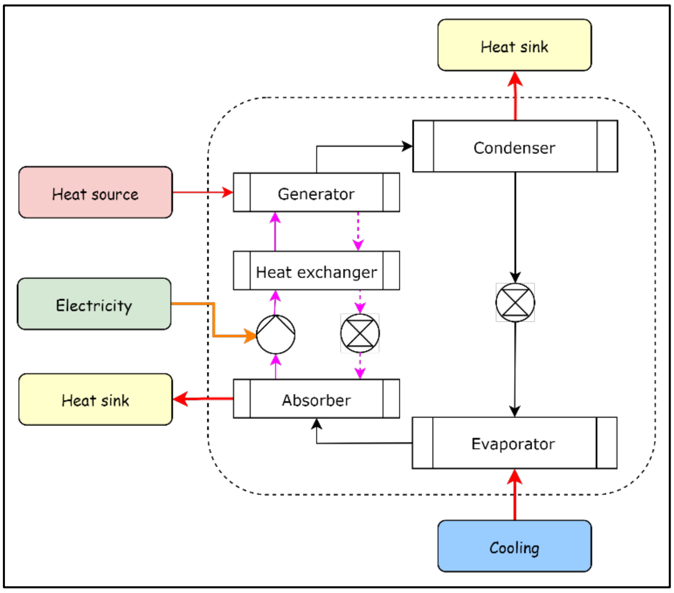

Figure 10: Schematic diagram for absorption cooling generator (closed system)

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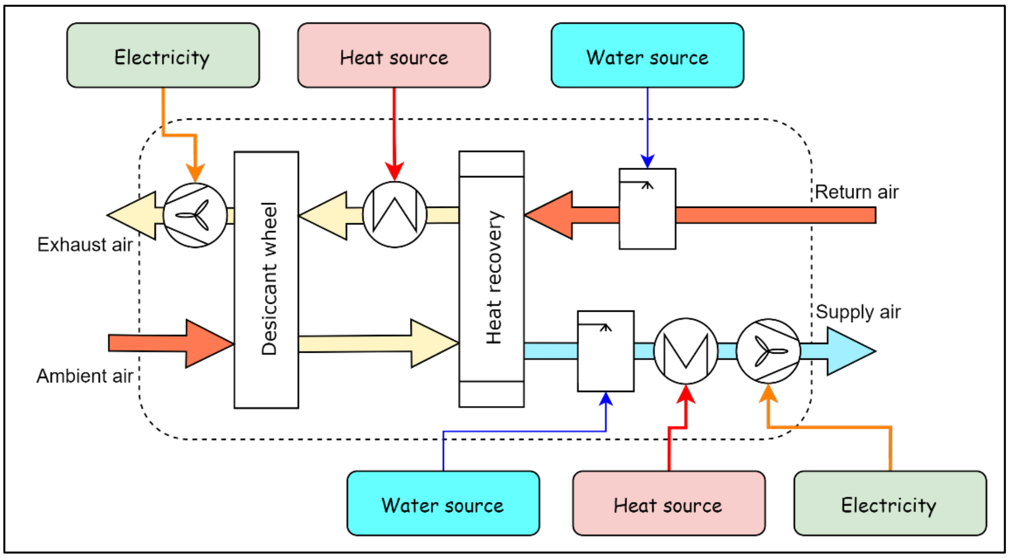

Figure 11: Schematic diagram for a solid desiccant and evaporative cooling system (open system)

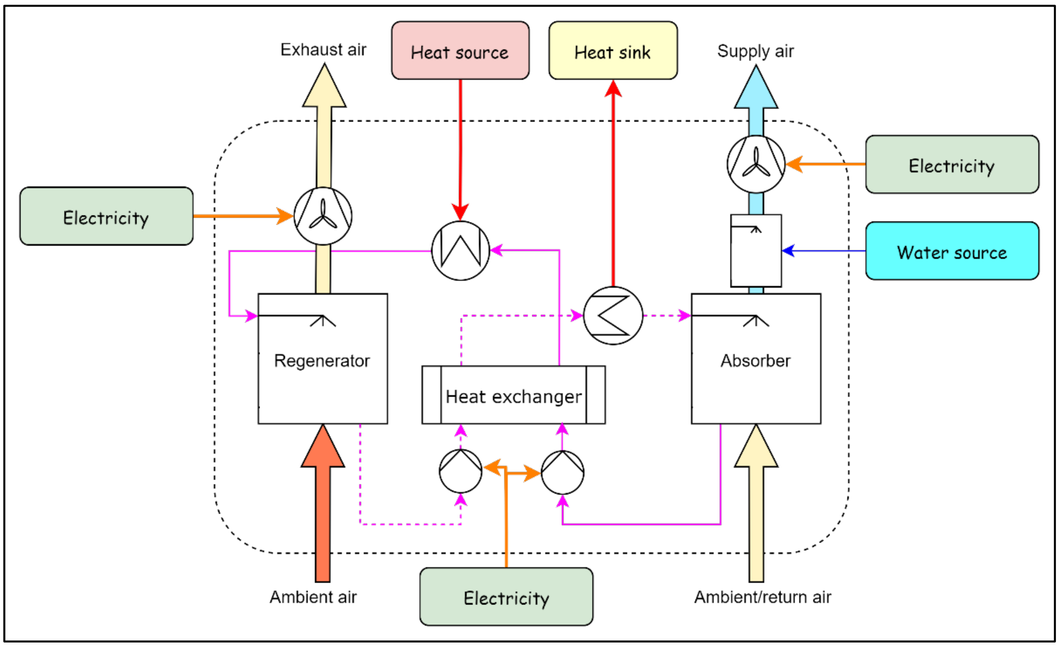

Figure 12: Schematic diagram for liquid desiccant and evaporative cooling system (open system)

Free cooling system

This system utilises a natural cold source, such as water, air, or ground, to dissipate heat from the space or the process that requires cooling [1]. The main component of a free cooling system is the heat exchanger, which transfers heat from the space or the process requiring cooling to the natural cold source. Heat exchangers can be air-air, water-air, or water-water (refer to Figure 13 and Figure 14). There are applications as well, where a heat exchanger is not required. However, a heat exchanger is often used to separate the media from the heat source and the heat sink.

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Evaporative cooling is an adiabatic process that reduces the sensible air temperature by evaporating water, thus increasing the relative humidity in an air stream. This process can be direct or indirect, as shown in Figure 15 and Figure 16. It is important to note that free cooling systems only require energy inputs to drive pumps, fans and auxiliary processes.

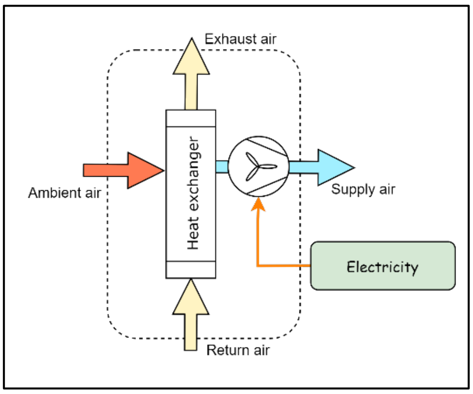

Figure 13: Schematic diagram for free cooling system (based on air)

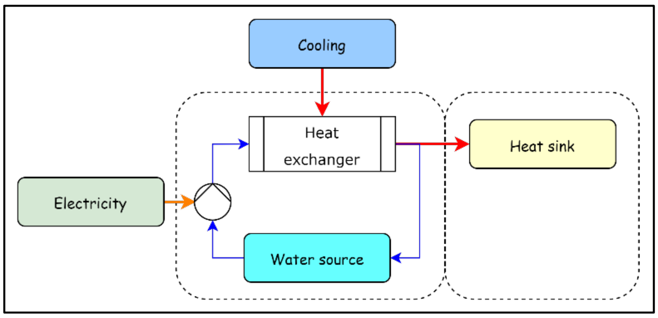

Figure 14: Schematic diagram for free cooling system (based on water)

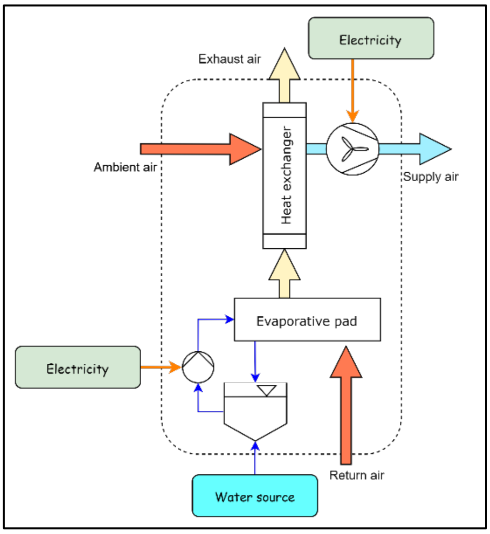

Figure 15: Schematic diagram for indirect evaporative cooling system

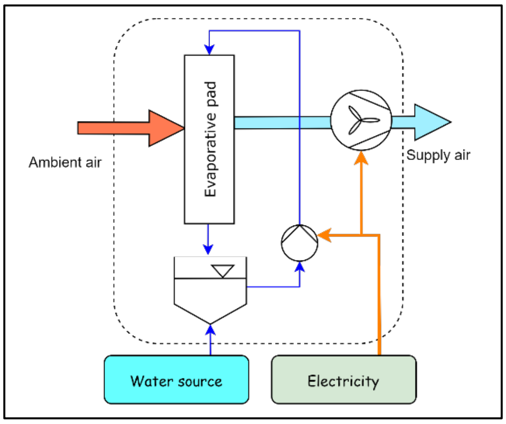

Figure 16: Schematic diagram for direct evaporative cooling system

Storages for cooling

Thermal energy storages (TES) are used to store heat or cold (CTES) and enable a temporal and local decoupling between thermal generation and demand. Generally, TES can be classified into three main types: latent, sensible and thermochemical storages. The temperature level, the storage material and the storage time period can be used for further classification among others. Sensitive storages are based on the temperature change of the storage medium, while latent storages are based on the heat of fusion and thermochemical

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storage on chemical reactions. [17–20] The schematic structure of the storage technologies can be seen in Figure 17 and Figure 18.

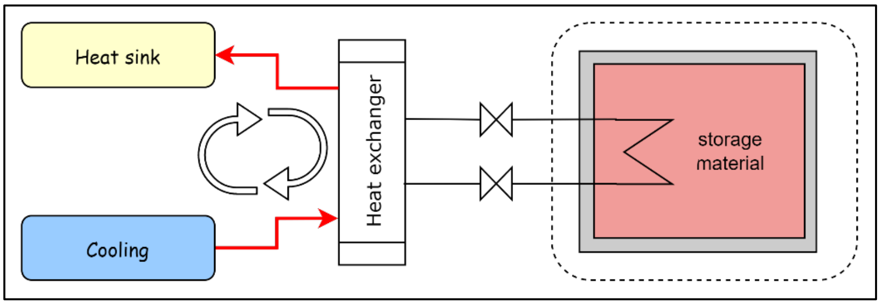

Figure 17: Schematic diagram for sensible and latent storage, based on [21]

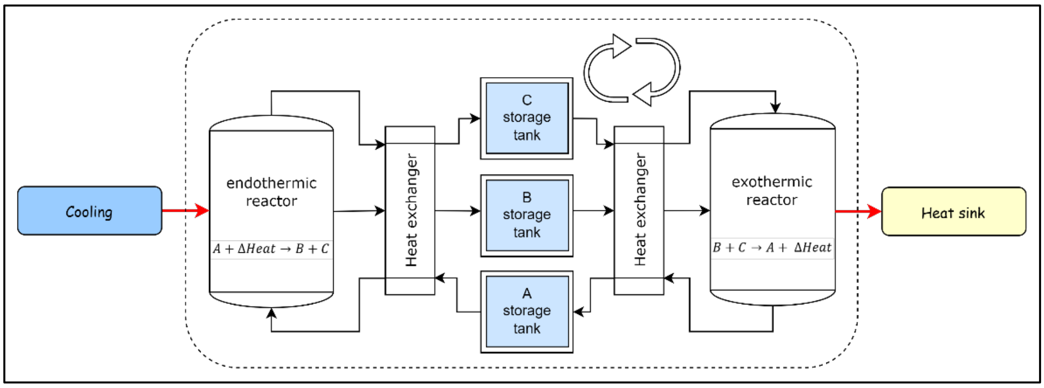

Figure 18: Schematic diagram for thermochemical storage, based on [22]

Mapping of cooling technologies and storages

Methodology

A list of parameters and characteristics was identified to compare different cooling technologies, considering key technological, operational, and economic aspects (see section *Key aspects - Cooling systems and applications*). This process resulted in a format for consolidating the mapping of cooling technologies. A systematic search of available literature in databases was then conducted using a combination of cooling technologies and format parameters as keywords. The study filtered results based on three publication periods: before 2016, between 2016 and 2020, and prioritising articles published after 2020. Relevant technical reports, presentations, and manufacturers' datasheets were also considered, in addition to peer-reviewed articles. If no results were found after 2020, earlier publications were cross-referenced. The information was consolidated into a single format, which included cooling and thermal energy storage technologies.

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Portfolio for cooling technologies

Table 2 to Table 10 show the consolidated information for the following cooling technologies:

- Water evaporative systems: direct and indirect evaporative cooler (Technologies 1-4)
- Thermal systems: absorption, absorption, ejector (Technologies 5-10)
- Mechanical systems: central and local, variable refrigerant flow (Technologies 11-14)
- Natural flow systems: water and air (Technologies 15-16) and geothermal cooling systems based on TES (Technology 17)

Table 2 to Table 10 provide characteristic data for the 17 cooling technologies. In the following table a definition of the collected and researched information is given:

Overall information	
Working principle	Working principle as per Figure 7 to Figure 18
Cooling generator	Cooling technology or system
Distribution medium	Supply product / medium (cooled)
TRL level	Technical Readiness Level
Type of cycle	Open or closed process/cycle
Cooling application	Application areas, such as space cooling
Performance and efficiency	
Electrical efficiency (COP_{el}) (kW/kW_{el})	Ratio of cooling capacity to electricity needed (typically, at the design or nominal operation point)
Thermal efficiency (COP_{th}) (kW/kW_{th})	Ratio of cooling capacity to thermal capacity (typically, at the design or nominal operation point)
Water consumption (l/kWh) (l/m³/min) - For DEC	Ratio of water consumption per cooling unit
Energy Efficiency Ratio (EER) (kWh/kWh)	Ratio of cooling energy to electrical energy (typically, at the design or nominal operation point)
Seasonal Energy Efficiency Ratio (SEER) (kWh/kWh)	Ratio of cooling energy to electrical energy for a cooling season/year
Operational information	
Energy source	Energy forms required to operate the cooling technology
Cooling capacity (kW)	Cooling capacity from a single unit (typically, at the design or nominal operation point)
Temperature of driving heat (°C)	Temperature level for required (driving) heat
Temperature of supplied cooling (°C)	Temperature level of supplied cooling and its distribution medium
Part load	Ability of the cooling technology to operate at part-load conditions
Lifetime (y)	Operational expectance on the lifetime of the cooling technology
Working Fluid	
Refrigerant	Medium used as a refrigerant
GWP	Information on the Global Warming Potential (GWP)
ODP	Information on the Ozone Depletion Potential (ODP)
Hazard level	Classification of the hazard level according to [23,24]
Miscellaneous	
Scalability	Degree for up-scaling the cooling technology
Maintenance level	Level of maintenance required during operation
Technical complexity	Technical complexity and expertise required for qualified staff to operate/maintain the cooling technology
Investment cost (€/kW)	Ratio of capital-related investment cost to cooling capacity
Notes	Additional information or constraints

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Table 2: Water evaporative systems (Part I)

Feature	1	Source	2	Source
Working principle	water evaporation (natural)		water evaporation (natural)	
Cooling generator	Direct Evaporative Cooler (DEC)		Indirect Evaporative Cooler (IEC)	
Distribution medium	air		air	
TRL level	up to 9	[16]	up to 9	[16]
Type of cycle	closed cycle		open cycle	
Cooling application	space and process cooling	[16]	space and process cooling	[16]
Performance and efficiency				
Electrical efficiency (COP_{el}) (kW/kW_{el})	up to 4.05* (natural fibres) up to 8.8* (pottery rods) up to 170* (corrugated-cellulose)	[25]	6 - 14 25 - 30 22.5 - 46.4*	[26] [27] [28]
Thermal efficiency (COP_{th}) (kW/kW_{th})	not applicable		not applicable	
Water consumption (l/kWh) (l/m³/min) - For DEC	5.68 - 26.5*	[29]	up to 2.4 0.51 - 2.84*	[26] [28]
Energy Efficiency Ratio (EER) (kWh/kWh)	8.12 - 12.3 up to 29.3 78 - 87 (small design)	[26] [30]	30 - 80 6 - 16** up to 60	[31] [32] [30]
Seasonal Energy Efficiency Ratio (SEER) (kWh/kWh)	no information		2.3 - 7.6*	[28]
Operational				
Energy source	electricity		electricity	
Cooling capacity (kW)	8.9 - 17 15.1 - 18.4 up to 5.6 10.70 - 20.89 (small design) 0.518 - 6.1*	[31] [26] [30] [10 [25]	6 - 10, 8 - 14, 40 - 75 28.13 - 167.5 13.3 - 33.5*	[26] [30] [28]
Temperature of driving heat (°C)	not applicable		not applicable	
Temperature of supplied cooling (°C)	∆7.7 - 23.7 ∆11.3* (natural fibres) ∆ 7* (pottery rods) ∆16* (corrugated-cellulose)	[26] [25] [25] [25]	17 - 26	[26]
Part load	yes		yes	
Lifetime (y)	> 10	[33]	> 10	[33]
Working Fluid				
Refrigerant	natural		natural	
GWP	not applicable	[34]	not applicable	[34]
ODP	0	[34]	0	[34]
Hazard level	A1	[34]	A1	[34]
Miscellaneous				
Scalability	high	[35]	high	[35]
Maintenance level	medium	[10,35]	medium	[10,35]
Technical complexity	low	[35]	low	[35]
Investment cost (€/kW)	50.3 (2003) 36 (2011) 104.4** (2018)	[36] [36] [36]	193 - 538 (2023) 182 (2015)	[37] [38]
Notes	* Experimental data ** Theoretical model		* Experimental data for different locations **Experimental model	
***Limitations Direct Evaporative Cooler*:** climate limitations, cooling effectiveness is limited by the air's wet-bulb, reliability risks, freezing danger in the winter, increasing the air's humidity, large air flows [10,35,39] ***Limitations Indirect Evaporative Cooler*:** climate limitations, cooling effectiveness is limited by the air's wet-bulb, reliability risks, not adiabatic process, large scale to achieve considerable cooling capacity, large air flows [10,35,39]				
Manufacturers Direct Evaporative Cooler: Aolan Company, Arctic, Brivis, Cambridge Air Solutions, Munters group, Seeley International, United Metal Product, EcoCooling ***Manufacturers Indirect Evaporative Cooler:*** Arctic, Applied Air, Cambridge Air Solutions, Munters group, Seeley International, United Metal Product, Condair				

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Table 3: Water evaporative systems (Part II)

Feature	3	Source	4	Source
Working principle	water evaporation (natural)		water evaporation (natural)	
Cooling generator	Dew-Point Evaporative Cooler (DPEC)		IEC + DEC	
Distribution medium	air		air	
TRL level	up to 9	[16]	up to 9	[16]
Type of cycle	open cycle		open cycle	
Cooling application	space and process cooling	[16]	space and process cooling	[16]
Performance and efficiency				
Electrical efficiency (COP_{el}) (kW/kW_{el})	8 - 20 31 - 34* (data centre) 10.1 - 13.8* (residential building) 20 - 42.8 (counter flow, corrugated surface) up to 11.43*** 16.5 - 52.5* (irregular corrugated)	[31] [27] [27] [27] [25] [39]	4 - 18	[26]
Thermal efficiency (COP_{th}) (kW/kW_{th})	not applicable		not applicable	
Water consumption (l/kWh)	2 - 2.5 2.5 - 3.0	[31] [38]	3.01 1.8 - 2.64 1.44	[31] [26] [40]
Energy Efficiency Ratio (EER) (kWh/kWh)	30 - 80 2.5 - 15.5* 6.8 - 14.2* 13.2 - 17.2*	[31] [32] [41] [41]	30 - 80 up to 100 16 - 39 14 - 35	[31] [30] [40] [40]
Seasonal Energy Efficiency Ratio (SEER) (kWh/kWh)	3.9 - 6.4**	[32]	no information	
Operational				
Energy source	electricity		electricity	
Cooling capacity (kW)	18 - 119 1.5 - 4.8* (irregular corrugated) 5.7 - 7.3*	[32] [39] [39]	7.03* 144.19 - 393.89 9 - 19, 52 - 101 21 - 50 48 - 118	[31] [31] [26] [40] [40]
Temperature of driving heat (°C)	not applicable		not applicable	
Temperature of supplied cooling (°C)	18* (data centre) 23.9 -26.2* (residential building) 17.2 - 25.4* (counter flow, corrugated surface) lower than 14*** Δ5.6 - 12.4 Δ5.9 - 19.1*	[27] [27] [27] [25] [39] [39]	14 - 25 Δ10.3 - 25	[26] [40]
Part load	yes		yes	
Lifetime (y)	> 10	[33]	> 10	[33]
Working Fluid				
Refrigerant	natural		natural	
GWP	not applicable	[34]	not applicable	[34]
ODP	0	[34]	0	[34]
Hazard level	A1	[34]	A1	[34]
Miscellaneous				
Scalability	high	[35]	high	[35]
Maintenance level	medium	[10,35]	medium	[10,35]
Technical complexity	low	[35]	low	[35]
Investment cost (€/kW)	281*** (2018) 398 (2015)	[41] [38]	no information	
Notes	* Experimental data ** Calculation *** Experimental model		* Evaluation of installed project	
Limitations Dew-Point Evaporative Cooler: climate limitations, performance depends on geometry, structure and system, reliability risks, water distribution and treatment system [27,35,39] ***Limitations IEC + DEC:*** climate limitations, reliability risks, increasing fan power, space and cost, large air flows [10,35,39]				
Manufacturers Dew-Point Evaporative Cooler: Aolan Company, Seeley International ***Manufacturers IEC + DEC:*** Arctic, Applied Air, Munters group, Cambridge Air Solutions, Oxycom, Seeley International				

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Table 4: Thermal systems (Part I)

Feature	5	Source	6	Source
Working principle	heat transformation (thermal)		heat transformation (thermal)	
Cooling generator	absorption chiller (liquid sorbent)		absorption chiller (liquid sorbent)	
Distribution medium	water or water-glycol		refrigerant or water or water-glycol	
TRL level	3 - 9 7 - 8 (solar)	[16]	3 - 9 7 - 8 (Solar)	[16]
Type of cycle	closed cycle		closed cycle	
Cooling application	space and process cooling	[16]	space and process cooling	[16]
Performance and efficiency				
Electrical efficiency (COP_{el}) (kW/kW_{el})	5 - 30***	[42]	no information	
Thermal efficiency (COP_{th}) (kW/kW_{th})	0.7 - 0.8 (1-stage) 1.1 -1.2 (2-stage) 0.55 - 0.8 (1-stage) 0.9 -1.4 (2-stage) 1.7 (3-stage) 0.490 - 0.740 (solar)	[11] [11] [43] [43] [43] [44]	0.3 - 0.7 0.5 - 0.7 0.427 - 0.550 (solar)	[11] [43,45] [44]
Water consumption (l/kWh)	4 3.5 2.5	[43] [46] [45]	6	[46]
Energy Efficiency Ratio (EER) (kWh/kWh)	no information		no information	
Seasonal Energy Efficiency Ratio (SEER) (kWh/kWh)	thermal: 0.63 - 0.68 (solar)** electrical: 5.8 - 9.1 (solar)**	[12] [12]	electrical: 3.4 - 5.9 (solar)**	[47]
Operational				
Energy source	heat + electricity		heat + electricity	
Cooling capacity (kW)	100 - 6000 15 - 23620* 6 - 11000 >4.5 (1-stage) >100 (2-stage) 560 - 3500 (3-stage)	[11] [12] [48] [43] [43] [43]	10 - 1000 30 - 6500* 100 - 1000	[11,45] [12] [48]
Temperature of driving heat (°C)	80 - 100 (1-stage) 130 - 160 (2-stage) 70 - 95 (1-stage) 80 - 110 (1-stage) 140 - 160 (2-stage) >200 (3-stage) 77.1 - 106 (solar)	[11] [11] [48] [43] [43] [43] [44]	100 - 180 80 - 120 85 - 110 (Solar)	[11] [43] [44]
Temperature of supplied cooling (°C)	6 - 20 6 - 15 7.5 - 25 (solar)	[11] [48] [44]	(-30) - 20*** (-9) - 6 (solar) (-60…-15) *** (-60-0) ***	[9,11,45] [44] [49] [50]
Part load	yes		yes	
Lifetime (y)	> 10	[11,33,51]	> 10	[11,33,51]
Working Fluid				
Refrigerant	natural		natural	
GWP	not applicable	[34]	0	[52]
ODP	0	[34]	0	[52]
Hazard level	A1	[34]	B2L	[52]
Miscellaneous				
Scalability	medium	[53]	medium	[53]
Maintenance level	high	[35,48]	high	[35]
Technical complexity	high	[35,48,53]	high	[35,53]
Investment cost (€/kW)	250 - 300 (1-stage) (2015) 300 - 350 (2-stage) (2015) 400 - 700 (2020) 450 - >1600 (1-stage) (2014) > 500 (2-stage) (2014) 150 - 1700 (1-stage) (2013) 1505 - 2099 (1-stage, solar) (2023)	[43] [43] [46] [9] [9] [54] [55]	500 - 1250 (1-stage) (2015) 400 - 700 (2020) 500 - >1500 (1-stage) (2014) 700 - 1500 (2013)	[43] [46] [9] [54]

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Feature	5	Source	6	Source
Notes	* Available on the market ** Without backup heat supply - Simulation *** System with CHP		* Available on the market ** Case study ***Included process cooling	
Limitations absorption chiller (water (R718) / solution of lithium bromide (LiBr) + water): large physical dimensions, potential crystallization at high concentrations, low energy efficiency at small temperature differences, corrosion protection is required, specialized maintenance personal, reliability and maintenance risks [12,16,35,43,44,46,48,51] ***Limitations absorption chiller (ammonia (R717) / water (R718)):*** large physical dimensions, operation at high pressure, in need of a column of rectifier, low energy efficiency at small temperature differences, corrosion protection is required, specialized maintenance personal [12,16,35,44,46,51]				
Manufacturers absorption chiller (water (R718) / solution of lithium bromide (LiBr) + water): EAW, York, Carrier, Colibri, Mattes, Broad Group, Yazaki, Thermax, AGO, Kawasaki ***Manufacturers absorption chiller (ammonia (R717) / water (R718)):*** Robur, Colibri, AWT, Mattes, ABB, Pink, SolarIce, AGO, Trane, BL thermodynamics				

Table 5: Thermal systems (Part II)

Feature	7	Source	8	Source
Working principle	heat transformation (thermal)		heat transformation (thermal)	
Cooling generator	adsorption chiller (solid sorbent)		desiccant (solid sorbent) + evaporative cooling system	
Distribution medium	water or water-glycol		air	
TRL level	3 - 9	[16]	3 - 4	[16]
Type of cycle	closed cycle		open cycle	
Cooling application	space and process cooling	[16]	space and process cooling + dehumidification	[16]
Performance and efficiency				
Electrical efficiency (COP_{el}) (kW/kW_{el})	no information		2 - 5 (solar) 33 - 40	[48] [45]
Thermal efficiency (COP_{th}) (kW/kW_{th})	0.5 - 0.72 0.2 - 0.7 (silica-gel) * 0.5 - 0.75 (zeolite)* 0.4 - 0.7 0.4 - 0.6 (silica-gel) 0.10 - 0.30 (silica-gel) ** 0.10 - 0.12 (zeolite)** 0.05 - 0.07 (activated-carbon/water) **	[56] [56] [56] [11] [43] [44] [44] [44]	0.51 (solar) 0.85 - 1.24 (solar) 0.5 - 1.0 0.6 - 0.8 0.5 - 0.7** (silica-gel) 0.7 -1.3 (solar) 0.28 - 0.59 (Pennington cycle) < 0.8 (recirculation cycle) 0.61 - 1.97 (SENS cycle)	[46,56] [56] [11] [48] [43] [57] [57,58] [57,58] [57,58]
Water consumption (l/kWh)	7.1 2.5	[46] [45]	5.3 3	[46] [45]
Energy Efficiency Ratio (EER) (kWh/kWh)	electrical: 7 - 12 (solar)***	[59]	no information	
Seasonal Energy Efficiency Ratio (SEER) (kWh/kWh)	no information		no information	
Operational				
Energy source	heat + electricity		heat + electricity	
Cooling capacity (kW)	5 - 1180 (silica-gel) * 4 - 350 (zeolite)* 10 - 1000 70 - 350 8 - 15 (silica-gel) * 5 - 50 (zeolite)*	[56] [56] [11] [11] [12] [12]	2 - 307 6 - 300	[56] [11]
Temperature of driving heat (°C)	53 - 82 55 - 100 60 - 90 60 - 95 (silica-gel) 55 - 100 (zeolite) 55 - 90	[56] [11] [12] [12] [12] [48]	45 - 95 50 - 90 (solar) 50 - 100 60 - 80 65 - 90** (silica-gel) 50 - 95 66	[56] [56] [11] [48] [43] [43] [46]
Temperature of supplied cooling (°C)	3 - 25 10 - 25 (silica-gel) * 7 - 21 (zeolite)* 6 - 20	[56] [56] [56] [9,11]	16 - 20 >16	[11] [12]
Part load	yes		yes	
Lifetime (y)	> 10	[60]	> 10	[33]

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Feature	7	Source	8	Source
Working Fluid				
Refrigerant	natural		natural	
GWP	not applicable	[34]	not applicable	[34]
ODP	0	[34]	0	[34]
Hazard level	A1	[34]	A1	[34]
Miscellaneous				
Scalability	medium	[46,53]	low	[35]
Maintenance level	medium	[46,53]	high	[35]
Technical complexity	moderate to high	[35,53]	moderate to high	[35]
Investment cost (€/kW)	350 - 3000 (2015) 400 - >1400 (silica-gel) (2014) 150 - 1700 (1-stage) (2013) 579 - 673 (solar) (2023)	[43] [9] [9] [55]	11 - 16 (2013) * 325 - 650 (silica-gel) (2015)	[48] [43]
Notes	* Available on the market ** Solar cooling system *** Case study		* [€/m³/h] ** Ventilation mode	
Limitations adsorption chiller: low energy efficiency at small temperature differences, intermittent operation, temperature fluctuations, variable speed pumps (solar collectors) [12,46] ***Limitations desiccant (solid sorbent):*** high regeneration temperature, large energy demand for ventilator [12,61]				
Manufacturers adsorption chiller: Mitsubishi Plastics, SolabCool, SorTech AG, InvenSor, Mayekawa, Bry-Air, ECO-MAX, Fahrenheit, HIJC ***Manufacturers*** desiccant (solid sorbent): Klingenburg, Munsters, Robatherm GmbH, Siegle + Epple GmbH & Co. KG				

Table 6: Thermal systems (Part III)

Feature	9	Source	10	Source
Working principle	heat transformation (thermal)		thermo-kinetic process (thermal)	
Cooling generator	desiccant (liquid sorbent) + evaporative cooling system		ejector	
Distribution medium	air		water or water-glycol	
TRL level	3 - 4	[10,16]	3	[10,16,53]
Type of cycle	open cycle		closed cycle	
Cooling application	space and process cooling + dehumidification	[16]	space and process cooling	
Performance and efficiency				
Electrical efficiency (COP_{el}) (kW/kW_{el})	9 - 11	[45]	no information	
Thermal efficiency (COP_{th}) (kW/kW_{th})	0.74 (solar) 0.90 - 1.28 (solar) 0.7 - 1.1	[46,56] [46,56] [48]	0.2 - 1.2 up to 0.5 0.17 - 0.32 (solar) up to 0.8 (hydrocarbons) 0.168 - 0.645 (solar) < 0.8**	[43] [62] [62] [62] [44] [63]
Water consumption (l/kWh)	2.9 3	[46] [45]	0.45 - 0.7	[43]
Energy Efficiency Ratio (EER) (kWh/kWh)	no information		no information	
Seasonal Energy Efficiency Ratio (SEER) (kWh/kWh)	no information		no information	
Operational				
Energy source	heat + electricity		heat + electricity	
Cooling capacity (kW)	6 - 300	[11]	35 - 3500* 280 - 18140 2 - 3 5 (solar)	[43] [64] [62] [62]
Temperature of driving heat (°C)	55 - 60 (LiCl, solar) 47 - 58 ($CaCl_2$) 60 - 72 (LiCl) 60 - 80 50 - 70 66 40 - 70	[56] [27] [27] [48] [43] [46] [65]	85 - 180 120 - 140 84 - 96 (solar) 85 - 130 (solar) 60 - 140**	[43] [62] [62] [44] [63]

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Feature	9	Source	10	Source
Temperature of supplied cooling (°C)	∆ 5.5 - 7.5	[56]	2 - 21 6 - 10 5 - 15 6 - 13 5 - 10 (solar) 5 - 15**	[43] [64] [62] [62] [44] [63]
Part load	yes		yes	
Lifetime (y)	> 10	[33]	> 10	[33]
Working Fluid				
Refrigerant	natural		natural	
GWP	not applicable	[34]	not applicable	[34]
ODP	0	[34]	0	[34]
Hazard level	A1	[34,62]	A1	[34,62]
Miscellaneous				
Scalability	low	[35]	high	[53]
Maintenance level	high	[35]	medium	[35,53,62]
Technical complexity	moderate to high	[35]	low to moderate	[35,53,62]
Investment cost (€/kW)	1314 (2015) 11 - 16 (2013) *	[12] [48]	75 - 250 (2015)	[43]
Notes	* [€/m³/h]		* Included process cooling ** District cooling	
Limitations desiccant (liquid sorbent): reverse dehumidification, desiccant unit corrosion, desiccant carry-over (Indoor spaces), crystallization of liquid desiccant, large pumps, bulky, large energy demand for ventilator, expensive operational cost, on-site water consumption [10,12,35,46,57,61] ***Limitations ejector***: operating under idealized design conditions, low performance coefficient, geometry ejector [62]				
Manufacturers desiccant (liquid sorbent): Menerga, Kathabar Inc., Ficom, L-DCS Technology GmbH, Ail Research, AEX - American Energy Exchange ***Manufacturers ejector***: GEA Jet pumps, Körting Hannover AG				

Table 7: Mechanical systems (Part I)

Feature	11	Source	12	Source
Working principle	vapour compression (mechanical)		vapour compression (mechanical)	
Cooling generator	compressor		compressor	
Distribution medium	air or water or water-glycol		refrigerant	
TRL level	9	[10,16]	9	[10,16]
Type of cycle	closed cycle		closed cycle	
Cooling application	space and process cooling		space and process cooling	
Performance and efficiency				
Electrical efficiency (COP_{el}) (kW/kW$_{el}$)	2.5** (air cooled) 3.5** (water cooled) 1.9 - 7.0 (1-stage, synthetic) 1.8 - 7.1 (1-stage, natural) 2 - 7.1 (2-stage, synthetic) 1.8 - 7.4 (2-stage, natural) 1 - 6.24*** (air cooled) 3.76 - 6.58*** (water cooled) 2 - 7* 2.2 - 11.8	[11] [11] [12] [12] [12] [12] [66] [66] [42] [2]	1.6 - 4.82* 2.2 - 8	[66] [2]
Thermal efficiency (COP_{th}) (kW/kW$_{th}$)	not applicable		not applicable	
Water consumption (l/kWh)	not applicable		not applicable	
Energy Efficiency Ratio (EER) (kWh/kWh)	1.9 - 3.9 (A/W chiller) <400 kW 1.9 - 4.1 (A/W chiller) >=400 kW 2.8 - 6.1 (W/W chiller) <400 kW 4 - 6.3 (W/W chiller) >400 kW 3 - 5.5 (water) 2 - 3.5 (air)	[10] [10] [10] [10] [11,12] [11,12]	1.7 - 6 3 - 5.5	[10] [12]
Seasonal Energy Efficiency Ratio (SEER) (kWh/kWh)	3.8 - 7.2 (A/W chiller) <400 kW 4.1 - 7.2 (A/W chiller) >=400 kW 5.1 - 9 (W/W chiller) <400 kW 5.9 - 9.8 (W/W chiller) >400 kW 2.2 - 7.02*** (air cooled) 3.08 - 11.12*** (water cooled)	[10] [10] [10] [10] [66] [66]	4.6 - 10.1 4.48 - 9.98*	[10] [66]

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Feature	11	Source	12	Source
Operational				
Energy source	electricity		electricity	
Cooling capacity (kW)	50 - 5000 20 - 1730 (water, natural) 28 - 600 (air, natural) 4.3 - 2148*** (air cooled) 5.9 - 4147*** (water cooled)	[67] [12] [12] [66] [66]	7.2 - 90**	[66]
Temperature of driving heat (°C)	not applicable		not applicable	
Temperature of supplied cooling (°C)	(-50) - 15 (-4) - 12 (water, natural) 6 - 12 (air, natural)	[67] [12] [12]	no information	
Part load	yes		yes	
Lifetime (y)	> 10	[10,11,33]	> 10	[10]
Working Fluid				
Refrigerant	natural and synthetic		natural and synthetic	
GWP	medium (CFC) medium (HCF) low (HFC) low (FIC) very low (HFO) negligible (natural)	[23]	medium (CFC) medium (HCF) low (HFC) low (FIC) very low (HFO) negligible (natural)	[23]
ODP	high (CFC) medium (HCF) very low (HFC) very low (FIC) 0 (HFO) 0 (natural)	[23]	high (CFC) medium (HCF) very low (HFC) very low (FIC) 0 (HFO) 0 (natural)	[23]
Hazard level	A2** (R1234ze(E)) A1** (R134a) A2** (R290) A2L** (R32) A1** (R407C) A1** (R410A) A1** (R513A)	[12,24,68]	A1** (R134a) A2** (R290) A2L** (R32) A1** (R407C) A1** (R410A) A3** (R600) B2L** (R717)	[12,24,68]
Miscellaneous				
Scalability	high	[53]	high	[53]
Maintenance level	high	[53]	high	[53]
Technical complexity	low	[53]	low	[53]
Investment cost (€/kW)	75 - 125** (2009) 260 (A/W chiller) <400 kW (2016) 181 (A/W chiller) >=400 kW (2016) 173 (W/W chiller) <400 kW (2016) 117 (W/W chiller) >400 kW (2016)	4, 5 [10] [10] [10] [10]	789 (2016)	[10]
Notes	* Field test data - completed system ** Refrigeration *** Commercial products		* Reversible (cooling mode) ** Commercial products	
Limitations for mechanical compressor system: environmentally harmful for conventional refrigerants, high maintenance costs [53]				
Manufacturers for chillers: Aermec, Arcelik, Blue box, Carrier, Ciat, Climaveneta, Clint, Clivet, Daikin, Embraco, Galletti, Grassi, Dorin, Bitzer, Bock (R744), Hitecsa, KTK, Lennox, LG, Maxa, Mitsubishi, Panasonic, Thermocold, Trane ***Manufacturers for variable refrigerant flow:*** Airwell, Alarko, Alpicair, Bosch, Carrier, Clivet, Daikin, Daitsu, Electrolux, Fujitsu, Haier, Heiwa, Hitachi, Kaysun, Lennox, LG, Panasonic, Sigma, Trane, York				

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Table 8: Mechanical systems (Part II)

Feature	13	Source	14	Source
Working principle	vapour compression (mechanical)		vapour compression (mechanical)	
Cooling generator	compressor		compressor	
Distribution medium	air		air	
TRL level	9	[10,16]	9	[10,16]
Type of cycle	closed cycle		closed cycle	
Cooling application	space and process cooling		space and process cooling	
Performance and efficiency				
Electrical efficiency (COP_{el}) (kW/kW$_{el}$)	2.61 - 3.62 2.22 - 4.28**	[66] [66]	2.11 - 6.45* (split, = <12 kW) 2.25 - 5.77* (multi-split, =< 12 kW) 2.13 - 4.3* (split, > 12 kW) 2.29 - 4.83* (multi-split, > 12 kW) 2.5 - 5.8	[66] [66] [66] [66] [2]
Thermal efficiency (COP_{th}) (kW/kW$_{th}$)	not applicable		not applicable	
Water consumption (l/kWh)	not applicable		not applicable	
Energy Efficiency Ratio (EER) (kWh/kWh)	2.4 - 5.1	[10]	2.5 - 4.3 2.6 - 6.5 (split <6kW) 2.6 - 5.3 (split ≥ 6kW and ≤ 12kW) 1.7 - 6 (split >12kW)	[67] [10] [10] [10]
Seasonal Energy Efficiency Ratio (SEER) (kWh/kWh)	3 - 6.5 2.45 - 5.29 2.44 - 6.29**	[10] [66] [66]	3.15 - 8.5 4.6 - 8.5 (split <6kW) 4.3 - 8.5 (split ≥ 6kW and ≤ 12kW) 4.6 - 10.1 (split >12kW) 4.59 - 11.2* (split, <12 kW) 4.59 - 9.11* (multi-split, < 12 kW) 4.59 - 8.87* (split, > 12 kW) 4.8 - 13.2* (multi-split, > 12 kW)	[67] [10] [10] [10] [66] [66] [66] [66]
Operational				
Energy source	electricity		electricity	
Cooling capacity (kW)	15.47 - 200.4**	[66]	3.4 - 4.9 (split, R290) 2.2 - 11.2 (multi-split, R744) 3 - 27** (split) 1.5 - 28** (multi-split)	[12] [12] [66] [66]
Temperature of driving heat (°C)	not applicable		not applicable	
Temperature of supplied cooling (°C)	11 - 14	[69]	10 -12 (split)	[10]
Part load	yes		yes	
Lifetime (y)	> 10	[10,33]	> 10	[10]
Working Fluid				
Refrigerant	natural and synthetic		natural and synthetic	
GWP	medium (CFC) medium (HCF) low (HFC) low (FIC) very low (HFO) negligible (natural)	[23]	medium (CFC) medium (HCF) low (HFC) low (FIC) very low (HFO) negligible (natural)	[23]
ODP	high (CFC) medium (HCF) very low (HFC) very low (FIC) 0 (HFO) 0 (natural)	[23]	high (CFC) medium (HCF) very low (HFC) very low (FIC) 0 (HFO) 0 (natural)	[23]
Hazard level	A2L** (R32) A1** (R410A)	[12,24,68]	A2L*** (R32) A1*** (R410A)	[12,24,68]
Miscellaneous				
Scalability	high	[53]	high	[53]
Maintenance level	high	[53]	high	[53]
Technical complexity	low	[53]	low	[53]
Investment cost (€/kW)	279 (2016)	[10]	300 (split <5kW) (2016) 226 (split > 5kW) (2016)	[10] [10]

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Feature	13	Source	14	Source
Notes	* Reversible (cooling mode) ** Commercial products		* Reversible (cooling mode) ** Air conditioning for homes *** Commercial products	
Limitations for mechanical compressor system: environmentally harmful for conventional refrigerants, high maintenance costs [53]				
Manufacturers for rooftop: Carrier, Ciat, Climaveneta, Clivel, Daikin, ETT, Hitecsa, Lennox, Systemair, Trane, Untes, York ***Manufacturers for local system (splits and packaged):*** Airwell, Aux, Bosch, Buderus, Ciat, Coolsmart, Daikin, Equation, Fuji electric, Fojitsu, General, GSS, Haier, Hitachi, LG, Midea, Mitsubishi, Panasonic, Toshiba, Viessmann				

Table 9: Natural flow systems (Part I)

Feature	15	Source	16	Source
Working principle	ambient air (natural)		water (natural)	
Cooling generator	air to water (heat exchanger)		water to water (heat exchanger)	
Distribution medium	water or water-glycol		refrigerant or water or water-glycol	
TRL level	up to 9	[10]	up to 9	[10]
Type of cycle	open cycle / closed cycle		open cycle	
Cooling application	space and process cooling		space and process cooling	
Performance and efficiency				
Electrical efficiency (COP_{el}) (kW/kW_{el})	<u>5 - 50**</u>	[42]	8.6 - 10.5 (snow) 50 - 2000 (seasonal snow/ice) 5.6 (ice)	[10,70] [71] [72]
Thermal efficiency (COP_{th}) (kW/kW_{th})	Not applicable		Not applicable	
Water consumption (l/kWh)				
Energy Efficiency Ratio (EER) (kWh/kWh)	no information		no information	
Seasonal Energy Efficiency Ratio (SEER) (kWh/kWh)	no information		17.9 - 18.7 (seasonal snow)	[73]
Operational				
Energy source	electricity	[10]	electricity	[10]
Cooling capacity (kW)			8 - 1600* (seasonal snow/ice) 2000 - 5000 (seasonal snow) 31.5 (ice)	[70] [73] [72]
Temperature of free cold source (°C)			10 - 13 (groundwater) 2 - 10 (seasonal snow) 4 - 7 (seawater) Δ 10	[10] [71] [74] [75]
Temperature of supplied cooling (°C)	7 - 12 (Fan coil) 18 - 23 (Floor and ceiling panels) 19 - 27 (Cooling tower)	[10]	7 - 12 (seasonal snow) up to 10 (groundwater) Δ 1 - 6.7****	[70] [74] [72]
Part load	yes		yes	
Lifetime (y)	> 10	[33]	> 10	[33,70]
Working Fluid				
Refrigerant	natural		natural	
GWP	not applicable	[34]	not applicable	[34]
ODP	0	[34]	0	[34]
Hazard level	A1	[34,62]	A1	[34,62]
Miscellaneous				
Scalability			no information	
Maintenance level			no information	
Technical complexity			no information	
Investment cost (€/kW)	80- 400 [2002] *	[76]	1067** (seasonal snow) (1999) 158 - 444***** (ice) (2022)	[70] cf. [72]
Notes	* in case of dry coolers used for free-cooling. Otherwise values of wet cooling towers applicable **Field test data		* Calculated ** Completed project *** Depends on the difference in temperature, flow and quality of the fluid ***** Cooling effect ***** Heat exchanger + ice storage tank	
Limitations for ambient air (natural): climatic restrictions, additional equipment is required [10]				

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Feature	15	Source	16	Source
Limitations for water (natural): geographic/climatic restrictions, ecological consequences, proximity to water source, additional piping and equipment, heat losses in the intake pipelines, risk of thermal shock in the deep seawater outlet, detailed knowledge on cooling demand requirements, main application for cooling districts, high investment [10,74,75,77]				

Table 10: Natural flow systems (Part II)

Feature	17	Source
Working principle	Ground source*, **	
Cooling generator	Air/Ground water (heat exchanger)/Waste Cold (heat demand)	
Distribution medium	ATES/MTES: Water/Mine water BTES: Water/Brine	
TRL level	ATES: 7-8 BTES: 8-9 MTES: 7-8	[78] [78] [cf. 79]
Type of cycle	ATES: open cycle MTES: open cycle BTES: closed cycle	
Cooling application	space and process cooling	
Performance and efficiency		
Electrical efficiency (COP_{el}) (kW/kW_{el})	BTES: 4-20 ATES: 30 - 40	[80]
Thermal efficiency (COP_{th}) (kW/kW_{th})	BTES: 0.7 -0.9 ATES: 0.65 - 0.95 0.675 - 0.9	[81] [81] [82]
[80–82]Water consumption (l/kWh)	not applicable	
Energy Efficiency Ratio (EER) (kWh/kWh)	No information	
Seasonal Energy Efficiency Ratio (SEER) (kWh/kWh)	BTES: 4-5	[80]
Operational		
Energy source	electricity waste & ambient cold**	[80–82]
Cooling capacity (kW)	Storage capacity BTES: 15 -30 kWh/m³ ATES: 30 - 40 kWh/m³ Charging/Discharging heat flow BTES: low with buffer required ATES: Low/medium with buffer required	[78,81]
Temperature of driving heat (°C)	not applicable ****	
Temperature of supplied cooling (°C)	MTES: 12 - 16 BTES: below 0 from 5 up to 20 ATES: 5 - 6 7 - 18 6 - 10 13 - 30	[79,83] [80] [84] [78,81] [80] [84] [74] [78,81]
Part load	yes	
Lifetime (y)	10-30	[85]
Working Fluid		
Refrigerant	natural	[3]
GWP	0	[34]
ODP	0	[34]
Hazard level		
Miscellaneous		
Scalability	Medium-high	[cf. 3,84,86,87]
Maintenance level	ATES: high BTES: low	[80]
Technical complexity	BTES: low	[80]
Investment cost (€/kW)	ATES: 50-60 €/m³ 220 €/kW BTES: 20-40 €/m³ 600-1100 €/kW	[84] [80] [84] [80]

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Feature	17	Source
Notes	*Borehole thermal energy storage (BTES) Aquifer thermal energy storage (ATES) Mine thermal energy storage (MTES) **usually with seasonal regeneration ***pumping energy strongly depends on storage depth **** UTES are not droven by heat, by are usually regerated seasonally by a heat source, Typical temperatures of the injected heat are approx. 5 °C [74]	

Portfolio TES

Table 11 show the consolidated information for the main types of TES. The overview of the TES has been separated from the tabular presentation of the cooling technologies, as the relevant technical parameters differ.

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Table 11: Thermal Energy Storage

Feature	Sensible TES	Source	Latent TES	Source	Thermochemical TES	
Mechanism	Increase of temperature	[88]	Heat of fusion	[88]	Enthalpy of reaction	[88]
Volumetric energy density (kWh/m³)	50	[88], [19], [18]	100	[88], [19], [18]	500	[88], [19], [18]
Gravatical energy density (MWh/kg)	20-30 10-50	[88], [18] [89], [44]	50-100 50-150	[88], [18] [89], [44]	120-150 120-250 500 500-1000	[89] [44] [18] [88]
Efficiency (%)	50-90 50-94	[88], [44] [89]	75-90	[88], [89], [44]	75-100	[88], [89], [44]
Duration of storage	Limited because of the losses	[88], [19], [18]	Limited because of the losses	[88], [19], [18]	Theoretically unlimited	[88], [19], [18]
Operating temperature	Charging step temperature	[88], [19], [18]	Charging step temperature	[88], [19], [18]	Ambient temperature	[88], [19], [18]
Power (kW)	1-10,000 1-50,000	[88], [44] [89]	1-1000 1-10,000	[88], [44] [89]	10-1000 10-5000	[88], [44] [89]
Expense (€/kWh)	Cheap/0.1-10	[88], [44]	Medium/10-50	[88], [44]	Expensive/8-100	[88], [44]
Investment cost (€/kW)	3400-4500	[89]	6000-15,000	[89]	1000-30,000	[89]
O&M cost, fixed and variable (€/kW/a)	70-250	[89]	120-750		20-1500	[89]
Technical Complexity	Simple	[88], [19]	Simple	[88], [19]	Complex	[88], [19]
Transportation distance	Shorter	[88], [18]	Shorter	[88],	Theoretically longer	[88], [18]
Maturity of technology	Commercialized	[19], [18]	Pilot-scale	[19],[18]	Laboratory-scale Laboratory/pilot-scale	[19] [18]
Insulation requirements	Yes	[19]	Yes	[19]	No	[19]
Material	Liquids (water) Solids (Earth material, concrete) Solid-liquid mix (water/pepples)	[44]	Ice, Water gel PCM* (Organic salts, inorganic, eutectic)	[44]	Salt hydrates, Metal hydrides	[44]
Storage period	Days - months	[89],	hours - days	[89], [44]	days - months	[89], [44]
Technical lifetime (y)	10 - 30+	[89]	10 - 30+	[89]	10 - 30+	[89]
TRL level	7 - 9	[89]	4 - 7	[89]	3 - 5	[89]
Advantages	Low-cost materials Reliable Simple system	[18] [18] [18]	Higher storage density compared to sensible TES Compact system	[18] [18]	Highest storage density Long-term storage Minor heat losses Heat storage at ambient condition	[18] [18] [18] [18]
Disadvantages	Low-energy storage density Higher thermal insulation requirement Shorter storage duration	[18] [18] [18]	Poor thermal conductivity Higher thermal insulation requirement Some materials highly corrosive	[18] [18] [18]	Expensive Complex system	[18] [18]

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Examples on system integrated cooling technologies

In general, for a cooling system (generator or free cooling) to be considered renewable, it must generate a significant portion of its thermal cooling energy from renewable sources. This means that the technology either inherently uses renewable sources or the energy consumed comes from renewable energy [1]. Therefore, identifying the type of energy input and the operational requirements of each cooling system facilitates sectoral coupling, integration with thermal energy storage systems and renewable energy sources.

In Table 12 and Table 13 identified[4] case studies based on the selected cooling technologies with the following characteristics are listed:

- Integration of sensible, latent or thermo-chemical storages for cooling
- Sector-coupling operation, i.e. the installed cooling system can meet demands of various sectors (cooling, heat, electricity, etc.) thereby having a flexible operation
- Ability to supply heating and cooling
- Grid serving operation, i.e. the cooling system allows a flexible operation regime and can operate (or not operated) according to grid-related demands (e.g. surplus electricity production, electricity prices, availability of heat, etc.)

Table 12: Integration for Thermal Energy Storage (Case studies)

Working principle	Heat transformation	Vapour compression
Cooling technology	Absorption chiller	Compressor
CTES Sensible	• SAC BMVBW and BPA [90] • District Cooling System Chemnitz [91]	• SAC BMVBW and BPA [90] • District Cooling System Chemnitz [91]
CTES Latent	• SAC/Ice storage [92,93] • SAC BMVBW and BPA [90]	• Energy Network Berlin Adlershof [94]

Table 13: Integration for Sector Coupling (Case studies)

Working principle	Heat transformation	Vapour compression	Natural
Cooling technology	Absorption chiller Desiccant evaporative cooling	Compressor	Heat exchanger
Grid serving operation	• Steam ejector applications [64]	• Energy Network Berlin Adlershof [94]	
Heating and cooling supply	• SAC/District heating [95] • SAC BMVBW and BPA [90] • Energy Network Berlin Adlershof [94]	• EUREF Energy Workshop [96]	• ATES Reichstag Berlin [97] • Minewater 2.0 Heerlen [79] • Geostar IEG Bochum [98] • ATES Reichstag Berlin [97] • Applied ATES-HP and BTES-HP systems [99]

Moreover, in Task 2.4: *State-of-the-art cooling systems based on RES and recommendations* will be analysed and discussed.

[4] No claim to completeness

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Conclusion

Resulting from the undertaken surveys there is no singular salient aspect or parameter that is particularly relevant for the design of the future sustainable cooling system. Notably, 5th Generation District Heating & Cooling systems, passive cooling systems, and storage technologies acquire high significance with further development potential. Particular emphasis is placed on the evaluation of subsurface structures as a solution for long-term thermal storage of cooling. As sources for renewable cooling supply, both renewable electricity and heat are essential, with electricity driven technologies being assigned a greater relevance especially for small scale applications.

In a further step a dedicated mapping of cooling technologies and thermal energy storages for cooling, that are currently available on the market and used in space cooling, highlights the diversity of technological solutions for the supply of cooling with TRL levels >8. Many further cooling technologies based on other working principles such as thermoelectric, electrocaloric, pulse tube, etc. can be regarded as niche cooling solutions as they are currently at an early development stage with low expectations on market penetration or large-scale applications. Simplified schematics are drafted to highlight the basic setup and exchange of heat or mass flows for the cooling generators and storage solutions. Moreover, a detailed and consolidated overview on main key parameters and information is developed for water evaporative systems, thermally driven systems, mechanical vapor compression systems, natural flow systems and thermal energy storages based on sensible, latent and thermochemical heat storage. The characteristics of these 20 technologies for the supply and storage of cooling provide a more detailed insight into performance values, required energy sources, cooling capacities, supply temperatures, etc. In a further step, cases studies for cooling systems with integrated storages, the simultaneous supply of heating and cooling, grid-serving or sector-coupled systems have been identified for some of the mapped cooling technologies. A detailed insight into state-of-the-art cooling systems with a high degree of system integration will be given in section *State-of-the-art cooling systems based on RES and recommendations*.

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Assessment of Cooling Demand and Market Overview

Task objectives

In examining the escalating need for cooling, a fundamental task arises: determining the current energy consumption dedicated to cooling buildings, a substantial share of our overall energy use. As previously discussed, a considerable portion of this cooling demand relies on electrical energy due to the high market share of conventional compression chiller technology (99%) [10]. However, accurately quantifying the exact electricity usage for cooling remains a complex challenge.

Our initial focus entails a comprehensive examination of current cooling requirements, reaching beyond energy statistics and the actual saturation rates in satisfying this cooling demand with active cooling systems. This investigation is not merely about understanding our current energy landscape; it forms the basis for predicting future trends. Looking ahead to 2030, our primary goal is to forecast the increasing demand for cooling and its subsequent impact on electrical consumption.

This report serves as a strategic guide, navigating over the complexities inherent in understanding and addressing the evolving dynamics of cooling requirements.

The importance of cooling demand assessment

Literature review

In literature, notable information regarding the cooling sector is lacking, making the precise cooling energy demand elusive. Nevertheless, several research projects endeavour to shed light on this demand. These research projects will be addresses here shortly:

The HEAT ROADMAP project (2015) [100] addresses this gap by evaluating the building surface cooled through an analysis of nominal cooling power installed and specific mean power per unit of surface. The project extended its reach to 2050, estimates the power sold based on the power installed in 2015 and the market saturation data from the United States of America. The evaluation of the total cooled floor surface area at market saturation takes in consideration the Cooling Degree Days (CDD) and Gross National Income (GNI) per capita for residential sector and only the CDD for service sector. At the end, the project arrives for

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the EU27+UK of an estimation for 2015 of 51 TWh for residential cooling (6.3 % of saturation) and 133 TWh for cooling in service buildings (21.3 % of saturation), with a projection for 2050 of 237 TWh for residential and 333 TWh for service buildings.

In the STRATEGO project (2016) [101,102], the assessment of cooling demand in 2010 initiates with data derived from energy consumption of district networks in service buildings and from estimations for residential buildings (accounting for 45 % of the service demand). The project employs European Cooling Index (ECI), derived from the Ecoheatcool project (2010) [103], leveraging CDD and thermal resistance of typical building envelopes in every country. This index is instrumental in illustrating the distribution of cooling demand. The saturation rate, a crucial parameter, is sourced from different outlets, including ENTRANZE, INSPIRE, ODYSSE, JRC reports[5] and national databases. When no information is available, a default value of 10 % is assumed. The estimations yield a specific cooling demand of 37 kWh/m^2 for residential buildings and 74 kWh/m^2 for service buildings. The potential total demand in 2010 stands at 722 TWh for residential and 446 TWh for service, with the current cooling supply amounting to 47 TWh for residential and 145 TWh for service. These figures correspond to 5% and 26% of total buildings, respectively. However, it is essential to note the limitations of this estimation methodology. The reliance on only twenty district cooling values, the fixed residential demand at 45% of service, uncertainties regarding saturation levels for residential buildings and the surface areas for service buildings collectively contribute to potential inaccuracies in the overall assessment.

M. Jakubcionis estimated the potential cooling demand in the residential (2017) and service (2018) sectors using the United States of America as proxy [104]. By leveraging all available data for the US market, which can be considered saturated in terms of space cooling for buildings, the cooling demand is also calculated for Europe based on the CDD. In this calculation, the cooling demand is multiplied by a percentage representing the proportion of buildings that can use cooling, with both the values evaluated as a function of CDD. Thus, the assessment assumes that complete saturation is never achieved. The potential cooling demand is as estimated in 2017 at 292 TWh for the residential sector and in 2018 at 174 TWh for the service sector. The weakness of this methodology lies in the significant assumption that, under equivalent climatic conditions, cooling in the US is comparable to that in the EU, whereas in reality, habits and lifestyles can make a substantial difference.

[5] Reports from Stratego [101,102].

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In HOTMAPS project (2019) [105] two distinct approaches are used to assess the cooling demand. In the top-down approach, the estimation of space cooling begins with data from various sources (Euroheat & Power) at country level. Subsequently, this data is distributed at the NUTS3 level (province level), utilizing a range of indicators (buildings data, CDD, specific cooling demand). Further granularity is achieved at hectare level through the incorporation of indicators as gross floor area of buildings, population density, economic activity and climate conditions. With this approach, the actual useful energy demand for space cooling is estimated in 2016 at 54 TWh for residential and 153 TWh for service sector. In the bottom-up approach, the cooling demand derives from an analysis of technologies and market dynamics. For the different space cooling technologies, equivalent full-load hours, cooled floor area and number of units installed are distributed between sectors (residential and various service sectors). Further classification identified their installed capacity, their cooling seasonal performance factor and yearly hours of operation per sector. The work input (electricity) per air conditioning type has been calculated: the average capacities per space cooling type have been divided through their respective cooling seasonal performance factor. The final energy consumption (electricity) has been calculated: the number of units per sector has been multiplied by their average equivalent full-load hours within a year and its work input (electricity). The calculation is assessed for EU15 and then extended to cover the entire EU27+UK. In this case, the actually satisfied cooling demand in 2016 is 15 TWh for residential and 95 TWh for service. The HOTMAPS project proves to be the most comprehensive and reliable source on the subject, therefore it has been taken as the reference and starting point for the current evaluation.

Future prevision

The demand for cooling is poised to increase globally in the coming years. Final energy consumption for cooling in Europe has grown by 241% from 1990 to 2016. However, despite the growth, the percentage of buildings equipped with cooling systems remains relatively low in 2016, indicating significant potential for further expansion [2]. According to the study of M.A.D. Larsen et al [106] the cooling demand in Europe will rise from 25% to 50%, depending on the scenarios, from 2010 to 2050, but some countries, like Belgium, Netherlands, Denmark and UK, will double their demands. Several factors drive the demand for cooling: climate conditions, economic growth, demographic change (such as population growth, urbanization, aging populations and health-related issues), energy efficiency of cooling equipment, building energy performance, demand-side management, and adoption of alternative cooling solutions such as district cooling and solar cooling [2]. According to the study of M. Santamouris [6], the penetration level of cooling (percentage of buildings equipped with air conditioning) is influenced by various factors including climate, economic indicators like income and electricity prices, equipment costs, demographics, regulatory policies governing buildings and equipment. Additionally, technological advancements play a crucial role.

Considering all these factors presents a significant challenge. However, in particular for Europe, climate conditions, household incomes and technological advancements appear to be the primary drivers of cooling demand.

In the analyses [107], the growth of cooling demand for residential sector in Europe between 2000 and 2015 was decomposed in different factors. It turns out that the main drivers are the diffusion of air conditioning equipment (percentage of buildings equipped with air conditioning), the rising of cooling demand (due to the climate), the number of households and the efficiency of the systems. However, the diffusion of air conditioning system played the major role.

Importance of cooling demand estimation

The estimation of cooling demand in buildings and its future evolution holds significant importance. Various studies focusing on forecasting the future demand for cooling in EU buildings may present differing results and parameters. Nevertheless, they converge on the prediction that energy consumption for cooling purposes is poised to rise. Consequently, the proportion of energy allocated for cooling is also expected to increase. Particularly, southern EU countries are anticipated to experience the most substantial surge in future energy demand for cooling. While cooling energy consumption presently constitutes a modest portion of the total EU energy usage, the peak electricity demand for cooling, predominantly fulfilled by electricity, is projected to escalate across Europe. The most pronounced increments are foreseen in countries like France, Italy, and Spain. With hotter summers and more frequent heatwaves expected due to climate change, the imperative to cool buildings to safeguard public health will inevitably lead to heightened energy consumption. Although active cooling systems in residential buildings are less prevalent in the EU compared to similar regions worldwide, the EU market for such systems is rapidly expanding [108]. Presently, air conditioning stands out as the predominant cooling strategy for those who can afford it, notwithstanding its associated drawbacks. The utilization of air conditioning units and reversible heat pumps contributes to climate change through two main channels: electricity generation emissions and refrigerant emissions. While technological advancements can

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mitigate greenhouse gas emissions from active cooling systems, the surge in demand for equipment and electricity remains a challenge. This presents hurdles in achieving the EU's objectives of reducing both final and primary energy usage.

The importance of estimating the energy demand for cooling buildings lies in the ability to predict and efficiently manage future energy demand, enabling adequate resource planning and better preparation for the impacts of climate change. These estimations provide a crucial framework for developing strategies and policies aimed at promoting energy efficiency, reducing greenhouse gas emissions, and ensuring the long-term sustainability of the building sector.

The assessment of cooling demand

Methodology

The assessment of cooling demand starts with the building stock database derived from the open source dataset of HOTMAPS [105], predominantly sourced from the EU Buildings Stock Observatory [109]. The dataset encompasses square meters for every country (EU27+UK), categorized into residential and services sectors. The residential sector is divided into single-family and terraced houses, multifamily houses and apartment blocks. Every category is divided into different periods of construction. Non-residential buildings are categorized in offices, trade, education, health, hotels-restaurants and other (Table 14).

Table 14: Building stock subdivisions

Sector	Subsector	Building type
Residential	Single family- Terraced houses	Before 1945
		1945 - 1969
		1970 - 1979
		1980 - 1989
		1990 - 1999
		2000 - 2010
		Post 2010
	Multifamily houses	Before 1945
		1945 - 1969
		1970 - 1979
		1980 - 1989
		1990 - 1999
		2000 - 2010
		Post 2010

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Sector	Subsector	Building type
	Apartment blocks	Before 1945
		1945 - 1969
		1970 - 1979
		1980 - 1989
		1990 - 1999
		2000 - 2010
		Post 2010
Service	Offices	
	Trade	
	Education	
	Health	
	Hotels and Restaurants	
	Other non-residential buildings	

The sensible cooling loads were derived from the assessment conducted in the Cheap-GSHPs project [110]. In this project, four types of residential buildings and five types of service buildings (three administrative, one office and one day care centre) are analysed. Refer to Figure 19 and

Figure 20 for visual representation. Furthermore, for each type of residential building, three levels of insulation (no insulation, low insulation, good insulation) were considered. Energy consumption was determined through dynamic simulation conducted for twenty different cities around Europe, accounting for various latitudes and climates. For a more in-depth understanding of calculation methodology, consult [111].

	RB 1	RB 2	RB 3	RB 4
External view				
S/V ratio	0.86	0.40	0.35	0.43
Net area (m^2)	210	126	1330	681
% glazed area	14%	12%	25%	14%
No. storeys	2	3	5	5
No. dwellings	1	1	20	10
Urban structure	stand alone	contiguous	stand alone	stand alone

Figure 19: Residential Building (RB) types: general information

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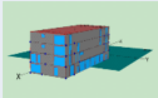
	NRB 1	NRB 2	NRB 3	NRB 4	NRB5
External view					
S/V ratio	0.5	0.5	0.33	0.37	0.26
Net volume (m³)	5700	5700	3951	3366	5713
% glazed area	85%	50%	49%	45%	35%
No. storeys	5	5	4	2	2
No. people	100	100	454	201	50
Building Use	Administrative Building	Administrative building	Administrative building	Day care center	Office building

Figure 20: Non-Residential Building (NRB) types: general information

The profiles were allocated to the buildings stock basis using the following assumptions:

- The average of RB1 and RB2 was assigned to single family and terraced house.
- RB3 was assigned to multifamily houses.
- RB4 was allocated to apartment blocks.
- The average of NRB1, NRB2, NRB3 and NRB5 was assigned to offices.
- NRB4 was assigned to educational buildings.
- For trade, health, hotels-restaurants and other service buildings, energy consumption data were taken from the HOTMAPS project [105].
- No insulation was considered for buildings constructed before 1980
- Low insulation was considered for buildings constructed between 1980 and 1999
- Good insulation was considered for buildings constructed from 2000.

The specific cooling demand is determined through linear correlations with CDD, expressed by the equation:

$$Cooling\ demand = M * CDD + B \tag{1}$$

Where M and B are the coefficients from [110] and CDD are the Cooling Degree Days calculated as the weighted average:

$$\text{CDD} = \frac{\sum_j CDD_j * P_j}{\sum_j P_j} \tag{2}$$

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Where CDDj are the CDD of region j and Pj represents the population of the region j. The CDD at regional level (NUTS2) were calculated using the methodology outlined in [111] to ensure consistency with the data from which the relationships used have been derived. Therefore, a reference temperature of 18°C and a threshold temperature of 20°C were utilized to calculate the CDD. The temperatures were sourced from the Copernicus database, the original data source is ECMWF ERA5 Reanalysis [112], with daily average for the years 2013-2022 considered for each European region (NUTS2). Regional population data was obtained from EUROSTAT [113] for the year 2021, except for UK where data are available only for 2019.

To determine the average sensible cooling load, the different energy consumption of various building types have to be weighed. The cooled square meters obtained from HOTMAPS [114] were used to calculate a weighted average of the cooling load of different categories of buildings. The process was carried out for both residential and service sectors. Using the estimated cooled surface area instead of the total surface area allows for accounting the fact that some building categories are more cooled than others, and this can vary from country to country. The graphical representation of the process used is represented in Figure 21.

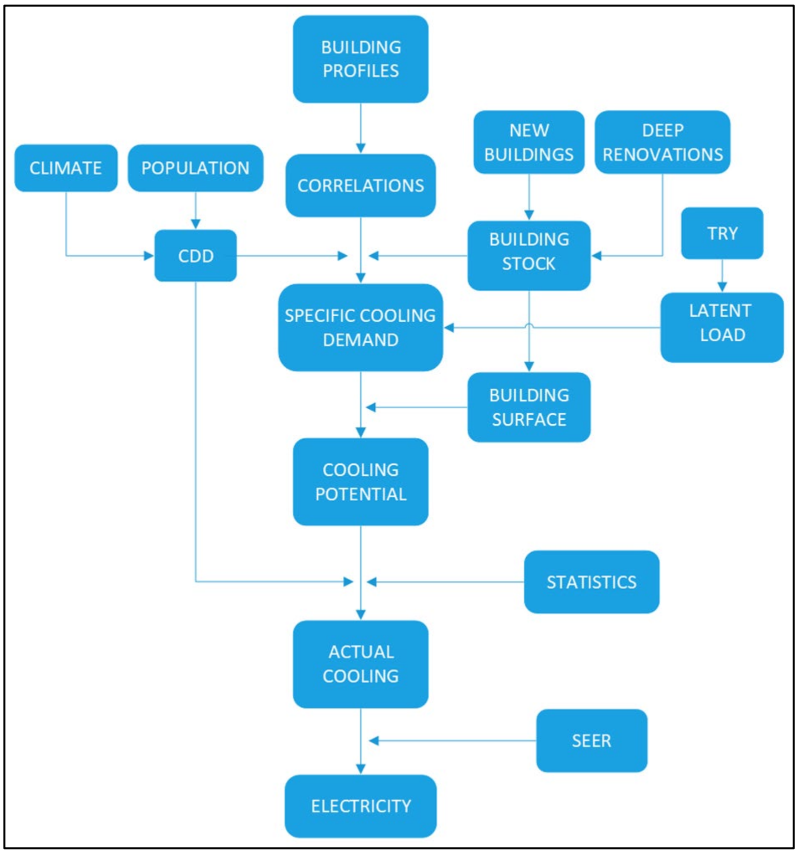

Figure 21: Process diagram

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For the evaluation of the latent load, an hourly vapor balance was conducted, assuming an average dwelling size of 80 square meters for residential areas. The internal vapor production was set at 9 kg per day, with internal conditions of 26°C and 50% humidity, and an hourly air exchange of 0.5 volumes per hour. The temperatures, pressure and external humidity conditions were derived from the Energy Plus Test Refence Year of a selected city chosen for every county. By calculating the excess vapor to be removed for each hour and summing it over the cooling period, the total latent load was obtained. Dividing this total latent load by 80 square meters yields the specific latent load.

For the offices, a similar same approach was followed, with the distinction that an hourly air exchange of 1 volume per hour was considered, along with a vapor production of 60g/h per person, assuming one person per 40 cubic meters. Additionally, only working hours were considered, specifically from 8AM to 6PM, Monday to Friday.

In Table 15, the cities chosen for each country and the latent load evaluated for residential and office buildings are summarized.

Table 15: Latent load for residential and office buildings

COUNTRY	CITY	LATENT LOAD [kWh/m² y]	
		RESIDENTIAL	OFFICE
AUSTRIA	VIENNA	4.91	1.04
BELGIUM	BRUXELLES	5.60	1.50
BULGARIA	SOFIA	5.55	1.50
CROATIA	LJUBLJANA	5.38	1.08
CYPRUS	LARNACA	22.93	11.34
CZECH REPUBLIC	PRAGUE	3.62	0.93
DENMARK	COPENHAGEN	2.71	0.35
ESTONIA	HELSINKI	2.48	0.29
FINLAND	HELSINKI	2.48	0.29
FRANCE	PARIS	6.07	1.82
GERMANY	BERLIN	3.46	0.75
GREECE	ATHENS	11.79	4.91
HUNGARY	DEBRECEN	8.82	3.31
IRELAND	DUBLIN	3.49	0.65
ITALY	BOLOGNA	12.74	5.05
LATVIA	KAUNAS	4.33	1.26
LITHUANIA	KAUNAS	4.33	1.26
LUXEMBOURG	BRUXELLES	5.60	1.50
MALTA	PANTELLERIA	20.38	9.78
NETHERLANDS	AMSTERDAM	6.07	1.75
POLAND	LODZ	4.48	1.01

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COUNTRY	CITY	LATENT LOAD [kWh/m² y]	
		RESIDENTIAL	OFFICE
PORTUGAL	COIMBRA	11.19	3.98
ROMANIA	BUCHAREST	9.56	2.42
SLOVAKIA	DEBRECEN	8.82	3.31
SLOVENIA	LJUBLJANA	5.38	1.08
SPAIN	MADRID	3.06	0.71
SWEDEN	STOCKHOLM	2.18	0.36
UNITED KINGDOM	LONDON	9.48	3.95

The building stock surface refers to the year 2016, and this surface was updated by incorporating the new building constructed between 2016 and 2022, as reported by EUROSTAT [115], for both residential and non-residential buildings at country level.

Additionally, deep renovations conducted between 2016 and 2022 were considered. The rate of renovation was considered as an average of the rate observed for the year 2012-2016 (the last available data) at country level, as reported in EU Report [116]. The surface area of the renovated buildings was included as buildings with good insulation and this value was subtracted from the surface area of buildings constructed before the year 2000.

Actual saturation of space cooling

Evaluating the actual energy consumption for cooling presents a significant challenge. Much of the literature data relies on outdated statistics or attempts to extrapolate buildings saturation level from very limited data. In the recent years, there has been a significant increase in the number of cooling systems installed in building [117], causing saturation levels to change rapidly. Relying on results from a decade or more ago can lead to significant different outcomes, especially in southern countries.

Since some national statistics exist for certain countries, primarily for residential buildings, this data can serve as a starting point for extrapolating correlation between saturation level and CDD. Obviously, the penetration of space cooling can vary greatly between countries with similar climates due to various factors, such as economic conditions and cultural habits. For this reason, these correlations, which only consider climate, have been used only for these countries where national data is lacking. Nevertheless, the real values from national statistics cover approximately 70% of the residential building surface of EU27+UK, the remaining 30% was estimated using the previously described approach. In Table 16, the values and their sources from various statistical studies are reported and these are represented in Figure 22,

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along with their linear correlation with the CDD. Using a linear correlation, instead of a logarithmic correlation, seems to fit better the statistical data available. Obviously, with a linear correlation the saturation level can exceed 100%, but in this case, this happens only for Cyprus, which was considered fully cooled (this probably does not reflect reality, but can be considered an acceptable approximation considering the small weight of this country).

Table 16: Source of cooling saturation for residential buildings

Country	CDD	Saturation	Source	Year
France	189	25.0%	[118]	2020
Germany	140	2.0%	[119]	2020
Greece	850	50.4%*	[120]	2022*
Italy	470	48.8%	[121]	2021
Malta	1093	84.0%	[122]	2021
Portugal	396	16.6%	[123]	2021
Spain	566	60.9%**	[124]	2022**
UK	26	5.0%	[125]	2021
Notes	*40.4 % in 2012 correct with an increasing of 1% a year for 2022 **48.9% in 2010 correct with an increasing of 1% a year for 2022			

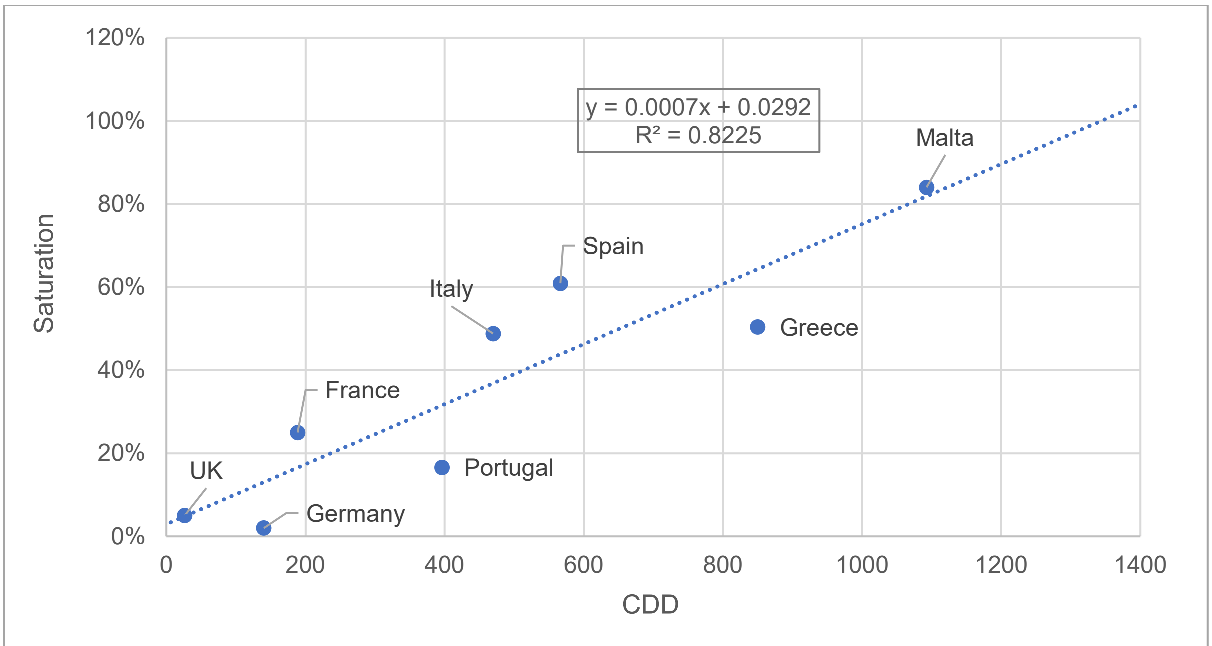

Figure 22: Statistics and correlation for cooling saturation in residential sector

Regarding the penetration of cooling in the service sector, it is indeed very difficult to find precise and up-to-date information. All data found in the literature are based on estimates and

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are not updated. Although it should be emphasized that cooling of tertiary buildings has been present for many years, so changes in recent years at a general level should not be too significant, unlike the residential sector. While providing exact values for each country has proven difficult, average values with a range of variation have been assessed based on data from other projects mentioned and some specific statistics for certain countries.

For instance, a report for France [118] suggest that approximately 40% of service buildings are cooled. In Italy, according to ENEA report [126] of 2015, 52% of service buildings are equipped with cooling systems. In Germany, data from VDMA report of 2017 [13] allows for an estimate that around 52% of service buildings are cooled. In the UK, the 2019 report [127] indicates that approximately 43% of service buildings are cooled.

Given the variability of different estimation, it is more appropriate to consider a range from the minimum to the maximum value when assessing the prevalence of cooling systems in the service sector.

Electrical energy consumption assessment

In evaluating electrical energy consumption, the average efficiency of the equipment stock was taken into consideration. As explained in the initial paragraph of this report on cooling technologies, the cooling demand can be met through diverse technologies and energy sources. Nevertheless, a predominant share of the demand is satisfied by vapor compression cycles, primarily relying on electricity. According to the EU Report [10] vapor compression systems provide the absolute majority (almost 100%) of Europe’s cooling needs. However, EUROVENT data suggest that thermally driven heat pumps constitute for approximately 1% of the EU’s cooling market. Given their limited share, they have not been considered in the present evaluation.

Table 17 and Table 18 show how the average SEER for residential and tertiary buildings is calculated using data from EU Report [10]. Since these data refer to 2016, adjustments were made to incorporate the increasing efficiency of different cooling systems over the years. In the report of IEA [2], the average efficiency improvement from 1990 to 2016 is 1.92% per year for residential sector and 2.15% per year for service sector. Given that the trends since 2050 appear very similar to those of previous years in the baseline scenario, these values were applied to calculate the SEER for 2022. The resulting averages are a SEER of 4.22 for the residential sector and 4.46 for the service sector.

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The electrical energy consumed for cooling is a mere division of the total energy demand to SEER.

Table 17: SEER in the residential sector, EU27+UK, the reference year 2016 [10]

TECHNOLOGY	FINAL ENERGY CONSUMPTION [TWh/y]	%	SEER
Movables	1.68	7.6%	2.00
Small split (<5 kW)	9.79	44.4%	4.10
Big split (>5 kW, inclusive ducted)	8.78	39.8%	3.80
Variable refrigerant flow systems	0.22	1.0%	4.00
Chiller (air-to-water) < 400 kW	1.4	6.3%	3.45
Chiller (water-to-water) < 400 kW	0.19	0.9%	4.70
TOT	22.06		3.78

Table 18: SEER in the service sector, EU27+UK, the reference year [10]

TECHNOLOGY	FINAL ENERGY CONSUMPTION [TWh/y]	%	EER
Movables	0.15	0.2%	2.5
Small split (<5 kW)	6.18	7.4%	4.2
Big split (>5 kW, inclusive ducted)	30.58	36.4%	3.95
Variable refrigerant flow systems	8.09	9.6%	3.9
Rooftop + Packaged	20.55	24.5%	3.8
Chiller (air-to-water) < 400 kW	4.78	5.7%	3.5
Chiller (air-to-water) > 400 kW	7.44	8.9%	3.45
Chiller (water-to-water) < 400 kW	1.36	1.6%	4.75
Chiller (water-to-water) > 400 kW	4.91	5.8%	5.35
TOT	84.04		3.95

Results

The results of the assessment of cooling demand are represented in the following diagrams. Figure 23 illustrates the specific energy demand for cooling across different countries, both for residential and service sector. It is evident that the service sector requires significantly more energy for space cooling, primarily due to internal loads and large windows with inadequate shading systems. While the diagrams indicate a clear correlation between CDD and energy demand, this relation is not linear because other factors determine the load of every country, like the types and age of buildings. The weighted average of specific cooling demand for EU27+UK is 26.1 kWh/m^2 for residential and 64.2 kWh/m^2 for service buildings.

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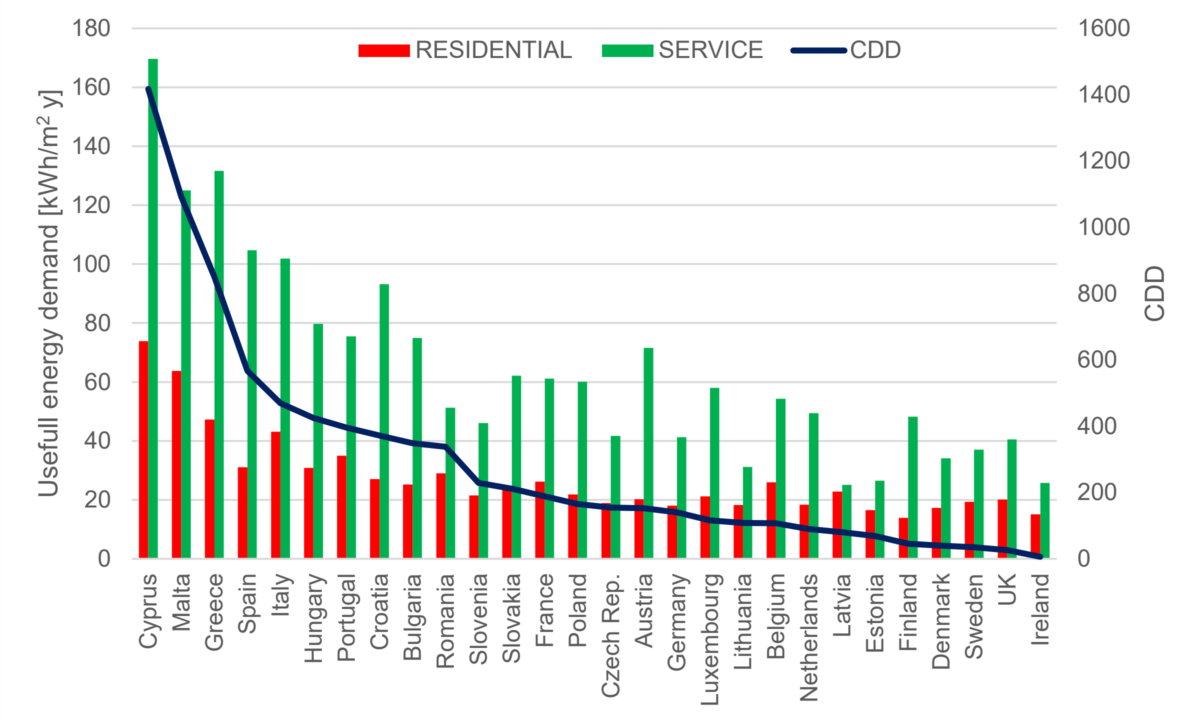

Figure 23: Specific cooling demand for each country

Figure 24 and Figure 25 compare the specific cooling demand evaluated from different projects respectively for residential (Figure 24) and service (Figure 25) sectors. The differences vary from country to country. As a general observation, it can be noted that for residential sector, HOTMAPS and STRATEGO appear to overestimate the cooling demand, especially for the moderate climate, compared to the current evaluation. For the service sector, the energy demands are more similar, although in some specific countries, STRATEGO and HRE4 seem to overestimate the demand.

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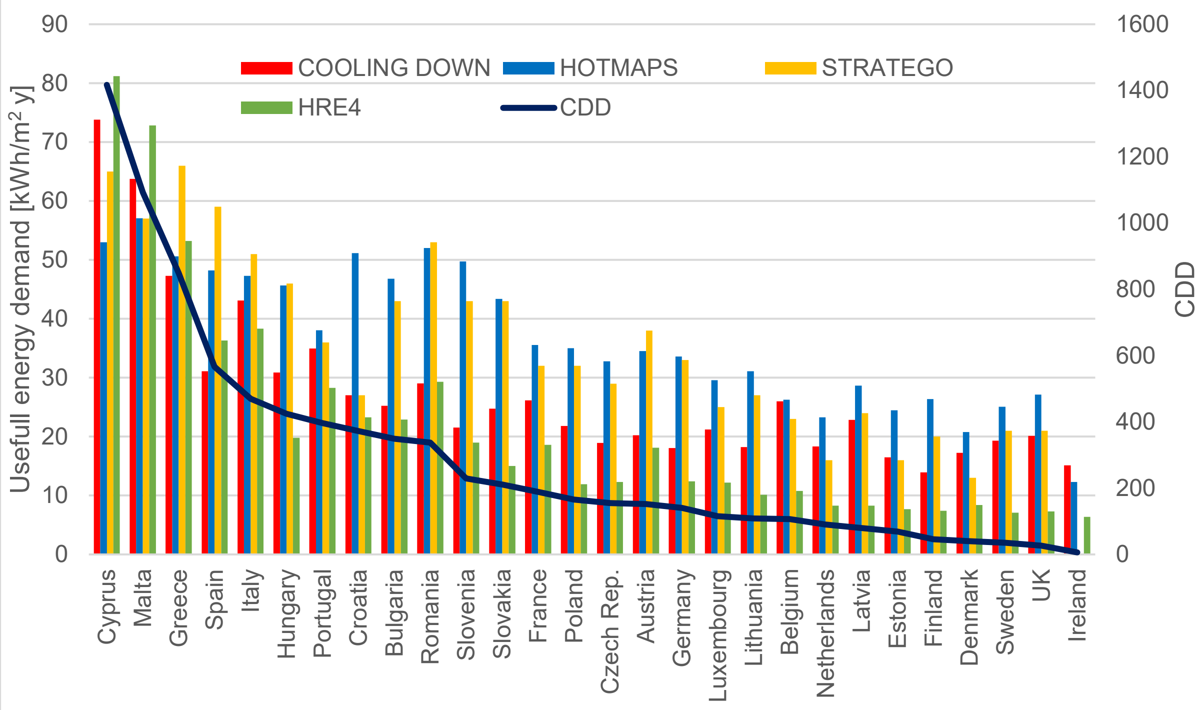

Figure 24: Specific cooling demand for residential buildings for each country

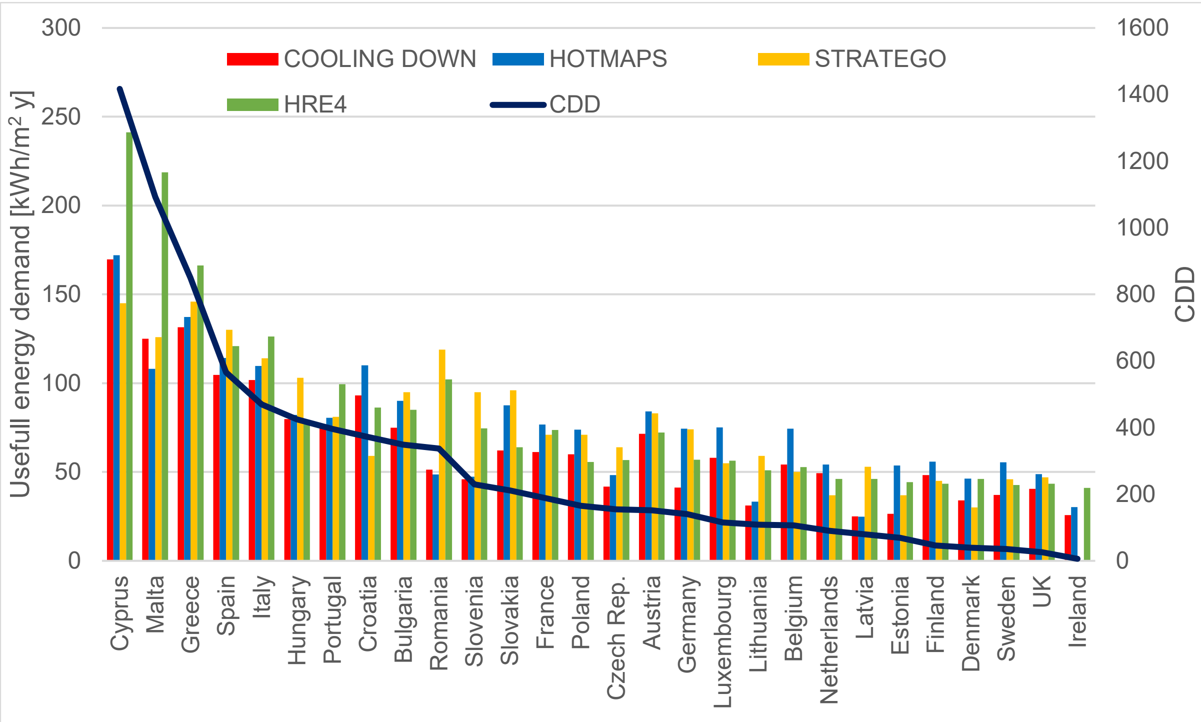

Figure 25: Specific cooling demand for service buildings for each country

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In Figure 26, the total potential cooling demand is represented for every country across both residential and service sectors. Italy, France, Germany, Spain and UK have the highest potential need for space cooling, collectively accounting for 66% of the total potential cooling demand of the entire EU27+UK. Regarding residential buildings, Italy is by far in the first place, followed by France, Germany and Spain. For service sector, Germany holds the top position, followed by France, Italy and Spain.

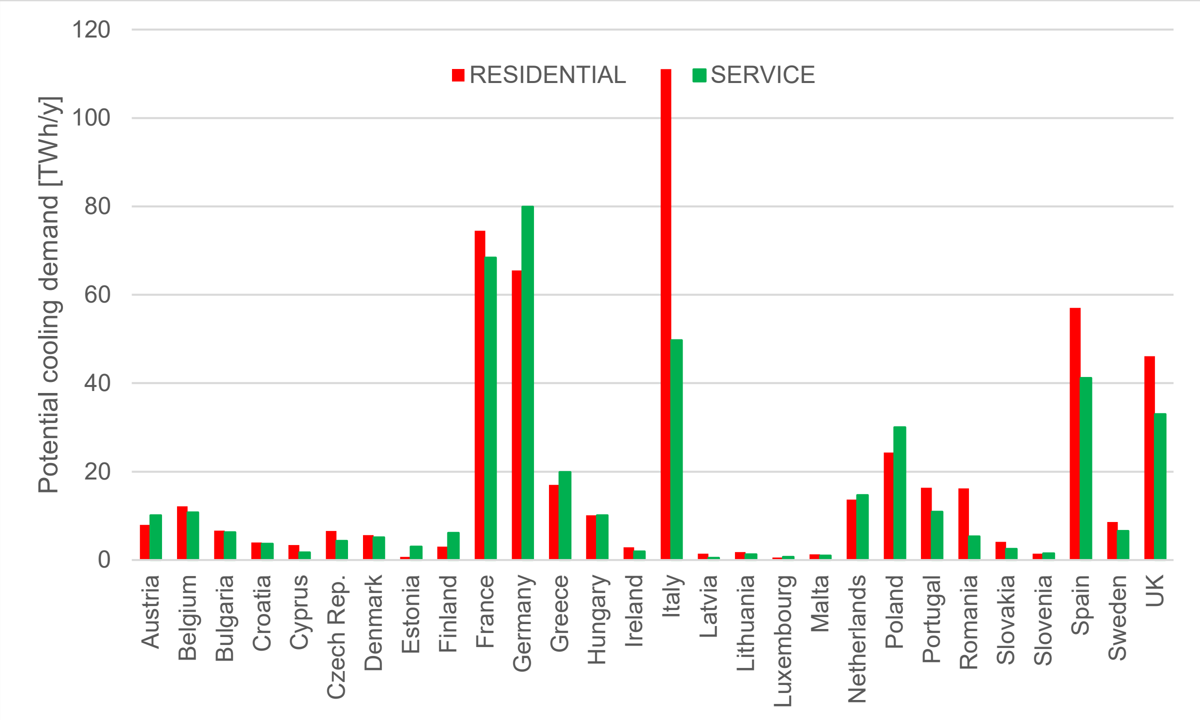

Figure 26: Total potential cooling demand for each country

To compare the total potential cooling demand, the specific cooling demand of different projects was multiplied by the building surface considered for this project, obtained as explained earlier. This approach ensures that the comparison is not affected by differences in building surface area. The calculations were performed at country level and the total cooling potentials for the EU27+UK are represented in Figure 27.

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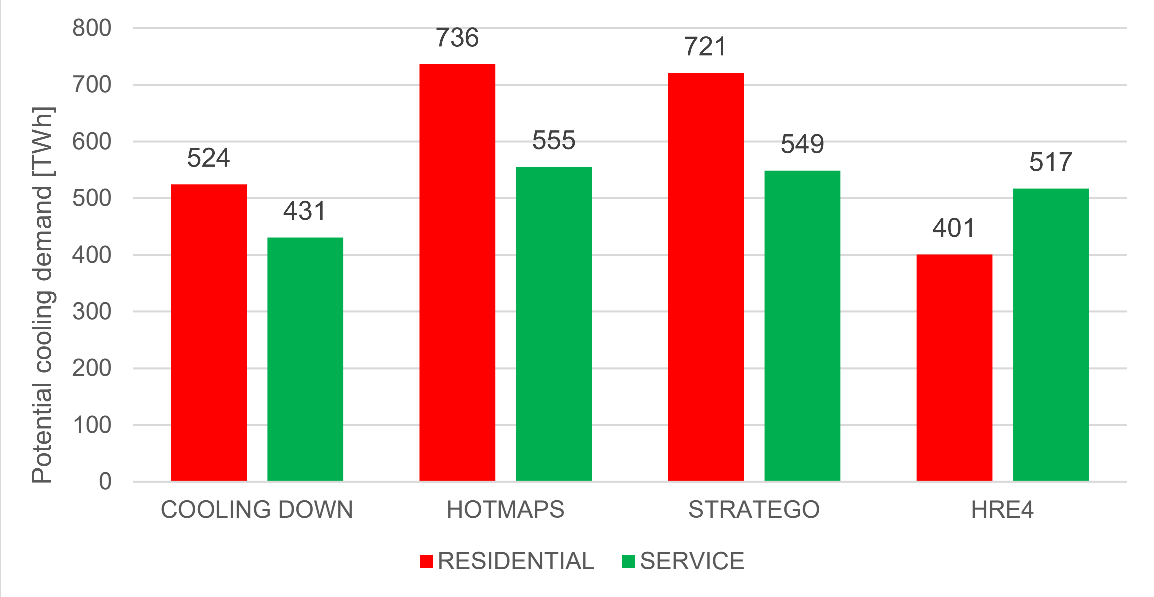

Figure 27: Comparison of total potential cooling demand for residential and service buildings

Figure 28 puts in comparison the potential cooling demand with the actual cooling demand for residential buildings across different countries. Italy has the highest actual energy demand, follow by Spain, France, Greece and Romania. Together, these five countries account for 81% of the total energy demand for cooling in EU27+UK.

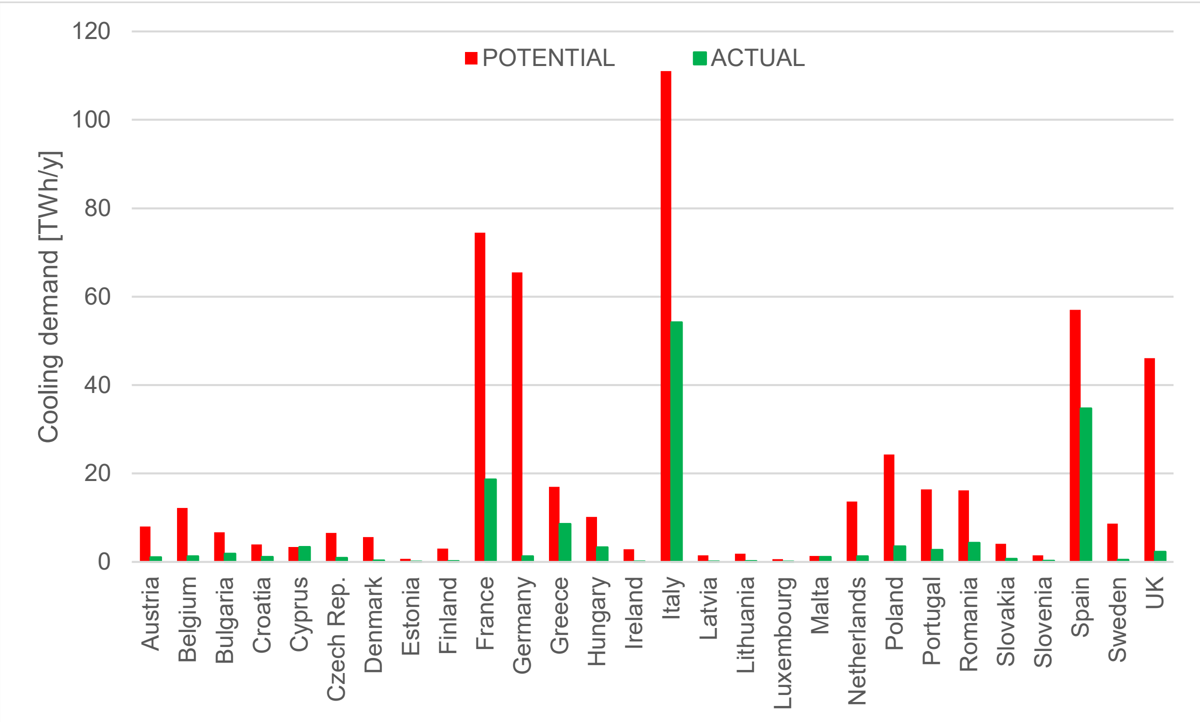

Figure 28: Potential and actual cooling demand in residential buildings

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In Figure 29 the potential and actual cooling demand are put in comparison for service buildings. As explained, the saturation in this sector was reported as an average value with an interval of uncertainty, due to different estimations found. Also, for the current energy required for service building, Italy is at the first place, follow by Germany, Spain, France and Greece. These countries account for 72% of the actual energy required for space cooling.

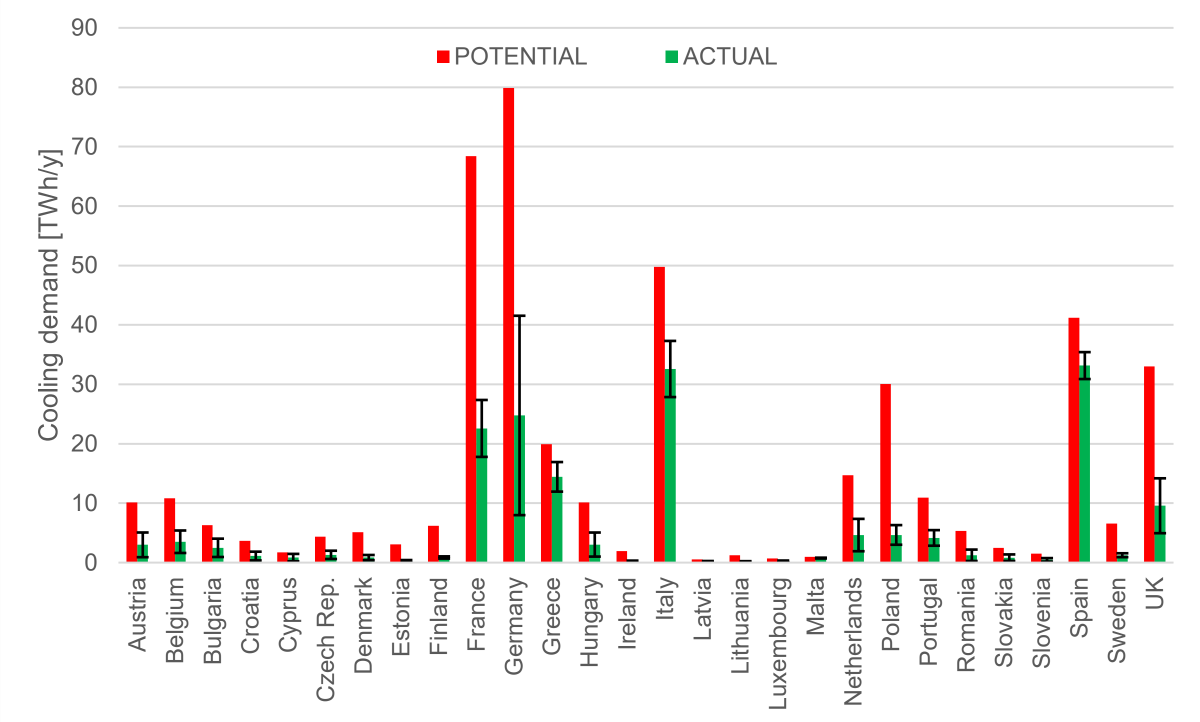

Figure 29: Potential and actual cooling demand in service buildings

In Figure 30, the actual cooling demand calculated in Cooling Down is compared with estimations from other projects. It is evident that while the values for service sector are similar, the reported values for the residential sector in other projects are significantly lower. This is primarily due to the substantial growth in saturation levels within the residential sector in recent years. The present analysis is based on updated statistical values regarding saturation, whereas other projects rely on outdated data or less current assumptions. The most significant finding arising from these results is that the energy consumption for cooling in the residential sector has probably been underestimated until now.

In Figure 31, the potential electricity demand is represented for the different countries, the total electricity potential for entire Europe is 124 TWh for residential and 97 TWh for service buildings. Together, they would account for 7.8% of European electricity consumption, considering the average between 2018 and 2022 from EUROSTAT as a reference.

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The Figure 32 illustrates the actual electricity consumption for cooling: the total for residential sector is 35 TWh and for service sector is 39 TWh. Together, they represent the 2.6% of the European electricity consumption, but for some countries the rates are considerably higher, like Greece with 10.5%, Italy with 6.8% and Spain with 6.6%.

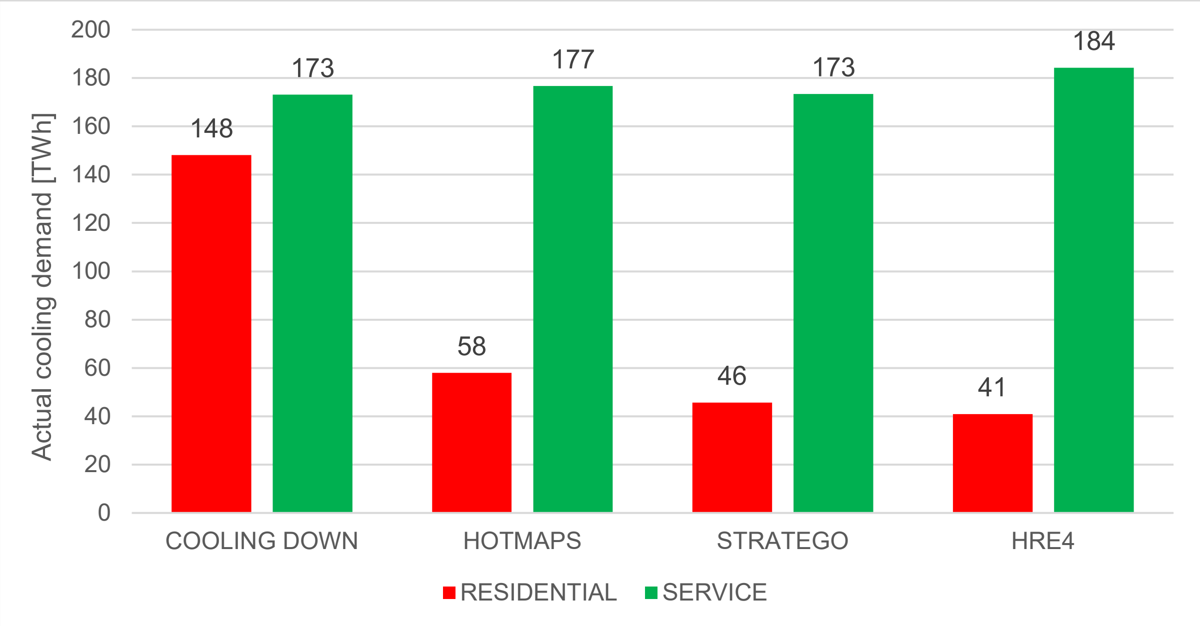

Figure 30: Comparison of actual cooling demand for residential and service buildings.

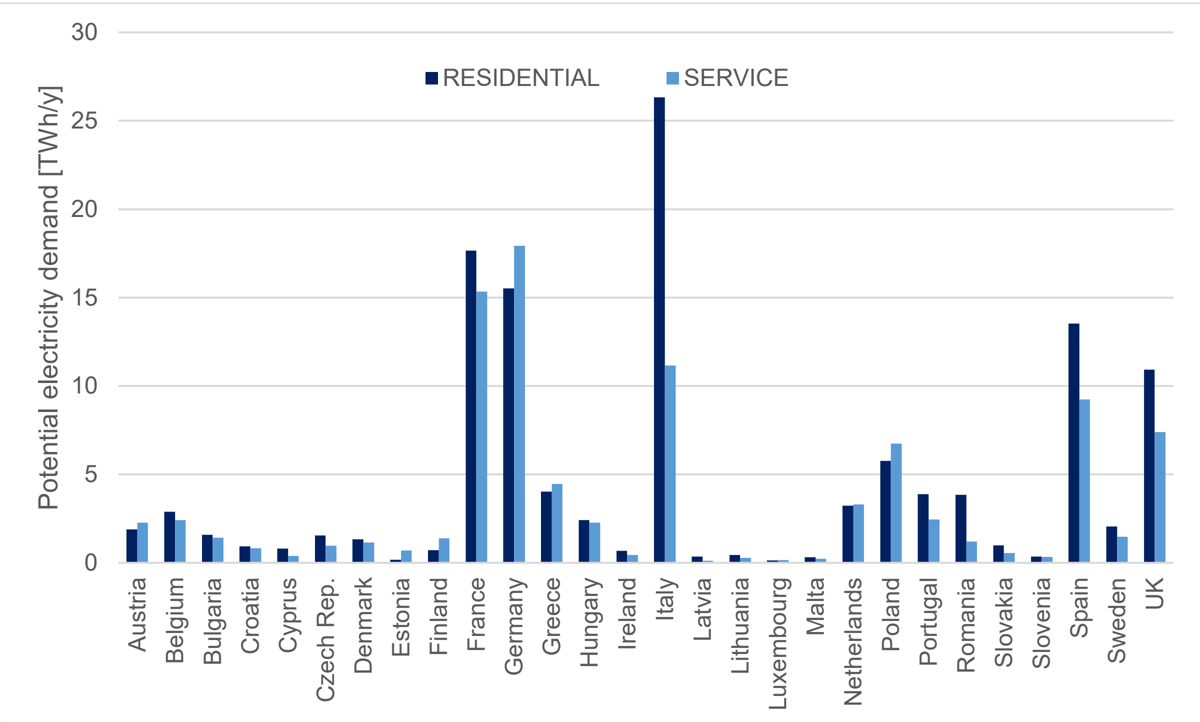

Figure 31: Potential electricity demand for space cooling.

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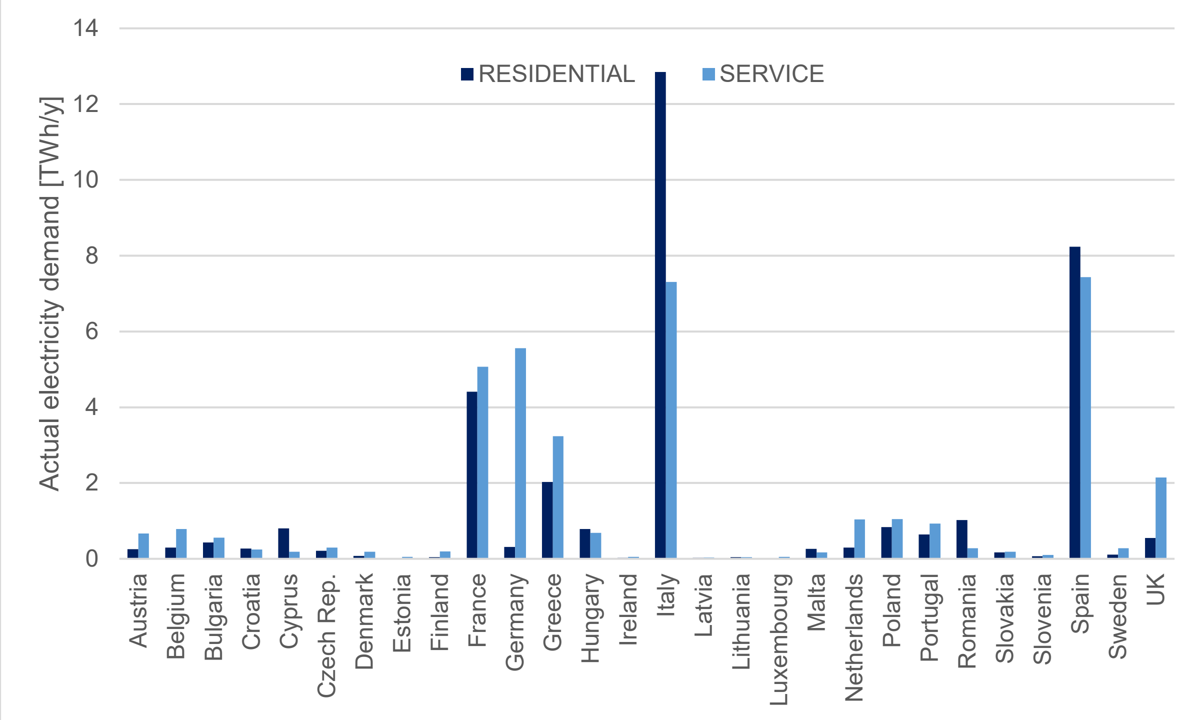

Figure 32: Actual electricity demand for space cooling.

The results for the assessment of cooling demand are reported in Table 20 (see Annex 4).

Future projection of 2030 cooling demand

Methodology

To assess the cooling demand for 2030, first step involved updating the building stock. The inclusion of new building and the deep renovations for the years 2022-2030 was approached in the same manner as described for the years 2016-2022. For new buildings, an average ratio from the years 2016-2022 was considered, and this same ratio was applied to the years 2022-2030. Likewise, for deep renovations, the same ratio from the years 2016-2022 was utilized also for 2022-2030.

The climate factor was also taken in consideration, updating the CDD values for 2030. Starting from the average CDD for the years 2013-2022, calculated as explain previously, the CDD for 2030 were calculated using linear regression based on the values from 2014-2023 and applied until 2030. Specifically, the slope coefficient was multiplied by eight years to calculate the incremental CDD between 2022 and 2030.

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The specific cooling demand was recalculated, take into account the updated buildings stock and the new CDD.

To account for the efficiency increase of cooling equipment, the SEER values were updated using the same method described for the correction of the values from 2016 to 2022. At the end, an average value of SEER of 4.80 was obtained for the residential sector and 5.14 for the service sector.

The final aspect considered in evaluating future cooling demand is the change in saturation. For residential buildings the climate factor was utilized to update the saturation values, using the previously obtained correlation to assess missing saturation values (see Figure 22). The new CDD values for 2030 were applied in this correlation to determine the new saturation rates. However, for the countries where real statistic values exist, corrections were implemented increasing those values, as follows:

$$Saturation_{2030} = Saturation_{2022} + m \cdot (CDD_{2030} - CDD_{2022}) \quad (3)$$

Where m represents the slope coefficient of the correlation (refer to Figure 22).

With this method, only the climate factor was considered, while other aspects such as the increasing demand for comfort were neglected.

In the service sector, the saturation is less influenced by climate factors, as already explained, and therefore cannot be relied upon to predict future saturation levels. The saturation of the service buildings was corrected considering an average annual growth rate for all Europe. For France this value is 1.3% between 2020 and 2030 according to the report [118]. For Italy, the average increase between the 2007 and 2014 was around 1.1% per year [126]. In Germany, between 2009 and 2017, the average yearly growth ratio was 1.4% according [13]. Although these values may not be all the most accurate, it appears that an average annual growth rate of 1.2% can be reasonably applied to most of the EU countries. This means that from 2022 to 2030 the saturation ratio in the service sector is expected to increase by 9.6%.

Results

In Figure 33, the specific cooling demand for residential buildings in 2030 is represented in comparison with that of 2022. In Figure 34, the same is represented for service buildings.

It can be observed that the cooling demand will increase for all the countries by the end of the decade.

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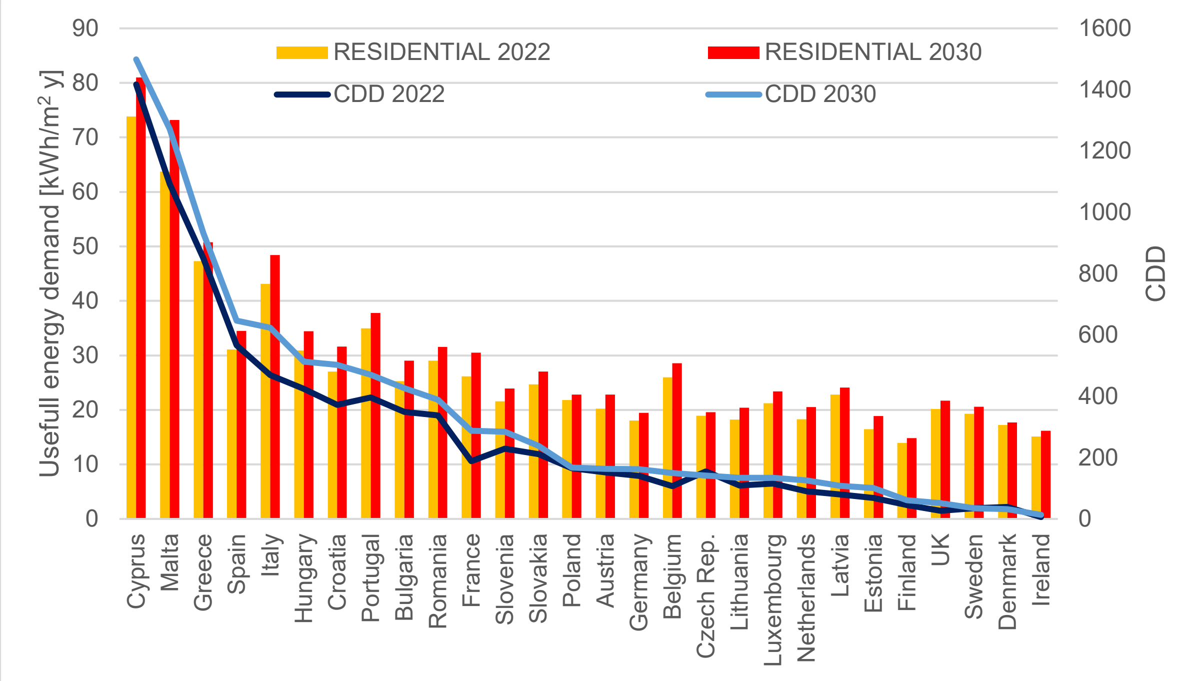

Figure 33: Specific cooling demand for residential sector, 2022 and 2030 compared

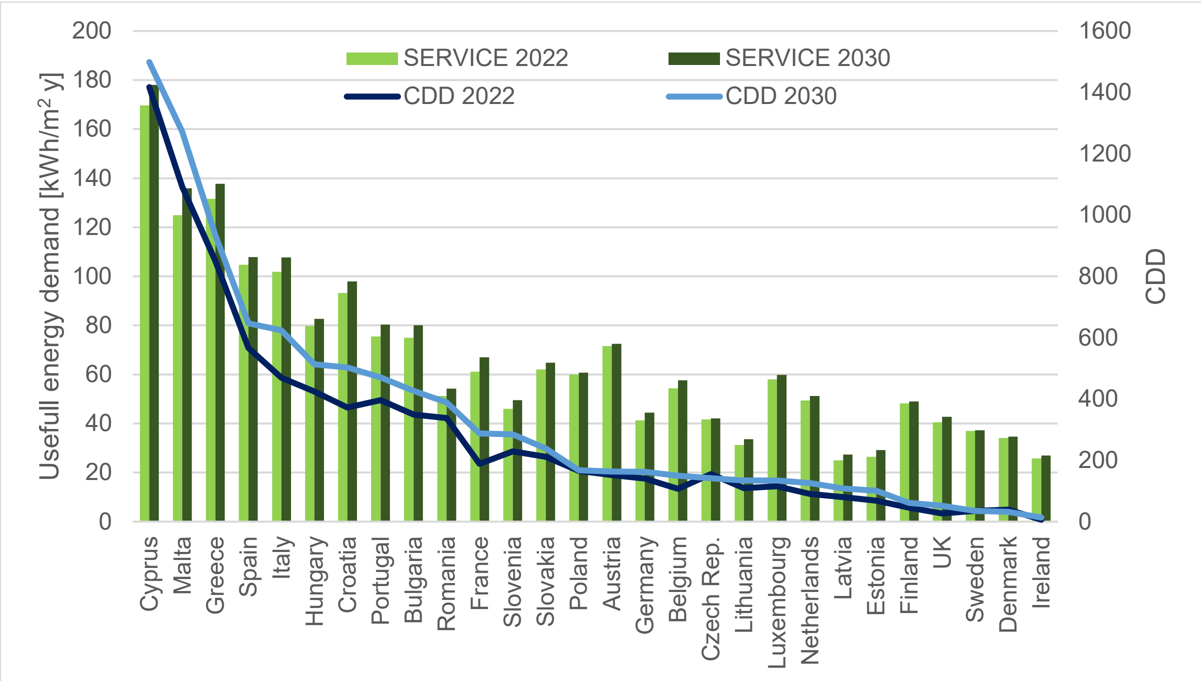

Figure 34: Specific cooling demand for service sector, 2022 and 2030 compared

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The total potential cooling demands are represented in Figure 35 and Figure 36, for residential and service sector respectively. By 2030, the total potential demand for all Europe is projected to reach 630 TWh for residential use, indicating a 20.1% increase compared to 2022. Similarly, the projected demand for service sector is estimated to reach 545 TWh by 2030, reflecting a 27.2% increase compared to 2022.

The Figure 37 and Figure 38 represent the actual cooling demand for residential and service sector in 2030 compared with the demand in 2022.

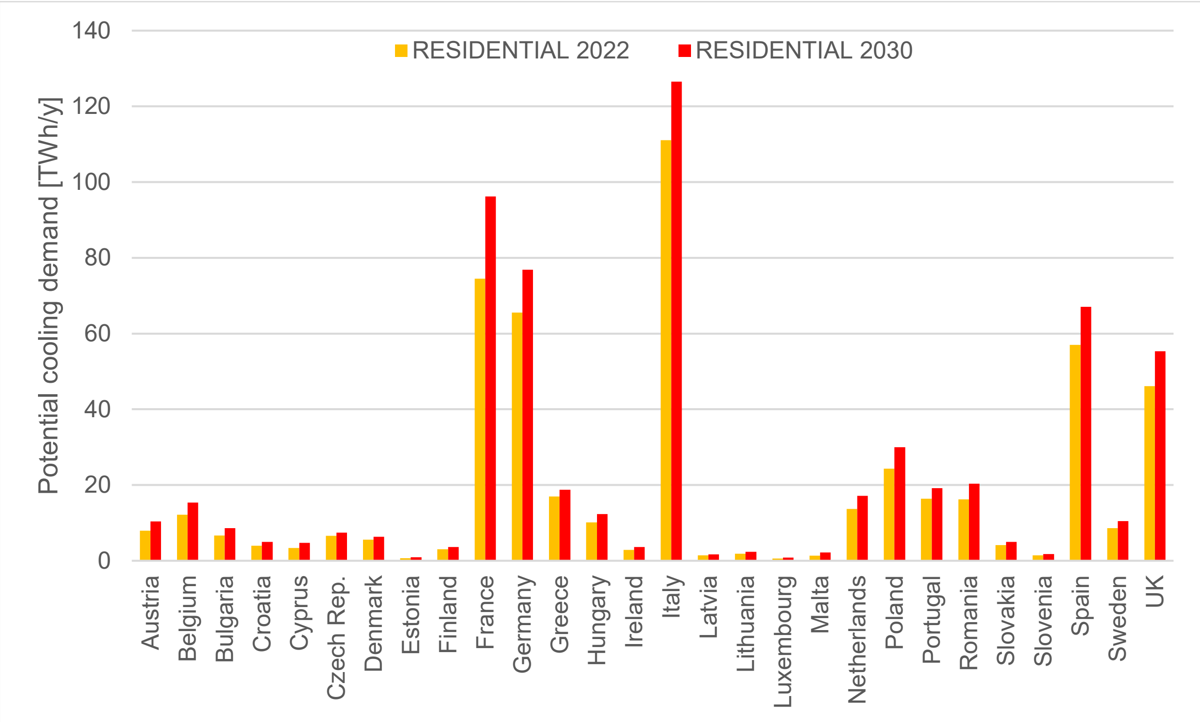

Figure 35: Total potential cooling demand for residential sector, 2022 and 2030 compared.

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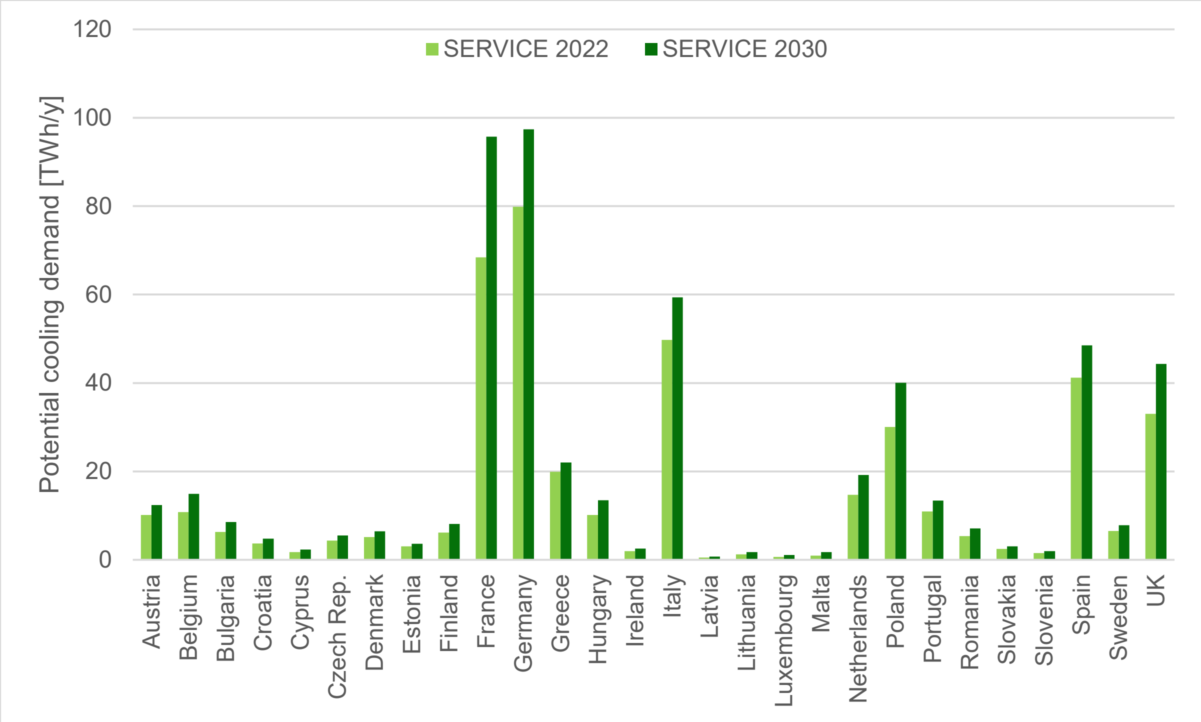

Figure 36: Total potential cooling demand for service sector, 2022 and 2030 compared.

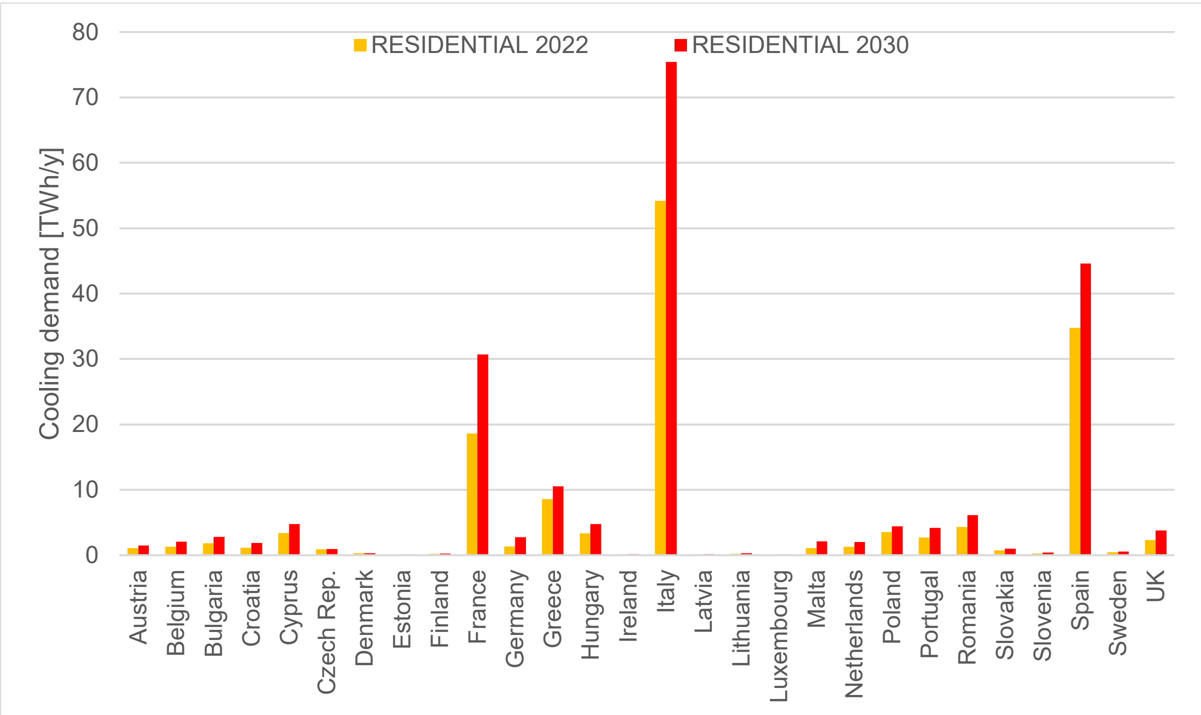

Figure 37: Actual cooling demand for residential sector, 2022 and 2030 compared.

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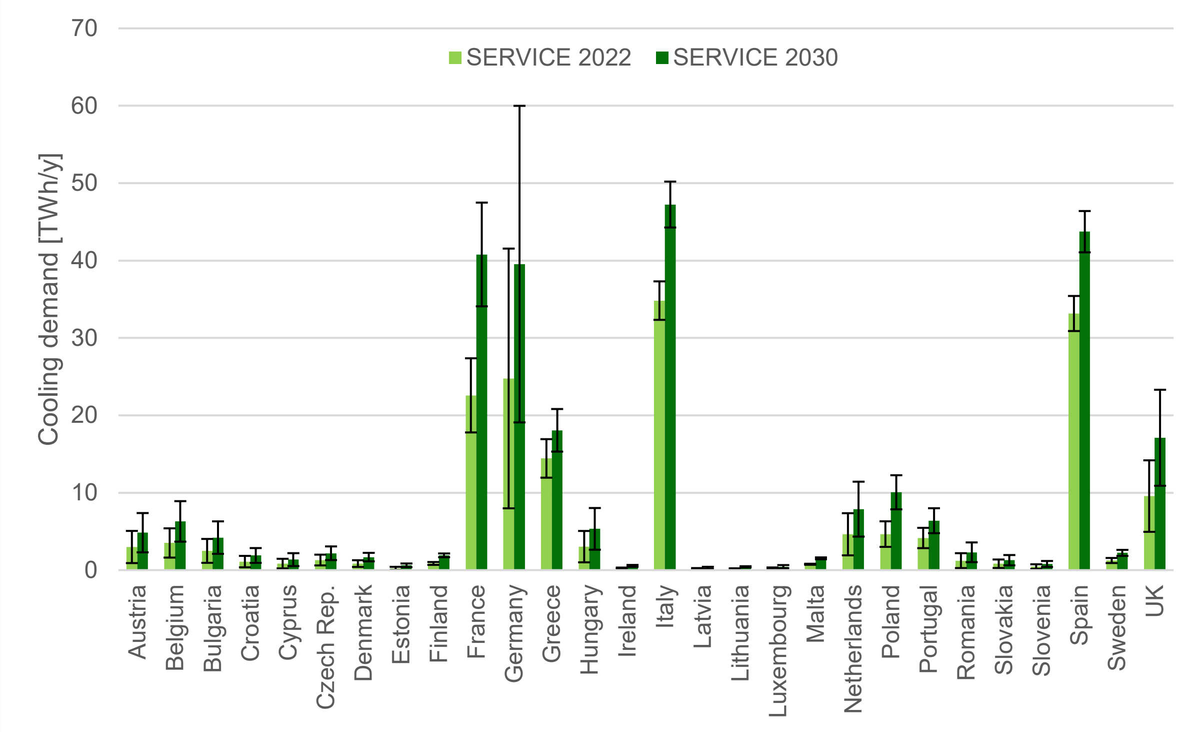

Figure 38: Actual cooling demand for service sector, 2022 and 2030 compared.

In the Figure 39, the potential and actual cooling demand for EU27+UK are compared for residential and service sectors and for 2022 and 2030. The potential will increase by 20% for residential and 27% for service building from 2022 to 2030. The actual demand will increase by 41% for residential and 55% for service sector.

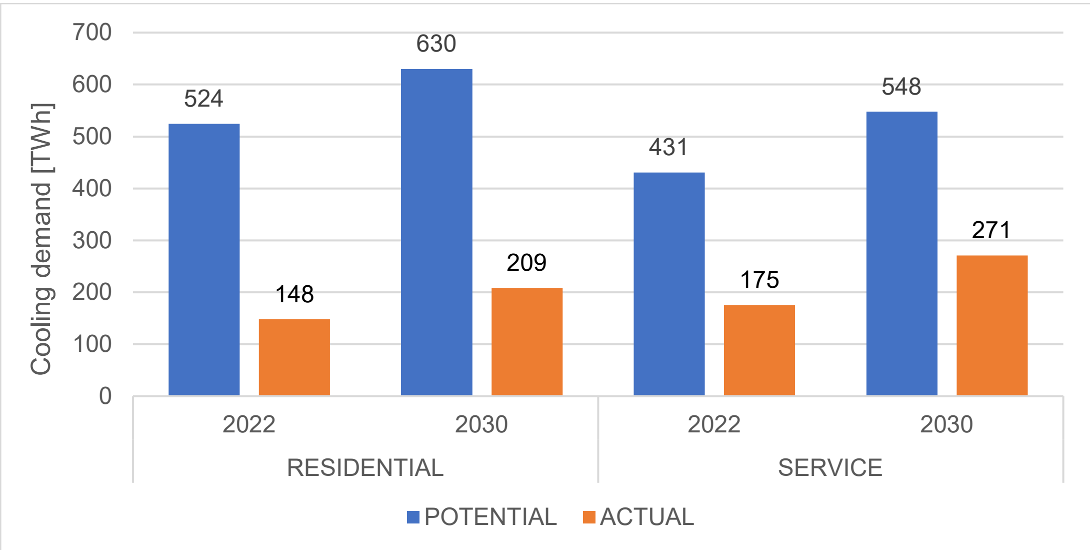

Figure 39: Potential and actual cooling demand for Europe

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The comparison of electrical energy demand for cooling between 2030 and 2022 is illustrated in Figure 40 for the residential sector and Figure 41 for the service sector. In 2030, the total electricity demand for Europe is projected to be 35 TWh for residential and 52 TWh for the service sector, representing respective increases of 24% and 35% compared to 2022. It can be noted that the rise in cooling demand is partially counterbalanced by improvements in cooling system efficiency, resulting in energy reductions of approximately 12% for residential and 13% for the service sector.

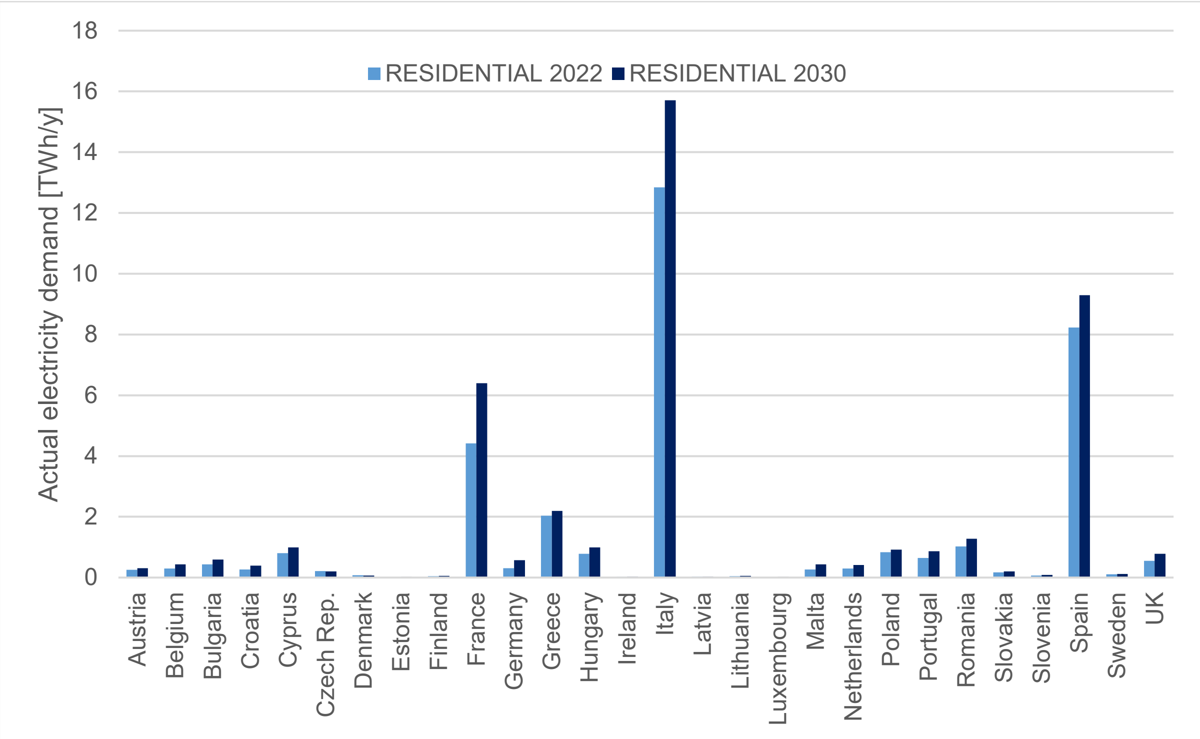

Figure 40: Actual electricity demand for space cooling in residential, in 2022 and 2030

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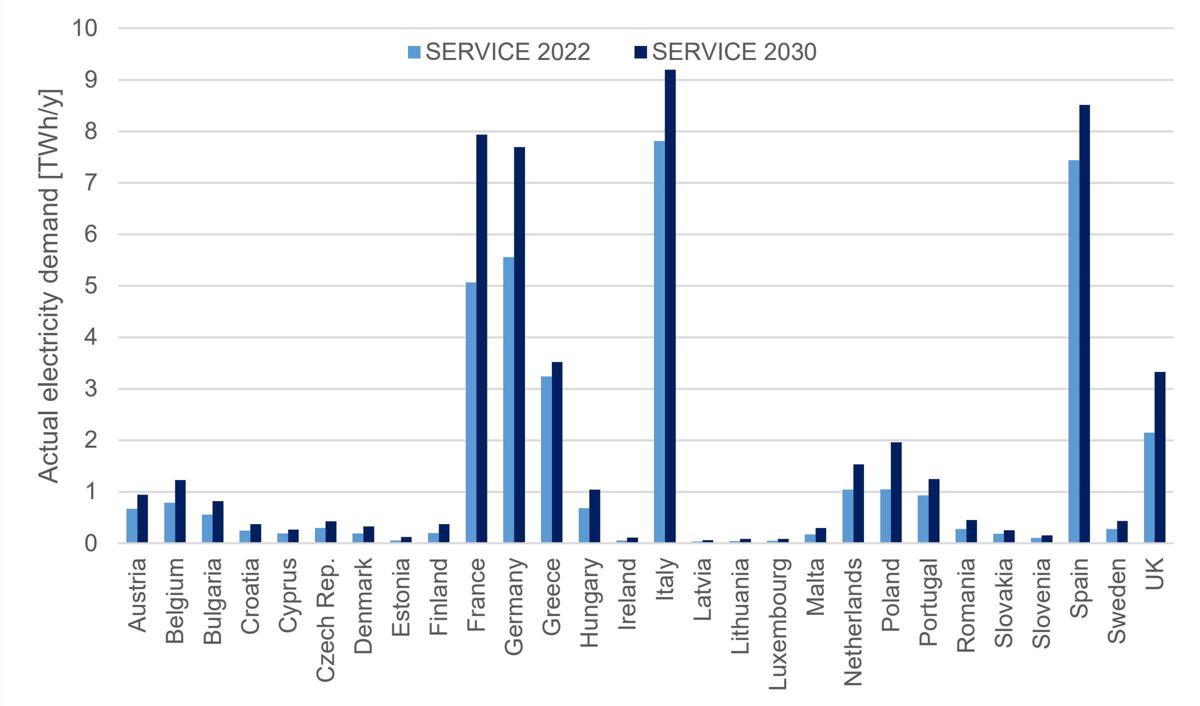

Figure 41: Actual electricity demand for space cooling in service, in 2022 and 2030

The results for the future projection of 2030 cooling demand are reported in Table 21 (see Annex 5).

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State-of-the-art cooling systems based on RES and recommendations

Task objectives

This chapter focuses on integrated cooling systems based on renewable energy sources (RES) and their potential to increase overall efficiency and reducing CO2 emissions. This chapter begins with a literature analysis on the importance integrating thermal energy storages (TES) into cooling applications and their central role in fully renewable cooling systems. Based on several case studies, the potential of implementing TES in cooling systems is illustrated and an outlook on the further development of technology integration is given by analysing relevant TES specific KPIs and market barriers.

Furthermore, to gain insights into the current state-of-the-art of integrated cooling systems based on RES, state-of-the-art integrated cooling systems that are based on RES were researched and clustered. Two clusters were identified as especially important: “Cooling systems integrated into heating systems” and “Cooling systems integrated into electricity systems”.

For each cluster a representative case study was selected and analysed in detail to identify:

- System set-ups and operation strategies
- Chances and challenges in the planning and implementation
- Critical phases and difficulties
- Involved stakeholders
- Key learnings.

To do this, two interviews were conducted and two planners who were significantly involved in the planning and commissioning of the projects were questioned about the planning and implementation processes and their experiences. The results of the interviews provide valuable perspectives and real-life examples of a successful integration of renewable energy sources in cooling systems and the integration of cooling applications into both the heating and the electricity sector. This gives comprehensive insights in the potential of integrated cooling systems and their planning and implementation, considering the current state of the art, sector-coupling benefits, and insights from the perspective of industry experts.

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The importance of integrated cooling systems

As shown in Task 2.2: The Assessment of Cooling Demand and Market Overview, the growing impact of climate change and rising comfort standards lead to increasing cooling demands in Europe. While the state-of-the-art of cooling technologies is mostly well developed (see Task 2.1: *Mapping of Cooling Systems and Applications*), the current state of integrated cooling systems, especially those based on RES, is not yet as advanced but holds great promise [128]. Sector-coupling and the smart integration of cooling applications into larger energy systems can enhance the efficiency of the overall system and increase the share of renewable energies [128]. The two most important sectors for the integration of cooling systems are the heating sector and the electricity sector. For the integration of cooling applications into the heating sector, major advantages arise from the possibility of combined heat and cold generation in Combined Cold, Heat and Power plants (CCHP) or heat pumps and the possibility to utilize 'waste' heat of cooling applications as a heat source for heat pumps. The integration into the electricity sector enables the integration and utilization of renewable energy sources like wind and solar energy. In addition, cooling applications can offer flexibility for the electricity sector and open up the possibility of adapting generation to the changing conditions of volatile renewable energy sources by utilizing integrated thermal energy storages [129].

The role of thermal energy storages within cooling systems

Potential of TES integration

An essential component of cold supply systems in addition to cooling technologies are TES as a buffer between generation and demand [20]. In the context of increasing cooling demands and fluctuating energy sources, the role of TES in efficient energy supply systems continues to grow. Furthermore, thermal energy storages applied in cooling (CTES) make the use of waste cold possible and the peak shaving potential of CTES can play a central role in the context of sector coupling [130]. Historically, CTES have been used for mobile refrigeration applications in particular, although the range of applications has expanded to include building and industrial cooling applications. Besides the research on storage materials, optimal integration of CTES are currently large subject of research [131].

[132] for example investigates the optimal integration of CTES coupled to district cooling and a local power grid in Sweden. In a scenario analysis it can be shown that renewable electricity recovery via power-to-cold can be increased and capital-intensive grid expansions prevented, due to the peak shaving and load shifting potential of the CTES.

The use of CTES in combination with decentral CHP systems also offers optimization potential, as [133] showed in a case study with a resulting investment cost reduction of 29.5%. [134] also deal with the smart grid application of CTES. They present a multi-timescale CTES system for power balancing at building level. The case study in Beijing shows an optimization potential for the load factor both on the short-term and long-term scale while reducing the overall power consumption through the coupling of a seasonal water/ice storage and a dual-operation chiller with seasonal energy management, day-ahead power management and power demand response.

On a more abstract level, [135] investigate the issue by developing an design approach hybrid renewable energy systems at building level. The considered hybrid system contains various renewable resources, thermal and electrical demand, storages and heat pumps as shown in Figure 42.

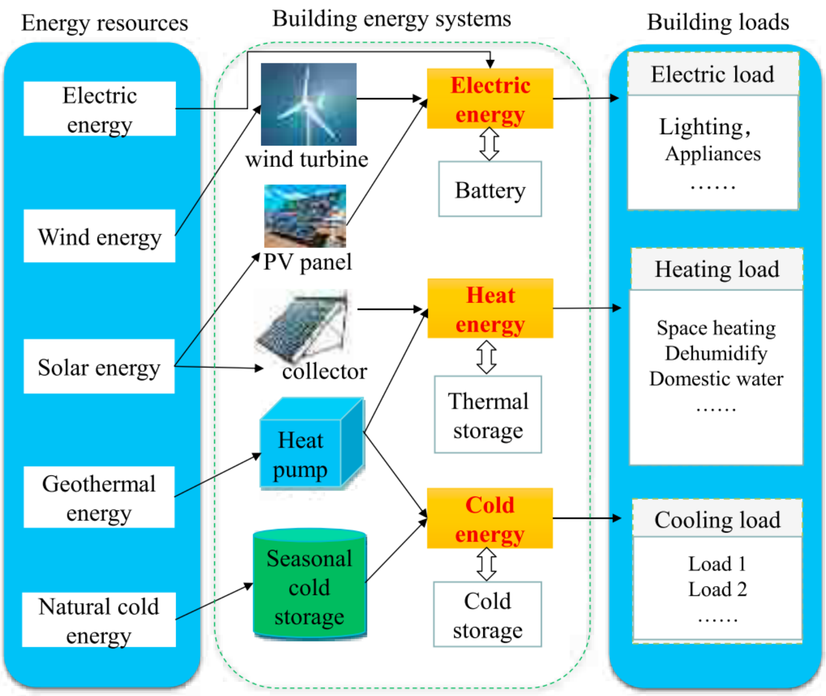

Figure 42: Schematic of the hybrid renewable energy system, source: [135]

By minimizing the life cycle total cost (LCC) for the overall system, the optimal design for the overall system including long-term and short-term TES can be identified. As part of a case

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study in Beijing, an LCC reduction of 15% was achieved with this approach, whereby the effect of the CTES is not explicitly stated.

KPIs and barriers

As a central component of renewable energy systems, the further market integration of TES technologies is key in the transformation of the energy system. To identify actions for a faster market ramp-up and create a common basis for comparison, [136] identifies literature- and roadmap-based a set of barriers and KPIs for TES, KPIs and barriers can be clustered in categories: technical, socio-economic, regulatory and environmental. The central technical KPIs for TES include the storage capacity and time and charging respectively discharging temperature and capacity. Among the socio-economic and environmental KPIs, the TRL, cost and LCA-related impact parameters can be assigned. The complete overview of the KPIs can be found in Figure 43.

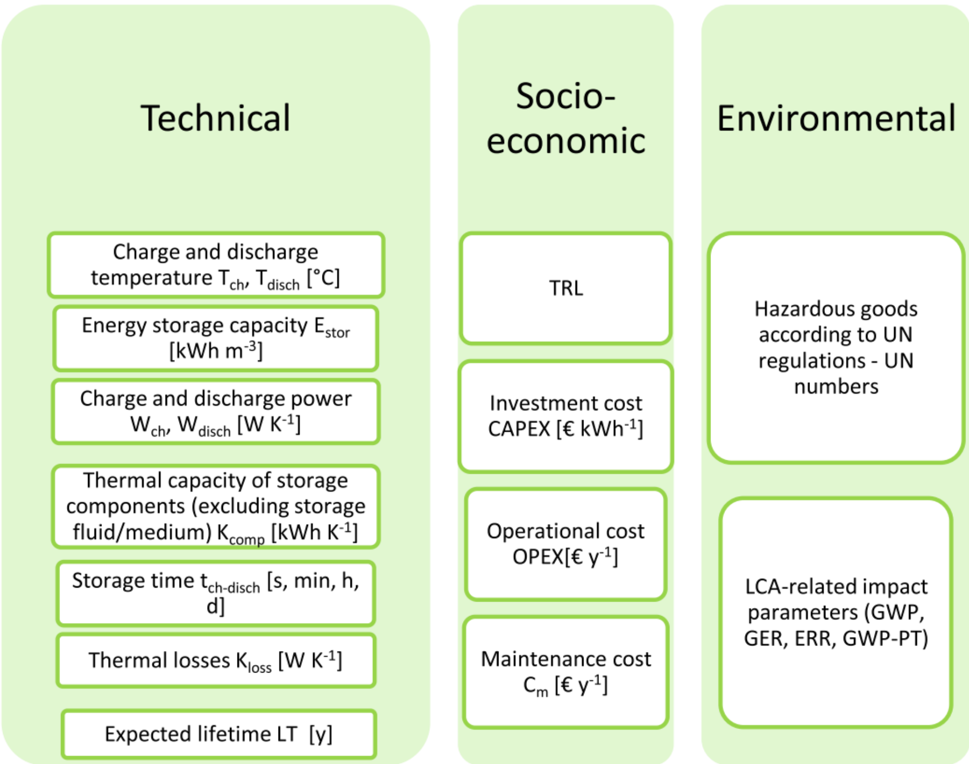

Figure 43: Clustered list of TES specific KPIs, based on [136]

Further reliability, low power and bulkiness of TES were identified as central technical barriers the, but in particular socio-economic factors such as insufficient knowledge of available resources and insufficient understanding of decision-makers and planners are the key obstacles. Which in turn lead to a lack of a regulatory framework and uniform planning

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standards. Based on this analysis, a large number of possible measures were identified to counteract the barriers [136]. Table 19 shows the complete list of identified barriers:

Table 19: Actions to contrast barriers to TES, based on [136]

Type of action	Description	Time target
Technical	Material development for TCM/PCM, with special focus on TCMs for low and medium temperatures and PCMs for solar buildings and temperature regulation applications	2030
	Development of molten salts with lower melting temperatures	2025
	Thermal storage materials with a high heat capacity and high thermal conductivity	–
	System optimization for UTES	2020
	Improve components for TCMs (vessels) and PCMs (capsules)	2030
	Improve control strategies and units	2035
	Exploitation of heat below 90 °C	–
	Retrofitting of current solution, especially in refrigeration plants and water heaters	2030
Socio-economic	Cost reduction	2025
	Accessible dataset of global energy storage technologies project overview (including costs and performance) and heat available and geolocalisation, accessible dataset of renewable energy production	2020
	Quantify distributed energy storage potential in buildings for DHW and cooling	2020
	Training and public engagement	–
Regulatory	Definition of standards and guidelines for design	
	Clarify ownership of storage and enable benefits-taking and new business models	2020
	Streamline the financing process for large-scale projects, support financing of early movers and commercial-scale projects	2025
	Eliminate price distortion and increase price transparency for power generation and heat production	2020
	Reduce fees/taxes on electricity from renewable sources	–
	Support R&D	2050
	Support distributed energy systems	2020
Environmental	Support to market diffusion for all technologies	varies
	Identify the environmental impact of TES	2030

In summary the research shows great potential for the use of CTES in particular in sector coupled cooling systems respectively integrated energy systems. However, the great potential is offset by a large number of diverse technical and socio-economic barriers that are slowing down the market ramp-up. In addition, the complex systems require a comprehensive, structured and optimized design and operating strategy.

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Integration of Cooling Systems into Heating Applications

The importance of integrating cooling systems into heating applications

Depending on the technology employed, there are multiple compelling reasons for integrating the generation of heat and cold. Many cooling applications, especially compression chillers can be understood as a transfer of energy from a lower temperature level to a higher temperature level, resulting in a decrease in the temperature on the cold side and an increase in the temperature on the warm side. Therefore, it is obvious to not only utilize the cold but also make use of the heat.

However, there is a technology where the connection between heating and cooling is even more apparent. Thermally driven heat pumps utilize heat to generate cold and are considered the ideal choice when the heat source is renewable. Another technology that combines all these factors and enables the local and temporal exchange of generated cold and heat is a 5th generation district heat and cold (5GDHC) grid:

"A 5th generation district heat and cold grid is based on the exchange of thermal energy between buildings with different needs. The principal grid carries a low temperature flow to active and distributed substations which upgrade the temperature to the required level. Distributed thermal storage buffers the fluctuation in supply and demand of heat and cold. This architecture maximizes the share of low-grade renewable and waste energy sources." [137]

5GDHC grids enable the exchange of energy between the actors involved in order to exploit synergies that occur when different purposes are considered collectively. The consumers in the district heating and cooling network can also act as producers by supplying energy to other participants. For example, the heat generated during refrigeration can be fed back into the heating network and used by other participants. This reduces the total energy consumption of the district by exploiting the simultaneity of the different demands. With the possibility of storing heat and cold seasonally through e.g. mine water, seasonal hot water storage, geothermal boreholes, this system also enables the integration of many renewable energy sources such as waste heat or solar energy.

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Best Practice Example: Minewater 2.0 Heerlen

System description

Minewater 1.0 is the term used for the initial mine water system at Heerlen, developed in the period 2003 - 2008. It started as a straightforward pilot system to investigate how the mine water of the abandoned coal mines of Oranje Nassau could be used as a geothermal source for the sustainable low-exergy heating and cooling of buildings. For the extraction of hot water with a temperature of about 28 °C, two hot wells in the northern part of Heerlen with a depth of 700 meters below surface and two cold wells in the southern part of Heerlen with a depth of 250 meters for the extraction of cold mine water with a temperature of about 16 °C and one intermediate injection well with a depth of 350-400 meters for the collective injections of used mine water, were used. A simple change-over system only able to supply heat in winter and cold in summer. In 2012/13 the Minewater project was upgraded from a straightforward pilot system to a full-scale hybrid sustainable energy structure called Minewater 2.0 [78]. At that time, a totally new concept which has the following landmarks:

- Energy exchange instead of only energy supply: Cluster grids were deployed to exchange heat and cold between buildings inside a cluster and between the cluster grids through the central mine water grid. The grid became a bidirectional grid able to supply heat and cold at any time. Each user becomes a prosumer, not only extracting heat or cold but also discharging cold and heat in return that can be used by other users in the grid, with an opposite demand.
- Energy storage: Use of the minewater reservoir as a seasonal storage, actively regenerated by the surplus of heat and cold in the grid during the year in addition to the geothermal regeneration to increase the renewable capacity.
- Able to implement multiple sources like waste heat from industry, data-centres or supermarkets.
- Expansion of the hydraulic and thermal capacity of the mine water reservoir and grid: Enlargement of the mine water grid by improving well pumps, implementing pressure boosting systems for fully automatic control and transforming them into bidirectional wells and reuse of the existing mine water return pipe for additional supply and disposal of cold mine water.

Since the concept is successful the owner and the public authorities decided in 2023 to invest 300 Mio. Euro into the expansion, the further development of the facility and the transfer of the concept to other communities.

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Operation and Control Strategies

The operation of the Minewater 2.0-System is based on a fully automatic and demand-driven supply of hot and cold mine water through usage of pressurized buffer systems at the extraction wells and sophisticated injections valves at the injection wells. For this purpose, all geographically dispersed mine water installations at buildings, clusters and wells are equipped with sophisticated process control units that communicate with a Central Monitoring System (CMS) through the internet.

The mine water pilot system (Minewater 1.0) showed that unwanted intermediate return temperatures cause depletion of the mine water reservoir. To eliminate this effect, it is necessary that the return line into the mine water is heated up or cooled down properly to the natural geothermal temperature and brought back to the corresponding hot or cold part of the mine water reservoir.

Critical for the correct water return temperatures to the mine water reservoir is the operation of the energy stations of the end-users. They must ensure that the hot water is cooled down (< 16 ˚ C) and heated up (> 28˚C) sufficiently. Therefore, this is included as a condition in the contract for end users.

These temperatures might change over the years, if the heat and cold extraction and infiltration don't maintain an energy balance on a yearly basis. This can lead to a decrease of temperatures but an increase of the geothermal capacity, compensating the unbalance. A new equilibrium will occur. It means that a 100% balance over the year is not a strict requirement.

The control system consists of three levels: Building, Cluster, and Mine water, each employing distinct control strategies related to temperature, flow, and pressure.

For the building level, this entails maintaining a temperature target of > 28˚C for hot return flows during cooling and < 16˚C for cold return flows during heating. For this purpose, it is essential for the buildings installation to supply a sufficiently high temperature (> 30˚C for cooling) or low temperature (< 14˚C for heating) to the heat exchanger on the secondary side, whether it is passively or actively generated. Regarding the cluster level, this means that the booster pumps at the mine water side deliver the required heat or cold, depending on the energy balance of the cluster grid. The pumps are controlled by the flow, based on the flow measured at the cluster side. In this way optimal heat exchange is guaranteed.

The mine water grid is controlled by pressure to keep up a minimum pressure at the cluster grid connection to prevent degassing of the mine water. All wells are bidirectional not only to extract mine

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water but also to injected. To keep up the pressure injection valves are used placed below the water level.

Planning and Implementation Process

In 2011, after a period of several years of operation of the Minewater 1.0 system, the management came to the decision to upgrade the system from a straightforward pilot system to a full-scale hybrid sustainable energy structure, which was called Minewater 2.0. The primary objective of this project was to introduce a new principle that enabled the energy exchange between the connected buildings and use of the mine water reservoir as a seasonal storage to increase capacity and prevent depletion to enable further expansion of the system. To ensure the profitability of the system, it is crucial that the high fixed costs, which primarily consist of investments and operating expenses, are shared among an adequate number of customers. This requires a minimum business volume estimated between 5-6 million Euros per year and the connection of approximately 4000 households. Which is not immediately feasible. The development of such a system greatly benefits from governmental financing. In Heerlen, the local authorities provided significant support, both financial and organizational, as they recognized the project's alignment with their mining history, tradition and sustainability goals (carbon neutral in 2040). These were the primary drivers for their involvement.
Additional important for the techno/economic feasibility of the project was the division of the district into clusters provided with cluster grids, as described above. Not only because they mostly balance their energy demands, but also due to the possibility to avoid expensive special materials resistant to the corrosive mine water, because the cluster grids are closed systems that run on clean water.

The first phase of the Minewater 2.0 project was the development of the concept, which took six weeks, executed by the mine water team, being the master of concept of the transformation and operator.
After the concept was clear, basic engineering was started executed by engineering consultants to work out the principles into workable installations and grid design providing a fully automatic and demand driven operation:

- Low-ex and hybrid decentralized energy stations
- Bidirectional exchange stations between cluster grid and energy stations
- Bidirectional exchange stations between mine water backbone and cluster grids (so called cluster installations)

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- Bidirectional mine water production and injection wells, provided with a buffer and boosting system and very sophisticated injection valves
- Bigger frequency-controlled ESP´s
- The first bidirectional cluster grid A
- Heat pump installation pension fund APG using the heat of the datacentre to heat the APG building and provided the surplus heat to the cluster grid A to be used by others.
- Exchange and heat pump installation of the Arcus school campus

The role of the engineering consultants is crucial in the planning and implementation process. As designers, they are responsible for the standardization of the choices and implementation of facilities. Given that the concept is not well-established, effective communication becomes even more important. Working closely with the mine water team, the engineering consultants continuously developed a blueprint for this type of project.

Operation and "start-up-phase"

During the design, built and commissioning, the operator and the engineering consultants worked closely together. The mine water team being operator and 'Master-of-concept' was responsible for the system to come to operation as it was supposed to be. This was continuously analysing by the operator's energy management. Especially the adjustments in the central operation system to reach a transient state needed a close collaboration of the operator and the equipment/facility designer and took two years. In this time there aroused an exchange of experiences, a close share of knowledge and a continuous adjustment of controller setpoints.

Just as important as the technical realization is the economical realization and for this the successful prospecting. For households in the Netherlands, the governmental cap on heating costs, takes the risk of supply decisions. Thus, there is no space for negotiation.

For the non-residential buildings a new pricing model appeared to be attractive. As the costs are mainly driven by invests and operation and not by the energy demand, fixed prices in euro/m² could be negotiated with the customers. This is deemed to be very attractive even for long contract durations (10 years) against the background of the highly fluctuating costs for fossil fuels. As an additional practice for customer retention, the possibility to buy the supplier's service installations after contract duration was identified.

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Big learnings

What made the project successful:

- Strong support from the authorities
- Providing clusters with cluster grids to overcome technical and economic barriers
- Market that understands the system/ concept of prosumers
- Openness for new pricing models
- Continuous steering in all phases from the (owner and) operator as 'master-of-concept'
- Importance of communicating and collaborating between operator and engineering consultants to meet the special technical requirements
- Creating blueprints for the design and execution of the units/system elements (Building blocks)
- Central operation system, which communicates via internet, supervised by the operations
- Cold supply improves the business case. Extra product and fee to cover investment costs and regeneration source to improve the systems efficiency.

Integration of Cooling Systems into the Electricity Sector

The importance of integrating cooling systems into the electricity sector

Electrification will be a key driver of the energy transition in Europe, due to the availability of renewable energy sources such as solar energy, wind energy and geothermal energy and their efficient conversion into electricity [138]. However, the intermittent nature of renewable energy sources poses challenges for the stability, reliability, and energy balancing of the electricity grid. For the grid it is crucial to maintain a secure electricity supply and continuously balance generation and demand. Traditionally, this has been achieved through demand-oriented trading on the electricity exchange. In times of high demands, the price for electricity is rising and additional power plants with higher production costs can sell their generated electricity. However, as renewable energy sources are not controllable in the same way, the trading of energy from RES brings new dynamics to the electricity exchange and may lead to a higher volatility in the prices. Therefore, it could become increasingly important and economically beneficial to develop solutions to align electricity demands with the generation of electricity from renewable energy sources rather than vice versa.

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Sector coupling promises to play a crucial role in adapting to electricity demands. Electromobility, Power-to-Heat (PtH) and Power-to-Cold (PtC) applications such as electric cars, heat pumps or chillers are not only expected to contribute significantly to the total energy consumption due to their high efficiency, but their systems also possess additional storage options and useful inertia to be able to shift the demands in time. This enables the potential to schedule heat or cold generation to times with a high share of renewable energy in the electricity grid or low electricity prices, leading to a new generation-oriented balancing in the electricity exchange.

However, not only does the energy balancing of the electricity demand and supply become increasingly important but also the short-term stability of the grid. The predominantly decentralized generation of electricity from renewable energy sources pose additional challenges for today's electricity networks. The frequent localized concentration of power generation can lead to overloads in some sections of the grid. Already today, plants for generating electricity from renewable energies such as wind turbines must be downregulated when power lines are at their maximum capacity [139]. Nonetheless, the flexibility of local Power-to-Heat and Power-to-Cold systems can also be a promising and effective way to alleviate the stresses of overloaded sections and minimize the necessity for further grid expansions [129].

From the perspective of PtH or PtC plant operators, already today, the utilization of flexibilities and participation in the electricity exchange is motivated by the variable electricity prices of the Day-Ahead or Intraday market of the electricity exchange, which can usually be transmitted by the electricity supplier or are accessible via their own participation in the electricity market. By adapting the operation of the PtH or PtC systems in line with the predicted demands and the variable electricity prices, system operators can effectively align their operations with the market conditions, assuming the necessary operation and control technology is available [129]. The electricity price itself is determined in the electricity market, considering factors such as the prognosed availability of renewable energy sources, estimated and requested demands and power generation and transmission costs [140].
Moreover, since many cooling applications occur during hot periods and often correlate with solar irradiation, the sector-coupling of the cooling sector and the electricity sector promises great benefits for both.

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Best practice example: EUREF “Energiewerkstatt” by GASAG Solution Plus

System description

The EUREF Campus is home to several technology companies, offices and research institutions, which have a high demand for cooling both office spaces and server rooms. The EUREF “Energiewerkstatt” by GASAG Solution Plus supplies 25 buildings with heating and cooling on the campus with a total area of 165,000 m². The EUREF Campus' energy centre consists of a variety of different energy plants, including a biomethane powered combined heat and power plant (CHP) with 400 kW electrical output and 431 kW thermal output, two low-temperature gas boilers with 2.1 MW thermal output each, high-efficiency pumps and a self-generated electricity combined heat and power plant with 50 kW electrical output and 100 kW thermal output. The cooling is provided by two 1 MW electricity-driven compression refrigeration machines and distributed via a district cooling network. Furthermore, two 22 m³ buffer tanks are installed in the EUREF Campus' energy centre, which can be used for either heat or cold storage, depending on the planned operation. The cooling supply is required at the EUREF Campus research site all year round for both office conditioning and server rooms. At low ambient temperatures, it is possible to use free cooling, which saves on the compression process and increases the efficiency of cooling generation. The electricity generated in the combined heat and power plant can be used either directly in the buildings or to generate heat or cold in the own compression refrigeration machines [96]. Figure 44 illustrate the EUREF “Energiewerkstatt” and Figure 45 shows the schematic diagram of the energy system.

Figure 44: Digital illustration of the EUREF "Energiewerkstatt" by GASAG Solution Plus [96]

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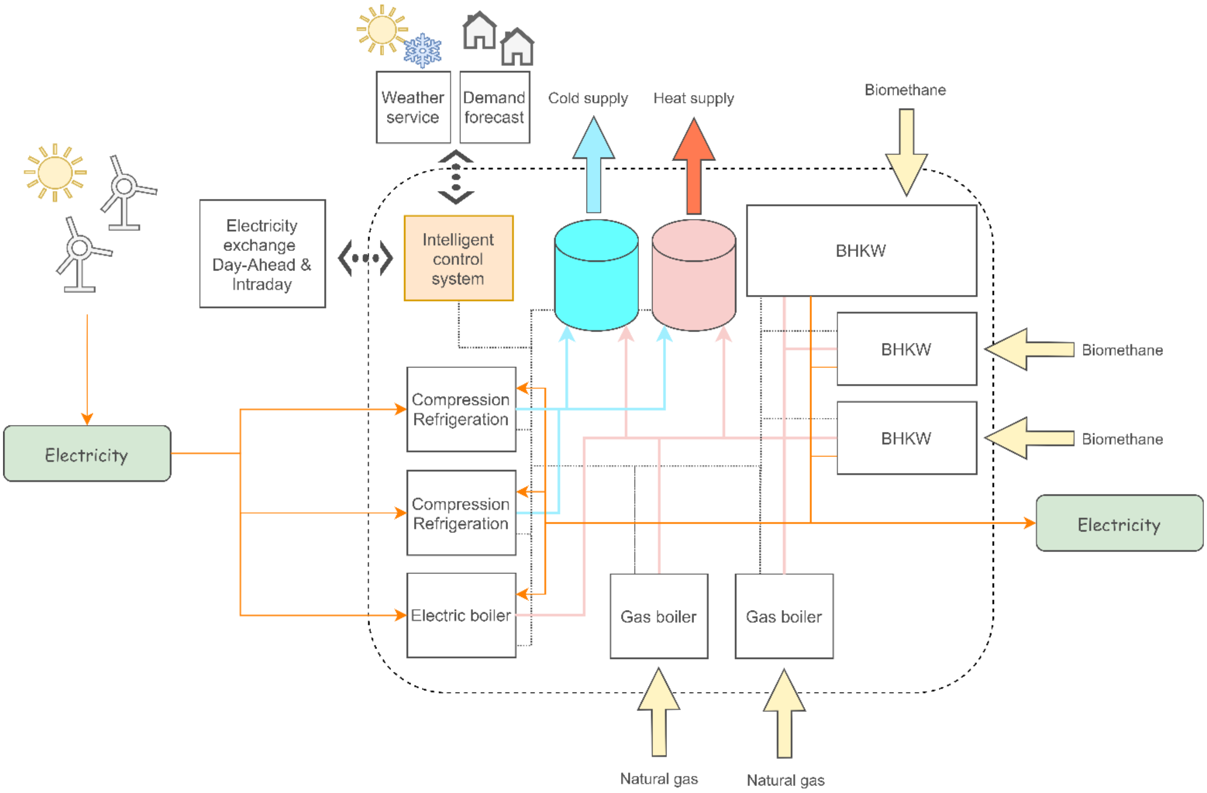

Figure 45: Schematic diagram of the EUREF "Energiewerkstatt". Own illustration based on [141].

Operation strategy

The system is controlled and operated by an intelligent and self-learning control system, continuously optimizing the operation of the facilities. The control unit was developed as part of the project "Entwicklung und Test einer Leitstandtechnologie zum zentralen Monitoring und zur effizienten und vorausschauenden Lenkung hybrider Energieanlagen innerstädtischer Gebäude" ("Development and testing of a control centre technology for central monitoring and efficient and predictive control of hybrid energy systems of inner-city buildings") [142] and includes trading mechanisms, establishes full automatization, and ensures a reliable operation. This enables flexible adaptations of the extensive number of energy converters and storage units depending on weather forecasts, prognosed heating and cooling demands and electricity costs or available renewable energy sources [141].

The principle of the intelligent control is the following. In a first step, a digital profile of all energy consumers is created, which is based on historical measurement and weather data. The profile is evaluated in a self-learning process. In a second step, the demand forecast is created based on the digital profiles of the consumers and current weather forecasts. In the final step, a stochastic optimization algorithm is used to determine the most ideal operation schedules for

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the energy converters in the energy systems, considering demand forecasts, current electricity prices, and calculated operation costs. The electricity prices are transmitted daily from the Day-Ahead electricity exchange and every 15 minutes from the Intraday market. Each day, the joint operation of all heating and cooling technologies and the two storages is optimized for the next day. The intraday operation additionally optimizes the operation schedule, utilizing electricity prices from the Intraday electricity market. The resulting electricity demands of the facility are then transmitted back to the electricity supplier, who procures the corresponding quantities for this day or the day ahead [142].

The control of each generation unit is oriented to the results of the operation optimization that is transferred to the plants from the central system. In case of demand deviations from the forecast, the operation control can overwrite the planned operation schedule and activate additional or reduced power in the cooling technologies or charge/discharge the storages to ensure a reliable supply [96].

Planning and implementation process

The planning and implementation of integrated energy systems based on renewable energies usually varies to conventional planning processes. Commonly, more stakeholders are involved than usual and new interactions between partners and components must be considered. For example, new operating and control algorithms have to be developed. Systems that used to be planned separately need to operate together and interact with each other. This requires enhanced communication and coordination and the willingness of all parties involved to cooperate with each other in all phases, from the development of the business model to the operation of the system. This is particularly important for the development of new components like high-level control systems.

Planning sector-coupled energy systems necessitates comprehensive planning tools and methods. While the integration of cooling applications into the electricity sector can enhance efficiency and promote climate-friendly practices, it also introduces higher levels of risk and uncertainty.

Stakeholder

The GASAG Solution Plus is the driving force behind the planning of the energy system on the EUREF-Campus. They are both the planner and operator of the facilities, responsible for developing the original concept and operating strategy. They also handle maintenance and

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repairs. The conceptual energy system was developed using their own innovative methods and conventional planning tools.

The intelligent control system for the energy centre was developed by another member of the GASAG Group Geo-En Energy Technologies GmbH as part of another research project. The development and implementation of the measurement, control and regulation system had to be closely integrated in the design process to ensure the planned operation. The hydraulic implementation was commissioned to external service providers but was also developed in close collaboration. With a contracting agreement, the companies on the EUREF campus purchase heat and cold for their office spaces or server rooms from the GASAG Solution Group for a monthly base price, plus a variable price for the energy supplied.

Furthermore, a communication channel to the electricity market had to be established. Participation in the electricity exchange can either take place directly, if the necessary IT infrastructure and exchange trader qualifications are available, or indirectly via the electricity providers or specialized brokers. The GASAG AG is a trading participant on the EEX electricity exchange and therefore has direct access to the spot market.

Big learnings

Automation and intelligent control played a crucial role in the planning, construction, and commissioning of the project. It involved generating data at the sensor and control level, as well as integrating machine learning methods to predict heating and cooling loads and optimize scheduling. Although these processes are not standardized yet, they are essential for the effectiveness of the system. Therefore, special attention was given to their development. The focus on automation and the effort put into the planning and development of the energy system and the intelligent control has contributed significantly to the success of the project.

The resulting flexibility and unbiased control have shown, for example, that the buffer tanks were mainly used for cold storage rather than heat supply. It has been demonstrated that the cooling system has a significant potential to adapt its production to the cost of electricity or renewable energy sources, which exceeds the possibilities of the heating system. This is because the biogas CHP's heat production costs could rarely be lower than other alternatives [139]. In summary, this has led to the EUREF Campus being supplied with 100% renewable heat and cold on the balance sheet [139].

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Conclusions and recommendations

This chapter demonstrates the benefits of integrating cooling applications into the heating and the electricity sector and the importance of incorporating cold storages in highly renewable energy systems. First, the literature analysis on the importance of integrating thermal energy storages in cooling systems as well as the best practice examples of Heerlen 2.0 and the EUREF "Energiewerkstatt" have both shown that the use of intelligent control systems, communication systems and databases is essential for optimizing the use of renewable energies and improving production costs. For integrating cooling applications into heating systems, the best practice example "Heerlen 2.0" illustrated the potential of integrating cooling systems into heating applications and how they profit from each other. For Heerlen 2.0, it was necessary to achieve a certain number of heating network connections to be economically viable. Therefore, the support from local and public authorities was of particular importance as they had to promote the system until it had reached the required dimensions. Nevertheless, it needs to be mentioned that the benefits of integrating cooling and heating applications can also be found at smaller scales. Besides, the possibility of storing heat and cold seasonally in an abandoned mine or other seasonal storage systems promises to be beneficial.

The best practice example of the EUREF "Energiewerkstatt" by GASAG Solution Plus demonstrates the benefits of integration cooling systems into the electricity sector. As the share of renewable energy in the electricity mix increases, electricity prices become more volatile and decrease in times of high availability of renewable energy sources. Participation of cooling system operators in the electricity market and the utilization of their flexibility promises to increase economic viability and further promote the use of renewable energy sources. However, the economic viability of integrated systems like the EUREF "Energiewerkstatt" does not only depend on the electricity prices from the electricity exchange but also on the prevailing political and regulatory framework. To effectively integrate renewable energy and utilize flexibility on a wider scale, there is a need for additional economic incentives. Currently, the alignment with electricity market prices has not reached typical end consumers due to government-mandated, rigid, and regulated components of the electricity price. These components, such as taxes, grid fees, and levies, account for more than 75% of the electricity price for consumers in Germany [138]. Consequently, the deployment of energy storage and demand management lacks sufficient incentives, as consumers still face high levies even during periods of low or negative wholesale prices, although they could help to

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relieve and balance the electricity grid. Therefore, there is significant potential to expand incentives and enable a more flexible electricity price orientation from the consumer's perspective. When considering grid-friendly operation of heating and cooling systems, it should be examined whether grid fees could be made more flexible to incentivize such operation or how additional incentives could be developed for this purpose. In addition, both case studies have shown that consistent project management across all phases from planning to operation appears to be a promising approach for the success of a project.

Furthermore, integrated cooling systems offer several general points of support for their widespread adoption. Firstly, there is a need for a market that fully understands the system and the necessity for new pricing models. Additionally, it is crucial to disseminate the knowledge held by a few companies to the wider public through the establishment of norms, guidelines, educational initiatives, and performance indicators. Moreover, it is worth exploring the potential recognition of the cold generated by integrated systems as CO2-neutral. These factors collectively contribute to the compelling case for the expansion of integrated cooling systems.

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References

[1] Badenes B, Urchueguía J. Analysis of the energy efficiency and the performance indicators of cooling systems: Deliverable number: D2.2; 2023.

[2] IEA. The Future of Cooling: Opportunities for energy-efficient air conditioning. Paris; 2018.

[3] Shah N, Waide P, Phadke A. Cooling the Planet: Opportunities for Deployment of Superefficient Room Air Conditioners. United States; 2013.

[4] IEA. Keeping cool in a hotter world is using more energy, making efficiency more important than ever – Analysis - IEA. [09-01-2024]; Available from: https://www.iea.org/commentaries/keeping-cool-in-a-hotter-world-is-using-more-energy-making-efficiency-more-important-than-ever.

[5] Feargus O'Sullivan. Across Europe, Gas-Strapped Cities Prepare to Power Down: Energy-saving limits on lighting and air-conditioner use have drawn heat in Spain, France and Germany. Bloomberg L.P. 2022, 4 August 2022; Available from: https://www.bloomberg.com/news/articles/2022-08-04/energy-crisis-spawns-limits-on-cooling-lighting-in-eu-cities.

[6] Santamouris M. Cooling the buildings – past, present and future. Energy and Buildings 2016;128:617–38.

[7] Eurostat. Cooling and heating degree days by country - annual data; Available from: https://ec.europa.eu/eurostat/databrowser/product/page/NRG_CHDD_A.

[8] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 2006;15(3):259–63.

[9] Calderoni M, Nicolazzi E, Lennard Z, Rocchetti M, Jakob U, Kiedaisch F. Requirements: context of application and industrial processes (D2.1). WP2 Requirements and Indicators of Solar Hybrid Systems; 2018.

[10] European Commission, Directorate-General for Energy, Pezzutto S, Novelli A, Zambito A, Quaglini G et al. Cooling technologies overview and market shares. Part 1 of the study “Renewable cooling under the revised Renewable Energy Directive ENER/C1/2018-493”: Publications Office of the European Union; 2022.

[11] Schmidt D, Goetschkes C, Pollerberg C. Kältetechnik in Deutschland - Steckbriefe zu Kältetechnologien. Oberhausen; 2020.

[12] Heinrich C, Wittig S, Albring P, Richter L, Safarik M, Böhm U et al. Sustainable cooling for building air conditioning and industry in Germany: Umweltbundesamt; 2015.

[13] VDMA. Energiebedarf für Kältetechnik in Deutschland: Eine Abschätzung des Energiebedarfs von Kältetechnik in Deutschland nach Einsatzgebieten 2017. Frankfurt; 2020.

[14] Hassine IB, Helmke A, Heß S, Krummenacher P, Muster B, Schmitt B et al. Integration Guideline: Guideline for solar planners, energy consultants and process engineers giving a general procedure

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to integrate solar heat into industrial processes by identifying and ranking suitable integration points and solar thermal system concepts. Deliverable B2; 2015.

[15] Reitze F, Toro FA, Fleiter T, Rehfeldt M, Schön M. Prozesskältebedarf in Industrie und Gewerbe – wo liegen die Bedarfsschwerpunkte in Europa? Karlsruhe; 2017.

[16] Pezzutto S, Quaglini G, Riviere P, Kranzl L, Novelli A, Zambito A et al. Screening of Cooling Technologies in Europe: Alternatives to Vapour Compression and Possible Market Developments. Sustainability 2022;14(5):2971.

[17] Chavan S, Rudrapati R, Manickam S. A comprehensive review on current advances of thermal energy storage and its applications. Alexandria Engineering Journal 2022;61(7):5455–63.

[18] Desai F, Sunku Prasad J, Muthukumar P, Rahman MM. Thermochemical energy storage system for cooling and process heating applications: A review. Energy Conversion and Management 2021;229:113617.

[19] Sadeghi G. Energy storage on demand: Thermal energy storage development, materials, design, and integration challenges. Energy Storage Materials 2022;46:192–222.

[20] Sarbu I, Sebarchievici C. A Comprehensive Review of Thermal Energy Storage. Sustainability 2018;10(1).

[21] Palomba V, Wittstadt U, Bonanno A, Tanne M, Harborth N, Vasta S. Components and design guidelines for solar cooling systems: The experience of ZEOSOL. Renewable Energy 2019;141:678–92.

[22] LNEYA - Water Cooled Chiller, Air Cooled Chiller, Chiller Manufacturer. Thermochemical Energy Storage System - LNEYA. [25-04-2024]; Available from: https://www.lneya-online.com/thermochemical-energy-storage-system.html.

[23] Alsouda F, Bennett NS, Saha SC, Salehi F, Islam MS. Vapor Compression Cycle: A State-of-the-Art Review on Cycle Improvements, Water and Other Natural Refrigerants. Clean Technol. 2023;5(2):584–608.

[24] Roy Z, Halder G. Replacement of halogenated refrigerants towards sustainable cooling system: A review. Chemical Engineering Journal Advances 2020;3:100027.

[25] Lai L, Wang X, Kefayati G, Hu E. Evaporative Cooling Integrated with Solid Desiccant Systems: A Review. Energies 2021;14(18):5982.

[26] Seeley International. Indirect Evaporative Air Conditioning (Brochure): Climate Wizard; 2023.

[27] Kian Jon C, Islam MR, Kim Choon N, Shahzad MW. Advances in Air Conditioning Technologies. Singapore: Springer Singapore; 2021.

[28] Romero-Lara MJ, Comino F, Ruiz de Adana M. Environmental and Water-Use Efficiency of Indirect Evaporative Coolers in Southern Europe. In: Innovations-Sustainability-Modernity-Openness Conference (ISMO'22). Basel Switzerland: MDPI, p. 13.

[29] UGA Poultry House Environmental Management and Energy Conservation. Evaporative Cooling Pad System Water Usage - UGA Poultry House Environmental Management and Energy

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

Conservation. [09-10-2023]; Available from: https://www.poultryventilation.com/resources/evaporative-cooling-pad-system-water-usage/.

[30] Watt JR. Evaporative Air Conditioning: Handbook. New York, London: Springer New York, NY; 1986.

[31] Duan Z, Zhan C, Zhang X, Mustafa M, Zhao X, Alimohammadisagvand B et al. Indirect evaporative cooling: Past, present and future potentials. Renewable and Sustainable Energy Reviews 2012;16(9):6823–50.

[32] Romero-Lara MJ, Comino F, Adana MR de. Seasonal energy efficiency ratio of regenerative indirect evaporative coolers—Simplified calculation method. Applied Thermal Engineering 2023;220:119710.

[33] ASHRAE. Owning and Operating Cost Database: Equipment Life/Mainteance Cost Survey. [19-11-2023]; Available from: http://weblegacy.ashrae.org/publicdatabase/service_life.asp.

[34] United Nations Environment Programme. GWP-ODP Calculator. [04-10-2023]; Available from: https://www.unep.org/ozonaction/gwp-odp-calculator.

[35] Goetzler W, Zogg R, Young J, Johnson C. Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies. United States; 2014.

[36] Baakeem SS, Orfi J, Bessadok-Jemai A. Thermodynamic and economic analysis of the performance of a direct evaporative cooler working under extreme summer weather conditions. J Mech Sci Technol 2018;32(4):1815–25.

[37] Benndorf F. Technology, Performance and Cost-effectiveness of Indirect Evaporative Cooling. [19-11-2023]; Available from: https://www.condair.de/en/fachartikel/bafa-promotion-indirect-evaporative-cooling.

[38] Rogdakis E, Tertipis D. Maisotsenko cycle: technology overview and energy-saving potential in cooling systems. Energy and Emission Control Technologies 2015(3):15–22.

[39] Lin J, Chua KJ. Indirect Dew-Point Evaporative Cooling: Principles and Applications. Cham: Springer International Publishing; 2023.

[40] Oxycom. IntCooll (Brochure); 2019.

[41] Duan Z, Zhao X, Li J. Design, fabrication and performance evaluation of a compact regenerative evaporative cooler: Towards low energy cooling for buildings. Energy 2017;140:506–19.

[42] Hay S, Seyer M, Huther H, Schickel C, Tuschy S, May R et al. Feldtest Absorptionskälteanlagen für KWKK-Systeme - FAkS Abschlussbericht. Berlin: Technische Universität Berlin; 2019.

[43] Henning H-M, Urbaneck T, Morgenstern A, Núnez T, Wiemken E, Thümmler E et al. Kühlen und Klimatisieren mit Wärme: Fraunhofer IRB Verlag; 2015.

[44] Sarbu I, Sebarchievici C. Solar heating and cooling systems: Fundamentals, experiments and applications. London, United Kingdom: Elsevier; 2017.

[45] Kohlenbach P, Jakob U, Jackson F. Solar cooling: The earthscan expert guide to solar cooling systems. New York: Routledge; 2014.

[46] Balaras C. Solar Assisted Air Conditioning: Know-How. Orlando, FL, USA: Unpublished; 2020.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

[47] Mugnier D, Neyer D, White SD (eds.). The Solar Cooling Design Guide: Case Studies of Successful Solar Air Conditioning Design. Berlin: Wilhelm Ernst & Sohn; 2017.

[48] Henning H-M, Motta M, Mugnier D (eds.). Solar Cooling Handbook: A Guide to Solar Assited Cooling and Dehumidification Processes. 3rd ed. Austria: AMBRA |V; 2013.

[49] colibri b.v. Absorptionskälteanlagen für Gefrierkühlung. [20-11-2023]; Available from: https://colibris.home.xs4all.nl/pdf_documents/german_docu/absorption_refrigeration_de.pdf.

[50] Bassols Absorption & Energieanlagen GmbH (BL Thermodynamics). experience meets innovation: Ammonia Absorption Refrigeration. [13-09-2023]; Available from: https://bl-thermo.com/wp-content/uploads/2021/01/BL_Thermodynamics.pdf.

[51] Wajid NM, Abidin AMZ, Hakemzadeh M, Jarimi H, Fazlizan A, Fauzan MF et al. Solar adsorption air conditioning system – Recent advances and its potential for cooling an office building in tropical climate. Case Studies in Thermal Engineering 2021;27:101275.

[52] Boruta P, Bujok T, Mika Ł, Sztekler K. Adsorbents, Working Pairs and Coated Beds for Natural Refrigerants in Adsorption Chillers—State of the Art. Energies 2021;14(15):4707.

[53] Abedrabboh O, Koç M, Biçer Y. Sustainability performance of space-cooling technologies and approaches. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2022;44(4):9017–42.

[54] Fraunhofer-Institut für Solare Energiesysteme, Institut für Luft- und Kältetechnik, Dresden, Bayerisches Zentrum für Angewandte Energieforschung. Evaluierung der Chancen und Grenzen von solarer Kühlung im Vergleich zu Referenztechnologien EvaSolK ; Schlussbericht - öffentlicher Teil ; Laufzeit des Vorhabens: 01.06.2010 bis 31.12.2012. Evaluierung der Chancen und Grenzen von solarer Kühlung im Vergleich zu Referenztechnologien.

[55] Bonomolo M, Jakob U, Neyer D, Strobel M, Vasta S. Integration of Solar Cooling Systems in Buildings in Sunbelt Region: An Overview. Buildings 2023;13(9):2169.

[56] Almasri RA, Abu-Hamdeh NH, Esmaeil KK, Suyambazhahan S. Thermal solar sorption cooling systems - A review of principle, technology, and applications. Alexandria Engineering Journal 2022;61(1):367–402.

[57] Abdelgaied M, Saber MA, Bassuoni MM, Khaira AM. Adsorption air conditioning: a comprehensive review in desiccant materials, system progress, and recent studies on different configurations of hybrid solid desiccant air conditioning systems. Environ Sci Pollut Res 2023;30(11):28344–72.

[58] Singh RP, Das RK. Progressive Development and Challenges Faced by Solar Rotary Desiccant-Based Air-Conditioning Systems: A Review. Processes 2021;9(10):1785.

[59] Roumpedakis TC, Vasta S, Sapienza A, Kallis G, Karellas S, Wittstadt U et al. Performance Results of a Solar Adsorption Cooling and Heating Unit. Energies 2020;13(7):1630.

[60] Alahmer A, Ajib S. Solar cooling technologies: State of art and perspectives. Energy Conversion and Management 2020;214:112896.

[61] Sahlot M, Riffat SB. Desiccant cooling systems: a review. Int. J. Low-Carbon Tech. 2016:ctv032.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

[62] Besagni G, Mereu R, Inzoli F. Ejector refrigeration: A comprehensive review. Renewable and Sustainable Energy Reviews 2016;53:373–407.

[63] Eveloy V, Ayou D. Sustainable District Cooling Systems: Status, Challenges, and Future Opportunities, with Emphasis on Cooling-Dominated Regions. Energies 2019;12(2):235.

[64] Noeres P. Thermische Kälteerzeugung mit Dampfstrahlkältemaschinen: Konzepte und Erfahrungen. KI - Kälte, Luft, Klimatechnik 2006(11).

[65] Kalpana, Subudhi S. Developments in liquid desiccant dehumidification system integrated with evaporative cooling technology. Intl J of Energy Research 2022;46(1):61–88.

[66] Certified product directory | Eurovent Certita Certification. [19-09-2023]; Available from: https://www.eurovent-certification.com/en/advancedsearch/result?program=VRF&product_type=VRF/A/R&keyword=#access-results.

[67] Fraunhofer ISI, Farunhofer ISE, IREES, Observ'ER, TU Wien EEG, TEP Energy GmbH. Mapping and analyses of the current and future (2020-2030) heating / cooling fuel develoment (fossil / renewables): Work Package 2: Assessment of the technologies for the year 2012. Final Report. Karlsruhe, Freiburg, Paris, Vienna, Zurich; 2016.

[68] Alawadhi M, Phelan PE. Review of Residential Air Conditioning Systems Operating under High Ambient Temperatures. Energies 2022;15(8):2880.

[69] Vavra C. Know when, how to specify a rooftop unit. Consulting – Specifying Engineer 2021, 14 April 2021; Available from: https://www.csemag.com/articles/know-when-how-to-specify-a-rooftop-unit/. [30-11-2023].

[70] Skogsberg K. Seasonal Snow Storage for Cooling Applications. Licentiate Thesis. Luleå; 2001.

[71] Skogsberg K, Nordell B. The Sundsvall hospital snow storage. Cold Regions Science and Technology 2001;32(1):63–70.

[72] Gu X, Wang R, Li T, Xu H. Design and Performance Analysis of Seasonal Ice Storage System for Cooling Chinese Solar Greenhouses. Japan Agricultural Research Quarterly 2022;56(2):147–61.

[73] Moe JM. Using stored snow as cooling at Oslo Airport, Norway. Proceedings of the Institution of Civil Engineers - Civil Engineering 2018;171(5):11–6.

[74] Braungardt S, Bürger V, Zieger J, Kenkmann T. Contribution of Renewable Cooling to the Renewable Energy Target of the EU. Freiburg; 2018.

[75] Hunt JD, Byers E, Sánchez AS. Technical potential and cost estimates for seawater air conditioning. Energy 2019;166:979–88.

[76] Schramek E-R (ed.). Taschenbuch für Heizung und Klimatechnik: einschließlich Warmwasser- und Kältetechnik. München: Oldenbourg Industrieverlag München; 2009.

[77] Tanja Kenkmann, Veit Bürger. Contribution of Renewable Cooling to the Renewable Energy Target of the EU (Policy report). Freiburg: Unpublished; 2012.

[78] Chicco JM, Antonijevic D, Bloemendal M, Cecinato F, Goetzl G, Hajto M et al. Improving the Efficiency of District Heating and Cooling Using a Geothermal Technology: Underground Thermal

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

Energy Storage (UTES). In: Calabrò F, Della Spina L, Piñeira Mantiñán MJ, editors. New Metropolitan Perspectives. Cham: Springer International Publishing; 2022, p. 1699–1710.
[79] Verhoeven R, Willems E, Harcouët-Menou V, Boever E de, Hiddes L, Veld PO et al. Minewater 2.0 Project in Heerlen the Netherlands: Transformation of a Geothermal Mine Water Pilot Project into a Full Scale Hybrid Sustainable Energy Infrastructure for Heating and Cooling. Energy Procedia 2014;46:58–67.
[80] Andersson O, Hellström G. Ground Source Cooling: Working Paper on Usable Storage Types and Configurations. In: COWI A/S, editor. Book of Workshops - Papers: Underground Cold Storage for Hybrid Cooling of Buildings. Soil Cool / Rekyl project; 2005.
[81] Lyden A, Brown CS, Kolo I, Falcone G, Friedrich D. Seasonal thermal energy storage in smart energy systems: District-level applications and modelling approaches. Renewable and Sustainable Energy Reviews 2022;167:112760.
[82] Mahon H, O'Connor D, Friedrich D, Hughes B. A review of thermal energy storage technologies for seasonal loops. Energy 2022;239:122207.
[83] Watzlaf GR, Ackman TE. Underground Mine Water for Heating and Cooling using Geothermal Heat Pump Systems. Mine Water and the Environment 2006;25(1):1–14.
[84] Sadeghi H, Jalali R, Singh RM. A review of borehole thermal energy storage and its integration into district heating systems. Renewable and Sustainable Energy Reviews 2024;192:114236.
[85] Cabeza LF, Galindo E, Prieto C, Barreneche C, Inés Fernández A. Key performance indicators in thermal energy storage: Survey and assessment. Renewable Energy 2015;83:820–7.
[86] Yang T, Liu W, Kramer GJ, Sun Q. Seasonal thermal energy storage: A techno-economic literature review. Renewable and Sustainable Energy Reviews 2021;139:110732.
[87] Xu J, Wang RZ, Li Y. A review of available technologies for seasonal thermal energy storage. Solar Energy 2014;103:610–38.
[88] Behzadi A, Holmberg S, Duwig C, Haghighat F, Ooka R, Sadrizadeh S. Smart design and control of thermal energy storage in low-temperature heating and high-temperature cooling systems: A comprehensive review. Renewable and Sustainable Energy Reviews 2022;166:112625.
[89] Pompei L, Nardecchia F, Miliozzi A. Current, Projected Performance and Costs of Thermal Energy Storage. Processes 2023;11(3):729.
[90] Römmling U, Albers J. Solargestützte Kälteerzeugung bei den umzugsbedingten Bundesbaumaßnahmen in Berlin. Wissenschaftliche Begleitung und messtechnische Auswertung. Solaroptimiertes Bauen, Teilkonzept 2: Schlussbericht. Berlin; 2008.
[91] Urbaneck T, Platzer B, Schirmer U. Optimierung von Kälteversorgungssystemen mit Erdsonden- und Aquiferspeichern durch Kaltwasserspeicher. bbr Fachmagazin für Brunnen- und Leitungsbau 2009;60(2009):80–4.
[92] Zetzsche M. Experimentelle Untersuchungen und regelungstechnische Optimierung einer Ammoniak/Wasser-Absorptionskältemaschine in Kombination mit einem solar angetriebenen Kühlsystem mit Eisspeicher: Universität Stuttgart; 2012.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

[93] Zetzsche M, Koller T, Müller-Steinhagen HM. Solar Cooling with an Ammonia/Water Absorption Chiller.
[94] Hanßke A. Energienetz Berlin Adlershof: Schlussbericht; 2019.
[95] Albers J. New absorption chiller and control strategy for the solar assisted cooling system at the German federal environment agency. International Journal of Refrigeration 2014;39:48–56.
[96] GASAG Solution Plus GmbH. Energiewende erleben. Effizient, klimaneutral, finanzierbar: EUREF-Energiewerkstatt by GASAG Solution. Berlin; 2022.
[97] Sanner B. Schlussbericht Thermische Untergrundspeicherung auf höherem Temperaturniveau: Begleitforschung mit Messprogramm Aquiferspeicher Reichstag; 2004.
[98] Bussmann G, Bracke R, Eicker T, Wittig V, Tuente H, Gueldenhaupt J et al. Geostar-a scalable borehole heat exchanger plant for growing district heating systems and constricted large urban infrastructures. In: Proceedings World Geothermal Congress; 2015.
[99] Hesaraki A, Holmberg S, Haghighat F. Seasonal thermal energy storage with heat pumps and low temperatures in building projects—A comparative review. Renewable and Sustainable Energy Reviews 2015;43:1199–213.
[100] Dittmann F, Rivière P, Stabat P. Space Cooling Technology in Europe: Technology Data and Demand Modelling. Paris; 2017.
[101] Werner S. European space cooling demands. Energy 2016;110:148–56.
[102] Persson U, Werner S. Quantifying the Heating and Cooling Demand in Europe: Work Package 2. Background Report 4. Halmstad; 2015.
[103] Dalin P, Nilsson J, Rubenhag A. The European Cold Market: Final Report. Ecoheatcool Work package 2; 2005-2006.
[104] Jakubcionis M, Carlsson J. Estimation of European Union service sector space cooling potential. Energy Policy 2018;113:223–31.
[105] Pezzutto S, Zambotti S, Croce S, Zambelli P, Garegnani G, Scaramuzzino C et al. Hotmaps. D2.3 WP2 Report - Open Data Set for the EU28: TU Wien; 2019.
[106] Larsen M, Petrović S, Radoszynski AM, McKenna R, Balyk O. Climate change impacts on trends and extremes in future heating and cooling demands over Europe. Energy and Buildings 2020;226:110397.
[107] Andreou A, Barrett J, Taylor PG, Brockway PE, Wadud Z. Decomposing the drivers of residential space cooling energy consumption in EU-28 countries using a panel data approach. Energy and Built Environment 2020;1(4):432–42.
[108] Lapillonne B. Future of Air-Conditioning. Executive Brief; 2019.
[109] Directorate-General for Energy. EU Building Stock Observatory (BSO); Available from: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/eu-building-stock-observatory_en.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

[110](None) DoIE-USdP, (None) IoASaC-NRC, (None) (ENERGESIS), (None) PES, (None) SUPdSI, (None) DoG-USdP. List of the combination between building typologies, geological contexts and climatic classes; 2016.

[111]Carnieletto L, Badenes B, Belliardi M, Bernardi A, Graci S, Emmi G et al. A European Database of Building Energy Profiles to Support the Design of Ground Source Heat Pumps. Energies 2019;12(13):2496.

[112]Copernicus Climate Change Service (C3S). Climate Data Store; Available from: https://cds.climate.copernicus.eu.

[113]Eurostat. Bevölkerung nach breiter Altersgruppe und NUTS-3-Region: Eurostat; 2023.

[114]Hotmaps; Available from: https://gitlab.com/hotmaps.

[115]Eurostat. Building permits - annual data: Eurostat; 2023.

[116]European Commission, Directorate-General for Energy. Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU: Final report: Publications Office; 2019.

[117]IEA. Share of population living in a hot climate, 2022, and penetration of air conditioners; Available from: https://www.iea.org/data-and-statistics/charts/share-of-population-living-in-a-hot-climate-2022-and-penetration-of-air-conditioners-2000-2022.

[118]CODA Stratègies, ADEME. La climatisation dans le bâtiment: Etat des lieux et prospective 2050. Rapport final; 2021.

[119]Schmidt D, Rogotzki R, Goetschkes C, Pollerberg C. Kältetechnik in Deutschland - Steckbriefe zu Kälteanwendungen. Oberhausen; 2020.

[120]Hellenic Statistical Authority. Survey on Energy Consumption in Households, 2011-2012. Piraeus; 2013.

[121](None) INdS. Consumi Energetici delle Famiglie Anno 2021: Riscaldamento e acqua calda quasi per tutti Condizionatori accesi sei ore al giorno; 2022.

[122](None) NSOM. Census of Population and Housing 2021: Final Report: Dwelling characteristics. Valletta, Malta; 2023.

[123]Statistics Portugal - Web Portal. [15-04-2024]; Available from: https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&indOcorrCod=0011544&contexto=bd&selTab=tab2&xlang=en.

[124]Eurostat. Consumos del Sector Residencial en España: Resumen de Información Básica.

[125](None) DfBEaIS. Cooling in the UK; 2021.

[126]Toso F, Mura A. Analisi sulla dotazione impiantistica di climatizzazione (estiva ed invernale) del patrimonio edilizio ad uso residenziale e terziario e valutazione dell'impatto economico in relazione a misure di politiche energetiche e ambientali; 2015.

[127](None) DfBEaIS. Energy Innovation Needs Assessment: Heating & Cooling; 2019.

[128]Jing R, Zhou Y, Wu J. Integrated energy system. In: Encyclopedia of Electrical and Electronic Power Engineering: Elsevier; 2023, p. 165–176.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

[129]WindNODE. Lets's talk about flex: Best practice manual | Identifying flexibility options.

[130]Selvnes H, Allouche Y, Manescu RI, Hafner A. Review on cold thermal energy storage applied to refrigeration systems using phase change materials. Thermal Science and Engineering Progress 2021;22:100807.

[131]Yang L, Villalobos U, Akhmetov B, Gil A, Khor JO, Palacios A et al. A comprehensive review on sub-zero temperature cold thermal energy storage materials, technologies, and applications: State of the art and recent developments. Applied Energy 2021;288:116555.

[132]Gunasekara SN, Bilek Z, Edén T, Martin V. Distributed cold storage in district cooling—Grid dynamics and optimal integration for a Swedish case study. Energy Reports 2021;7:419–29.

[133]Ehyaei MA, Mozafari A, Ahmadi A, Esmaili P, Shayesteh M, Sarkhosh M et al. Potential use of cold thermal energy storage systems for better efficiency and cost effectiveness. Energy and Buildings 2010;42(12):2296–303.

[134]Yan C, Wang F, Pan Y, Shan K, Kosonen R. A multi-timescale cold storage system within energy flexible buildings for power balance management of smart grids. Renewable Energy 2020;161:626–34.

[135]Xu S, Yan C, Jin C. Design Optimization of Hybrid Renewable Energy Systems for Sustainable Building Development based on Energy-Hub. Energy Procedia 2019;158:1015–20.

[136]Palomba V, Frazzica A. Comparative analysis of thermal energy storage technologies through the definition of suitable key performance indicators. Energy and Buildings 2019;185:88–102.

[137]5GDHC in short | 5GDHC. [03-04-2024]; Available from: https://5gdhc.eu/5gdhc-in-short/.

[138]Sensfuß F, Lux B, Bernath C, Kiefer CP, Pfluger B, Kleinschmitt C et al. Langfristszenarien für die Transformation des Energiesystems in Deutschland 3. Kurzbericht: 3 Hauptszenarien. Karlsruhe: Fraunhofer ISI, Karlsruhe; 2021.

[139]V. Pawlik. Windenergie - Abregelung der Stromeinspeisung in Deutschland bis 2022: Entwicklung der Ausfallarbeit durch Abregelung der Windenergie-Stromeinspeisung in Deutschland in den Jahren 2010 bis 2022. [04-04-2024]; Available from: https://de.statista.com/statistik/daten/studie/665177/umfrage/menge-des-abgeregelten-windstroms-in-deutschland/#:~:text=Im%20Jahr%202022%20wurden%20rund,die%20Netzstabilit%C3%A4t%20gew%C3%A4hrleisten%20zu%20k%C3%B6nnen.

[140]Eurostat. Electricity price statistics. [04.04.202]; Available from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics.

[141]WindNODE. Showcasing Smart Energy Systems from Northeastern Germany 2017-2020: Report 2020.

[142]Arne Höllen, VDI Zentrum Ressourceneffizienz GmbH. Potenziale der Technischen Gebäudeausrüstung und ihrer Automation zur Steigerung der Ressourceneffizienz: VDI ZRE Publikationen: Kurzanalyse Nr. 28; 2021.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

Annexes

Annex 1: Cooling Degree Day Index

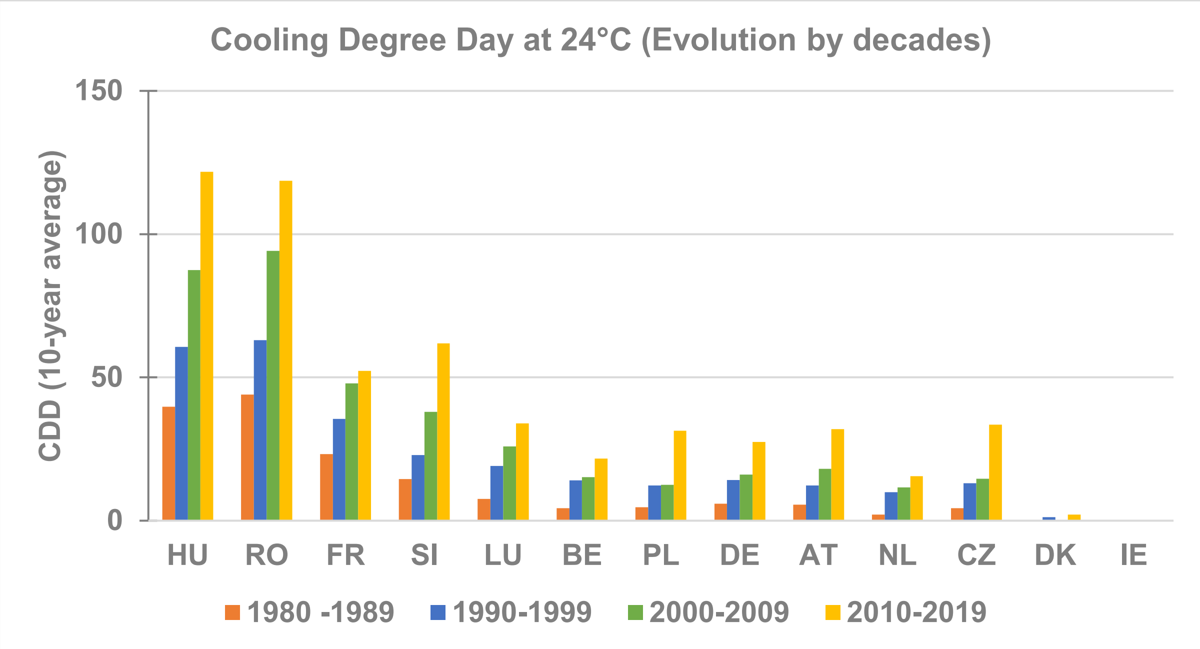

Figure 46: Change of CDD for countries with a predominance of Cfb, based on [7,8]
(warm temperature, no dry season and warm summer)

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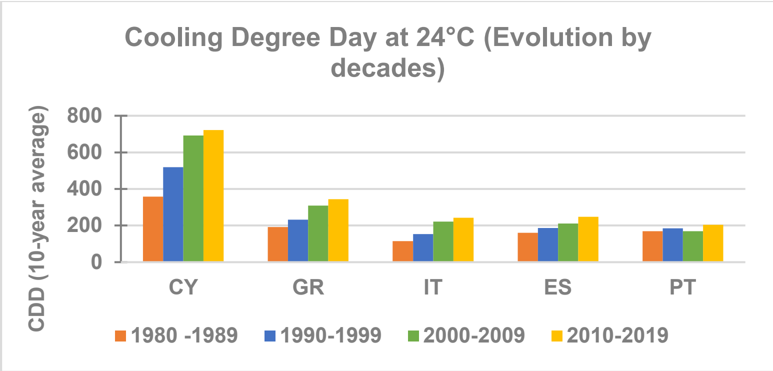

Figure 47: Change of CDD for countries with a predominance of Csa, based on [7,8]

(warm temperature, dry and hot summer)

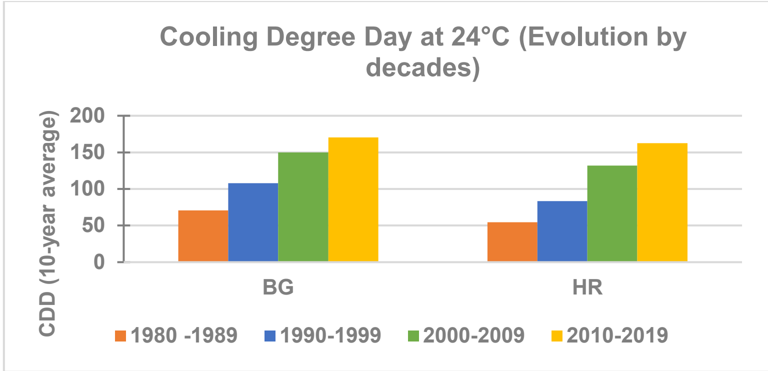

Figure 48: Change of CDD for countries with a predominance of Csc, based on [7,8]

(warm temperature, dry and cool summer)

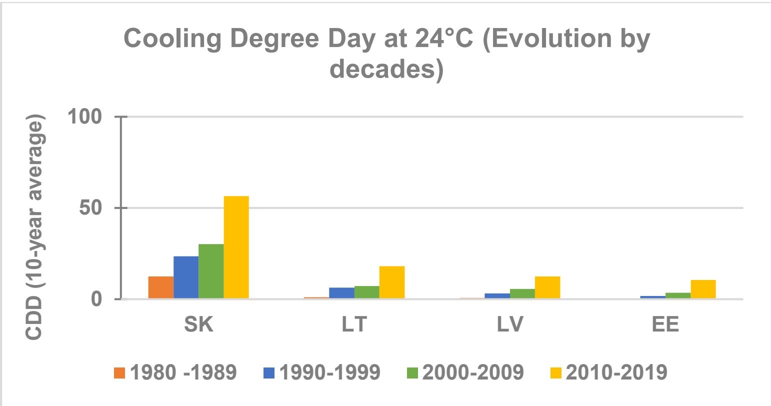

Figure 49: Change of CDD for countries with a predominance of Dfb, based on [7,8]

(boreal, no dry season and warm summer)

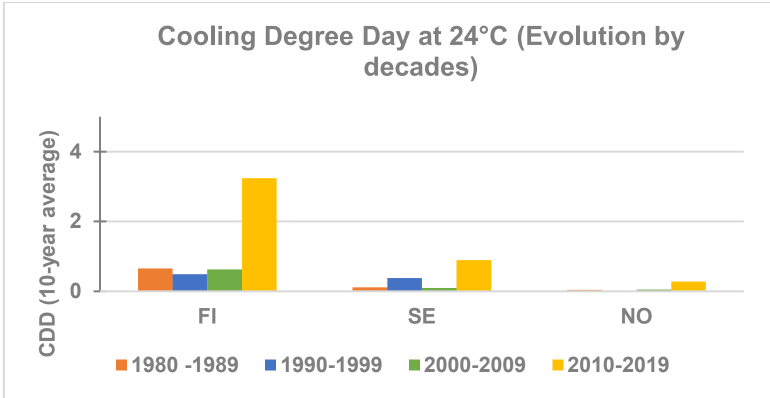

Figure 50: Change of CDD for countries with a predominance of Dfc, based on [7,8]

(boreal, no dry season and cool summer)

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Annex 2: Survey Results

Aspects		Webinar		Consortium	
		Rate	Not answer	Rate	Not answer
Technological	**Rate the role of the electricity-driven cooling technologies and their subordinate components in the future energy system**				
	Small-scale (<50 kW)	High	1	High	0
	Intermediate-scale (50 - 500 kW)	High	1	High	0
	Large-scale (>500 kW)	High	2	High	0
	Rate the role of the NOT electricity-driven cooling technologies and their subordinate components in the future energy system				
	Small-scale (<50 kW)	Medium	1	Low	2
	Intermediate-scale (50 - 500 kW)	Medium	1	Medium	2
	Large-scale (>500 kW)	High	1	Medium	2
	Rate the role of the passive cooling technologies and their subordinate components in the future energy system				
	Small-scale (<50 kW)	High	1	High	0
	Intermediate-scale (50 - 500 kW)	High	1	High	0
	Large-scale (>500 kW)	High	1	High	0
	Rate the role of the storage types in cooling systems and their subordinate components in the future energy system				
	Short term Storages (days to weeks)	High	1	High	1
	Long term Storages (seasonal)	Very high	1	High	1
	Rate the role of the storage types in cooling systems and their subordinate components in the future energy system				
	Latent storages	High	3	Medium	1
	Sensible storages	High	4	Medium	1
	Thermochemical storages	High	4	High	2
	Rate the role of the following cooling technologies or systems and their subordinate components in the future energy system				
	District cooling network, centralised generation	High	1	High	0
	District cooling network, decentralised generation	High	1	High	0
	Combined cooling, heat and power generation (CCHP)	Very high	1	Medium	1
	5th generation district heating and cooling systems	Very high	1	High	0
	Estimate the state of development of the following cooling technologies or systems				
	Electricity-driven cooling technology	Very high	0	High	0
	Not electricity-driven cooling technology	Medium	0	Medium	1
	Passive cooling systems	Medium	0	Medium	0
	Thermal storages in cooling systems	Medium	0	Medium	1
	District cooling networks	Medium	0	Medium	0
	District cooling networks with centralised generation	Medium	0	Medium	0
	District cooling network with decentralised generation	Medium	0	Medium	0
	Combined cooling, heat and power generation (CCHP)	High	0	Medium	1
	5th generation district heating and cooling systems	Medium	0	Low	1
	Rate the relevance on the renewable energy type in future cooling systems				
	Heat from renewable energies	Very high	0	High	1
	Electricity from renewables energies	Very high	0	Very high	1

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Aspects		Webinar Rate	Webinar Not answer	Consortium Rate	Consortium Not answer
Operational	**Estimate the relevance of the following parameters for cooling systems and applications**				
	Energy consumption	Very high	0	High	0
	Efficiency	Very high	0	Very high	0
	Maintenance	Very high	0	High	0
	Safety	High	0	High	0
	Rate the role of the following parameters for cooling systems and applications				
	Total energy consumption	Very high	0	High	0
	Primary energy consumption	High	0	High	0
	Energy efficiency	Very high	1	High	0
	Exergy efficiency	High	1	Medium	1
	Fail-safe operation	High	0	High	0
	Low-maintenance	High	0	High	0
	Estimate the relevance of the following aspects for the operation of cooling systems and applications				
	Operation optimization (ML, MPC, ...)	High	3	High	2
	Operation strategies	High	2	High	2
	Sector coupling	High	0	High	2
	Part load-operation	High	1	High	2
	Variable flow in external circuits	High	1	High	2
	Estimate the state of development of the following aspects for cooling systems and applications				
	Operation optimization (ML, MPC, ...)	High	4	Medium	2
	Operation strategies	High	3	Medium	2
	Sector coupling	Medium	1	Medium	2
	Part load-operation	High	3	Medium	2
	Variable flow in external circuits	High	3	Medium	3
Sustainability	**Estimate the relevance of the following parameters for the sustainability of cooling systems and applications**				
	Refrigerant	High	0	High	0
	Emissions	High	0	Very high	0
	Hazard	High	0	High	0
	Rate the role of the use for the following refrigerants in cooling systems and applications				
	Natural refrigerants	High	1	High	2
	Refrigerants with low GWP	High	2	High	1
	Refrigerants with low ODP	High	3	High	1
	Rate the role of the following aspects for cooling systems and applications				
	CO_2-emissions	Very high	0	Very high	0
	Resource efficiency (auxiliary media like water, additives, etc.)	High	1	High	0
	Holistic indicators (i.e. resulting from Life Cycle Assessments LCA)	High	0	High	0
	Hazards (toxicity, flammability, etc.)	High	0	High	0
	Replacement frequency of components (pumps, strainers, spray nozzles, etc.)	High	0	High	0
Economical	**Estimate the relevance of the following parameters for the economic feasibility of cooling systems and applications**				
	Cost of the cooling system	High	0	High	0
	Financing of the cooling system	High	0	High	0
	Market availability of the cooling systems	High	0	High	0
	Profitability of the cooling system	High	0	High	0
	Eco-friendliness of the cooling system	Very high	0	High	0
	Rate the role of the following aspects for cooling systems and applications				
	CAPEX (Capital-related costs)	High	0	High	0
	OPEX (operation- and demand-related costs)	Very high	0	High	0
	Exergoeconomic evaluation	High	1	Medium	1
	New development of technological solutions	High	0	High	1
	Low ROI values	High	1	High	1
	Subsidy schemes	High	0	High	0
	Funding schemes	High	0	High	0
	Cost-effective design and sizing of components	High	0	High	0

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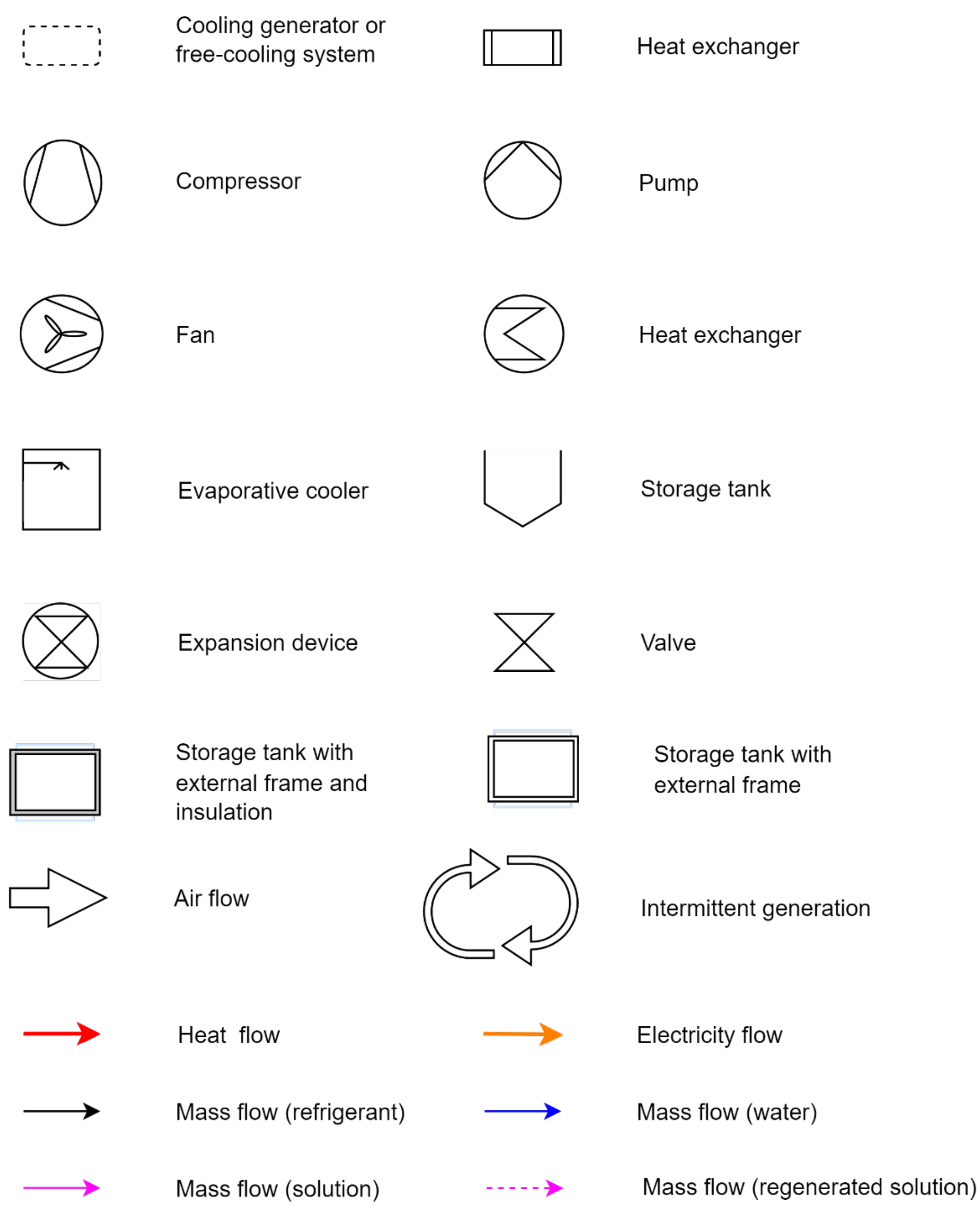
Annex 3: Symbology



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Annex 4: Results for the assessment of cooling demand

Table 20: Main results for the assessment of cooling demand

		Specific cooling demand			Total cooling potential			Actual cooling demand			Actual electricity demand		
		kWh/m^2 y			TWh/y			TWh/y			TWh_{el}/y		
Country	**CDD**	**RES**	**SER**	**AVG**	**RES**	**SER**	**TOT**	**RES**	**SER**	**TOT**	**RES**	**SER**	**TOT**
Austria	152	20.24	71.59	33.81	7.97	10.13	18.11	1.08	2.99	4.07	0.26	0.67	0.93
Belgium	107	25.99	54.30	34.43	12.18	10.81	22.99	1.27	3.51	4.78	0.30	0.79	1.09
Bulgaria	349	25.25	75.00	37.23	6.69	6.30	12.98	1.83	2.49	4.32	0.43	0.56	0.99
Croatia	372	27.03	93.21	41.15	3.94	3.68	7.62	1.14	1.10	2.25	0.27	0.25	0.52
Cyprus	1417	73.82	169.67	91.12	3.41	1.72	5.13	3.41	0.85	4.25	0.81	0.19	1.00
Czech Rep.	155	18.94	41.72	24.21	6.56	4.35	10.91	0.90	1.31	2.21	0.21	0.29	0.51
Denmark	40	17.24	34.12	22.58	5.61	5.13	10.74	0.32	0.85	1.17	0.08	0.19	0.27
Estonia	69	16.50	26.48	23.83	0.69	3.07	3.76	0.05	0.23	0.28	0.01	0.05	0.06
Finland	46	13.93	48.26	26.69	3.01	6.17	9.18	0.18	0.86	1.05	0.04	0.19	0.24
France	189	26.15	61.19	36.03	74.47	68.43	142.90	18.62	22.58	41.20	4.41	5.06	9.48
Germany	140	18.04	41.31	26.13	65.51	79.90	145.41	1.31	24.77	26.08	0.31	5.56	5.87
Greece	850	47.28	131.61	72.26	17.00	19.91	36.91	8.57	14.44	23.00	2.03	3.24	5.27
Hungary	425	30.89	79.73	44.50	10.16	10.12	20.28	3.32	3.04	6.35	0.79	0.68	1.47
Ireland	6	15.14	25.77	18.17	2.88	1.95	4.83	0.10	0.23	0.33	0.02	0.05	0.08
Italy	470	43.11	101.83	52.47	111.06	49.75	160.81	54.20	34.82	89.02	12.84	7.81	20.66
Latvia	80	22.84	25.06	23.39	1.47	0.53	2.01	0.13	0.17	0.29	0.03	0.04	0.07
Lithuania	109	18.23	31.22	21.95	1.84	1.26	3.10	0.19	0.18	0.38	0.05	0.04	0.09
Luxembourg	116	21.22	58.01	32.31	0.59	0.69	1.28	0.06	0.21	0.28	0.02	0.05	0.06
Malta	1093*	63.74	125.00	80.54	1.32	0.97	2.29	1.11	0.76	1.87	0.26	0.17	0.43
Netherlands	90	18.31	49.44	27.20	13.65	14.72	28.37	1.26	4.64	5.90	0.30	1.04	1.34
Poland	165	21.82	60.02	33.66	24.33	30.06	54.39	3.52	4.66	8.18	0.84	1.04	1.88
Portugal	396	34.97	75.48	44.54	16.37	10.93	27.31	2.72	4.15	6.87	0.64	0.93	1.58
Romania	338	29.01	51.28	32.51	16.21	5.35	21.56	4.31	1.23	5.53	1.02	0.28	1.30
Slovakia	211	24.72	62.09	31.98	4.13	2.50	6.63	0.73	0.83	1.56	0.17	0.19	0.36
Slovenia	229	21.56	46.02	29.53	1.47	1.52	2.99	0.28	0.46	0.74	0.07	0.10	0.17
Spain	566	31.08	104.69	44.07	57.05	41.19	98.24	34.74	33.16	67.90	8.23	7.44	15.67
Sweden	35	19.31	37.03	24.33	8.64	6.55	15.19	0.46	1.24	1.71	0.11	0.28	0.39
UK	26	20.14	40.53	25.49	46.09	33.00	79.09	2.30	9.57	11.87	0.55	2.15	2.69
EU27 + UK	**244**	**26.10**	**64.15**	**36.39**	**524.30**	**430.71**	**955.01**	**148.11**	**175.33**	**323.44**	**35.10**	**39.32**	**74.43**

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Annex 5: Results for the future projection of 2030 cooling demand

Table 21: Main results for 2030

		Specific cooling demand			Total cooling potential			Actual cooling demand			Actual electricity demand		
		kWh/m² y			TWh/y			TWh/y			TWh_{el}/y		
Country	CDD	RES	SER	AVG	RES	SER	TOT	RES	SER	TOT	RES	SER	TOT
Austria	163	22.80	72.50	36.33	10.40	12.38	22.78	1.49	4.84	6.33	0.31	0.94	1.25
Belgium	150	28.54	57.66	38.00	15.39	14.96	30.34	2.06	6.30	8.36	0.43	1.23	1.65
Bulgaria	426	29.01	80.01	42.52	8.62	8.57	17.18	2.82	4.21	7.03	0.59	0.82	1.41
Croatia	502	31.61	97.92	47.33	4.97	4.79	9.76	1.89	1.90	3.79	0.39	0.37	0.76
Cyprus	1499	81.01	178.08	98.63	4.76	2.32	7.08	4.76	1.36	6.12	0.99	0.26	1.26
Czech Rep.	142	19.59	42.11	25.37	7.42	5.51	12.93	0.95	2.18	3.14	0.20	0.42	0.62
Denmark	32	17.68	34.68	23.52	6.30	6.46	12.76	0.32	1.69	2.01	0.07	0.33	0.40
Estonia	101	18.88	29.20	26.36	0.89	3.65	4.54	0.09	0.62	0.71	0.02	0.12	0.14
Finland	61	14.84	48.97	28.59	3.64	8.10	11.74	0.26	1.91	2.17	0.05	0.37	0.43
France	287	30.53	66.99	41.91	96.22	95.74	191.96	30.69	40.79	71.48	6.39	7.94	14.33
Germany	163	19.49	44.47	28.40	76.90	97.39	174.28	2.76	39.54	42.30	0.57	7.70	8.27
Greece	932	50.77	137.75	77.00	18.78	22.01	40.79	10.55	18.07	28.62	2.20	3.52	5.71
Hungary	513	34.42	82.64	49.50	12.32	13.47	25.79	4.78	5.33	10.12	1.00	1.04	2.03
Ireland	13	16.20	26.90	19.39	3.60	2.54	6.14	0.14	0.55	0.69	0.03	0.11	0.14
Italy	624	48.41	107.75	58.74	126.55	59.34	185.90	75.43	47.24	122.67	15.71	8.67	24.39
Latvia	108	24.13	27.34	25.02	1.67	0.72	2.40	0.18	0.29	0.47	0.04	0.06	0.09
Lithuania	134	20.42	33.65	24.60	2.32	1.77	4.09	0.29	0.43	0.71	0.06	0.08	0.14
Luxembourg	134	23.40	59.83	35.90	0.82	1.10	1.92	0.10	0.45	0.55	0.02	0.09	0.11
Malta	1272	73.19	135.89	92.11	2.17	1.74	3.92	2.10	1.53	3.62	0.44	0.30	0.73
Netherlands	125	20.51	51.18	29.99	17.18	19.18	36.36	2.01	7.88	9.89	0.42	1.53	1.95
Poland	168	22.81	60.76	35.50	29.94	40.08	70.02	4.40	10.06	14.46	0.92	1.96	2.87
Portugal	470	37.77	80.27	48.30	19.18	13.42	32.60	4.18	6.39	10.57	0.87	1.24	2.11
Romania	389	31.58	54.27	35.40	20.35	7.08	27.42	6.13	2.31	8.44	1.28	0.45	1.73
Slovakia	239	27.03	64.84	34.61	5.02	3.02	8.04	0.99	1.29	2.27	0.21	0.25	0.46
Slovenia	284	23.92	49.54	32.88	1.78	1.98	3.77	0.41	0.80	1.20	0.08	0.15	0.24
Spain	647	34.47	107.82	48.26	67.06	48.53	115.60	44.61	43.73	88.34	9.29	8.51	17.80
Sweden	35	20.60	37.31	25.47	10.45	7.80	18.25	0.56	2.23	2.79	0.12	0.43	0.55
UK	52	21.69	42.72	27.77	55.34	44.31	99.65	3.76	17.10	20.87	0.78	3.33	4.11
EU27 + UK	**302**	**28.62**	**66.96**	**39.76**	**630.05**	**547.94**	**1177.99**	**208.71**	**270.99**	**479.70**	**43.48**	**52.22**	**95.70**

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COOLING DOWN

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