European Commission

Cooling Technologies Overview and Market Shares

Part 1 of the study "Renewable Cooling under the Revised Renewable Energy Directive ENER/C1/2018-493"

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Introduction

As part of the “Clean Energy for all Europeans” package [1], the EC proposed an update of the Renewable Energy Directive (RED - 2009/28/EC [2]). The revised RED was adopted in December 2018[3]). The RED II includes a specific chapter on mainstreaming renewable energy into heating and cooling (H&C), Article 23 and district heating and cooling (DHC), Article 24.. To do so, the RED II requires Member States (MSs) to raise the share of renewable energy in H&C yearly by an average of 1.3 percentage points (ppt) from 2021 to 2030. MSs are allowed to count waste heat and cold in 1.3 ppt up to 40% of the increment. In case a MS decides not to use waste heat and cold to the avreae annual increase, it must implement an annual average of 1.1 ppt increase in the share of renewables in H&C. Additionally, the RED II also promotes renewable energy sources (RES) in district heating and cooling (DHC), requesting MSs to raise the share of RES and waste heat and cold by at least 1 percentage point yearly (2021-2030). MS can fulfil this 1 ppt increase by waste heat and cold without limitation.

While the RED II outlines the methodology to calculate RES shares for electricity, transport and heating, it does not provide methods on how to take into account renewable cooling. The RED II specifies that the EC shall adopt delegated acts to supplement the directive at the latest by the 31st of December 2021, including a methodology for calculating the amount of renewable energy utilized for cooling and district cooling (DC), and amend the directive accordingly.

In this context, the European Commission launched this study to develop a methodology for defining renewable cooling and for calculating corresponding RES-HC and RES shares. This also requires a rigorous analysis of the status quo of cooling technologies and the cooling related energy demand. The specific goals of the study are:

- Providing an overview of technologies for cooling, related technologies and their technological development trends;
- Quantifying actual cooling demand as well as its development until 2030 and 2050;
- Providing options of renewable cooling definitions, which are in line with the RED II as well as elaborating options of possible methods for calculating renewable energy shares;
- Investigating impacts of proposed definitions on renewable cooling, related methods on calculations;
- Delivering well-grounded recommendations for choosing a fitting definition of renewable cooling, calculation methods as well as on how statistical reporting can be improved and utilized for renewable cooling;

During the project duration (from end of 2019 until August 2021) a series of stakeholder consultation events took place, including a survey of EU Member States energy statistics representatives and Eurostat, presentation and consultation at the CA-RES and CA-EED, two dedicated stakeholder workshops as well as bilateral meetings and consultations. These numerous feedbacks served to continuously improve and further develop the project results.

The first report of the study intends to provide an overview of technologies for cooling and their related technological development trends, as well as the quantification of the EU final energy consumption for cooling (country-by-country), with 2016 as baseline utilizing the most recent statistical data and information. Furthermore, it develops projections on final energy consumption for cooling until 2030. Lastly, it investigates in detail how much heat pumps (HPs) and DC can deliver renewable cooling.

The overall structure of the first report of the study is detailed below.

- In section 1 general definitions of cooling as well as space cooling, process cooling, and district cooling are included. Also, it describes the different types of cooling system functions. Moreover, efficiency metrics are provided and discussed.
- In section 2 the results of the comprehensive screening of cooling technologies are presented.
- In section 3 the final energy consumption for cooling in the base year 2016 is evaluated.
- In section 4 the past, present, and future cooling market in Europe are assessed.
- In section 5 the space cooling consumption based on a building stock analysis is computed as well as the comparison with results from section 3.
- In section 6 the contribution of free cooling is discussed.
- In section 7 the actual contribution of the thermally driven heat pumps is quantified.
- In section 8 passive cooling solutions are presented.

1.1. Definition of cooling, space cooling, and process cooling

In the context of this study, **cooling** is defined as the extraction of heat from an enclosed space or from a process to reduce or maintain the space or process temperature at a specific set point [4].

Particularly, in the current text, the term cooling entails both **space cooling (SC)** and **process cooling (PC)** definitions. In contrast, when it needs to be referred to one specific of the two cooling types indicated above, it is specified.

Space Cooling is defined as the removal of heat from the air to cool indoor air and ensure healthy conditions and thermal comfort to the occupants of an enclosed space (e.g. buildings). Space cooling lowers the temperature of the air. Typical set-points of indoor air temperature for cooling vary, occurring between 20 and 30 °C [5].

Space cooling applications usually take place in buildings. Space cooling applications are mainly present in the tertiary (offices, trade, education, health, hotels and restaurants, and other non-residential buildings - amongst others, transportation infrastructure like airports and railway stations, sports facilities like gyms, and infrastructure for military activities like military barracks) and residential (single-family, multi-family houses, and apartment blocks) sectors [6]-[7]. However, there are also SC applications in the industrial sector (e.g. SC applications for workers in factories or operators' comfort).

Process cooling is defined as the removal of heat from processes (e.g. plastic mould cooling [8]), from products, or from a confined space containing these processes or products in view of maintaining the required set temperature.

Within the definition indicated above, PC also takes place in the residential sector – for example for freezing[1] of perishable goods and keeping them at a storage temperature level. However, for this study, concerning PC, the residential sector hasn't been considered, because opportunities for use of renewable energy specifically for cooling in this sector are limited, and because the appliances (refrigerators and freezers) are covered by Eco-design and Energy labelling regulations [9].

[1] Please note that while cooling refers to a decrease in temperature, freezing relates to a change in state of a substance from a liquid to a solid through cooling down to a critically low temperature [5].

Cooling system energy input in case of transportation (e.g. cars, trucks, ships) is in general supplied by the transportation engine and thus pertains to transport and fuel efficiency regulations. **It is thus proposed that the scope of the renewable cooling definition is stationary cooling and does not cover cooling systems in means of transportation.**

In the following text, we refer to so-called **equivalent full load hours (EFLHs)**. These are defined as the number of hours a cooling device would have to operate at full load to provide the same amount of cooling delivered under real operation conditions (partial load) over a cooling season [10].

In this study, **useful energy demand (UED) and final energy consumption (FEC) for cooling** are distinguished**.** The useful energy demand is the net heat removed from space/process to be cooled. In contrast, the final energy consumption for cooling is the energy input of the cooling generators. As such, the two quantities differ by disparate conversion factors. The energy efficiency ratio (EER) for electrically driven cooling equipment is > 1. Because of that, the final energy consumption for cooling is lower than the useful energy demand for cooling [6].

Cooling can **occur naturally** without the intervention of a cooling system, when there is a temperature difference between the enclosed/indoor space or process and the outside temperature of ambient air, surface water, or ground and the natural flow of energy from hot to cold can operate and is used.

An **active cooling system** aims at satisfying the need for cooling and requires at least a pump or a fan. Under the active cooling system category, two different sub-categories are distinguished for this study: **free cooling and cooling generators.**

For **free cooling**, the natural heat flow from hot to cold is available, and it is intensified by pumps and/or fans. This includes free cooling solutions in the case of cooling systems using air as cold distribution vector, which are also ensuring the ventilation function, provided that cooling is the primary function.

In situations where the natural heat flow is not available or not used, a **cooling generator** is required. The latter requires an external energy input (of different forms depending on the cooling principle used, e.g. electricity in the case of electric vapour compression, heat in the case of absorption cooling) in addition to the energy required for pumps and fans.

The following definition of active cooling is thus proposed:

- An **active cooling system** is either a free cooling system or a cooling system embedding a cooling generator, and for which cooling is one of the primary functions.
- A **free cooling system** is a cooling system using a natural cold source to extract heat from the space or process to be cooled via fluid(s) transportation with pump(s) and/or fan(s) and which does not require the use of a cooling generator.
- A **cooling generator** refers to the part of a cooling system that generates a temperature difference allowing heat extraction from the space or process to be cooled, using a vapour compression cycle, a sorption cycle, or another energy-driven thermodynamic cycle.

When the **temperature difference** between the space or process to be cooled and the outside temperature **is not sufficient** to provide the required level of cooling by the natural flow from hot to cold, it still can be used and facilitated, but in addition, it needs to be **boosted by a cooling generator**.

In the following sections, active cooling systems are simply named “cooling systems”.

In the context of this study and following the fourth paragraph of Article 7(3) of the RED II **only active cooling is in the scope** of the renewable cooling calculation. While **passive cooling** refers to actions aiming at reducing the cooling load which does not require the movement of a cooling medium (fluid). The use of windows shades, blinds, building insulation, or green roofs are examples of passive cooling [11]–[13]. **Passive cooling is outside the scope of the renewable cooling calculation.**

1.2. Space cooling systems

This part aims at giving an overview of present cooling system architectures and their different components. The system architectures have implications concerning the evaporating and condensing temperature levels of the different cooling generators and components included or not in the metrics, which both affect efficiency.

1.2.1. Types of cooling systems

Space cooling is commonly generated with what we call air-conditioning (AC) systems. Air-conditioning systems that can supply both heating and cooling (H&C) are said **reversible** of which the related share on the EU market is currently growing [14]. In contrast, the share of reversible heat pumps in Southern European countries is relatively high (please see Table 1).

Table 1 Share of reversible heat pumps in Southern European countries [15], [16]

COUNTRIES	SHARES
Greece	82%
Cyprus	82%
Spain	79%
Malta	58%
Italy	56%
Portugal	56%
Croatia	40%
Slovenia	37%

For some product segments, such as split air conditioners, the offer is nearly 100 % reversible. The use of these systems in heating mode is estimated to be only about 30 % [17].

Air conditioning systems are of two main types, room air-conditioners (RACs) and centralized air-conditioners (CACs). The RACs are cooling systems serving one room or a number of rooms, while the CACs are used for cooling at a building scale.

This distinction has an impact on their applications (the RACs are more used in residences whereas the tertiary applications mainly rely on CACs) but also on their typical unitary cooling capacity due to the different building surfaces covered. Based on that distinction, the existing typologies of SC systems are presented in Figure 2 below.

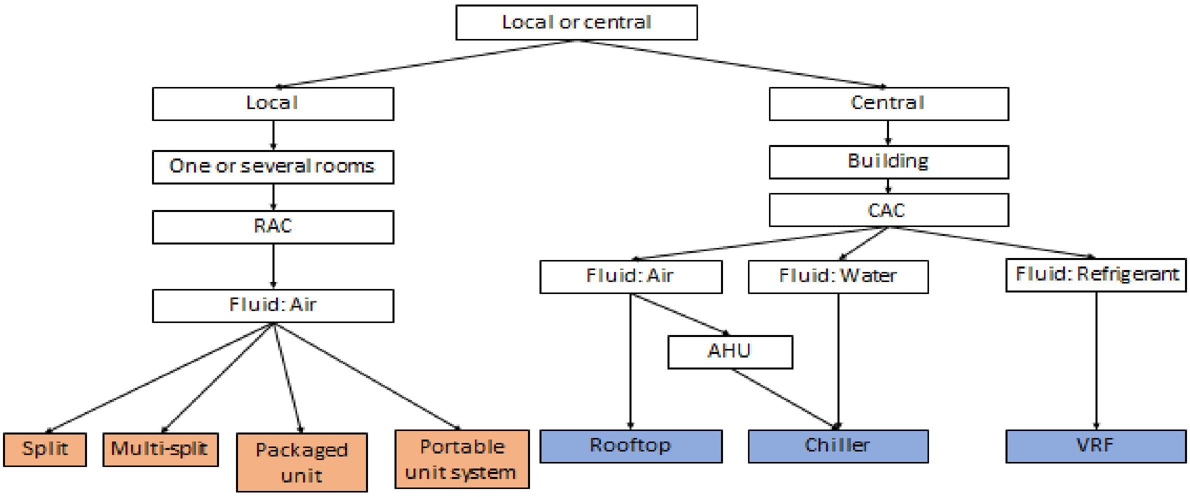

Figure 2 Classification of space cooling systems/devices

Figure 2 distinguishes between two main types of SC systems: RACs and CACs. RACs (also called individual or autonomous AC systems) use an independent unit in each room (or a number of rooms) to provide SC. Centralized air-conditioners are located on the roof or basement and prepare air, water, or refrigerant centrally before it is distributed across the entire buildings.

The four different types of RAC cooling generators (split, multi-split, packaged unit, portable unit) and the three different types of cooling generators in CAC systems (rooftop, chiller, variable refrigerant flow - VRF - system) are standardized products (up to a certain size). These cooling generators are all using vapour compression (VC) cooling technology. Absorption cooling is also available for chillers (please see Figure 8 and related explanation), although its use is limited (please see section 4).

The architecture of these different cooling systems is described below.

Split

A split system is an assembly of refrigeration system components installed on two mountings that form a functional unit. This kind of system includes two terminal units (an outdoor and indoor unit) bonded only by refrigerant flow pipes. The outdoor unit comprises a condenser, while the indoor unit includes the evaporator [6]. Figure 3 refers to a split system (high-temperature level: red, low-temperature level: blue).

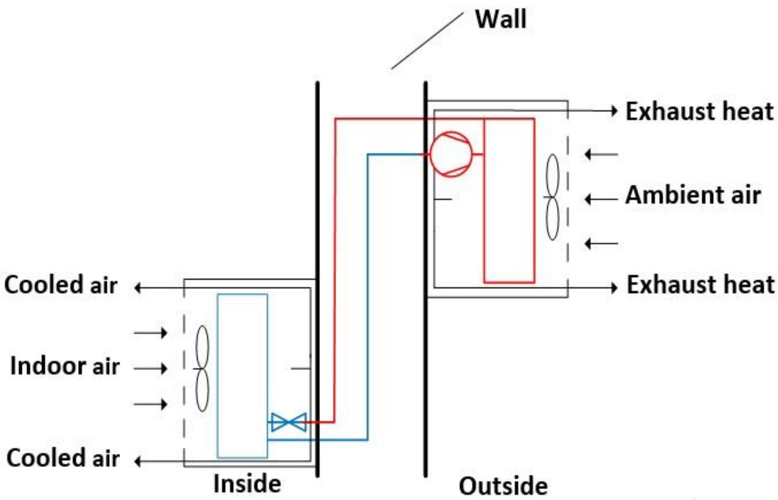

Figure 3 Split system [6]

The fan of the indoor side circulates indoor air on the inside heat exchanger (evaporator). The refrigerant absorbs the heat and rejects it on the outside air through an outdoor heat exchanger (condenser) that is circulated by the fan on the cold sink.

Multi-split

A multi-split system includes several indoor units (evaporator) bonded to a singular outdoor unit (condenser) [6] - see Figure 4.

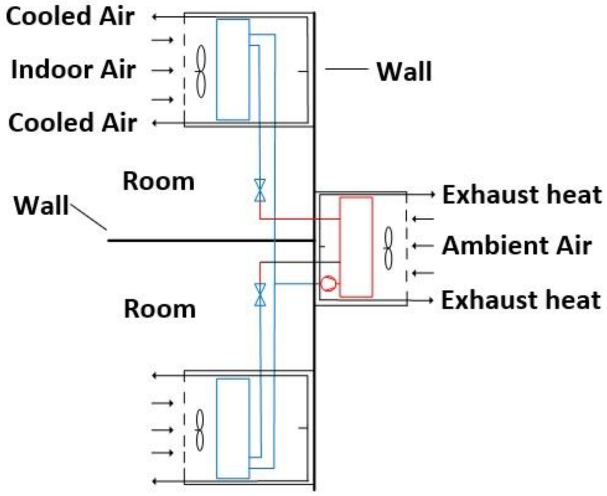

Figure 4 Multi-split system [6]

Packaged unit

A packaged AC unit is a self-contained unit assembled in a casing where all the AC components are enclosed in a single casing. The compressor, coils, etc. are all housed in a single-boxed cabinet [6], [18]. Packaged units in the residential sector are also called through-the-wall air-conditioners due to their specific mounting type – see Figure 5.

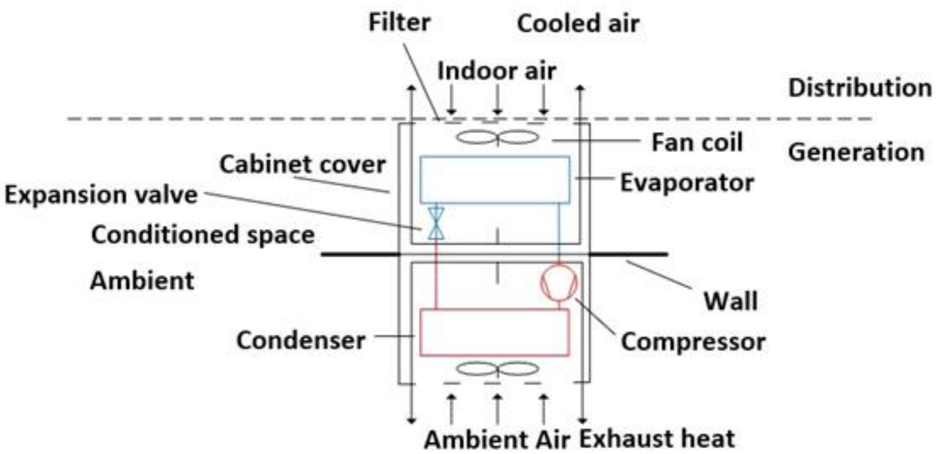

Figure 5 Packaged unit [6]

Portable unit system

Portable (or moveable) unit systems (moveables) come in one package containing all the parts, require no installation (or limited, i.e. make a hole in a window to install a hose), and often have wheels for easy displacement. The indoor air to be cooled is drawn into the condenser, which circulates the refrigerant (the cooling medium) and is rejected outside by a duct. This makes them rather slow to attain the desired cooling effect and highly inefficient since the hose usually needs to pass through an open window (or the portability would be compromised), which allows air to flow back from the hotter to the colder environment further favoured by the negative pressure created due to the net transfer of air to cool the condenser [19] - See Figure 6.

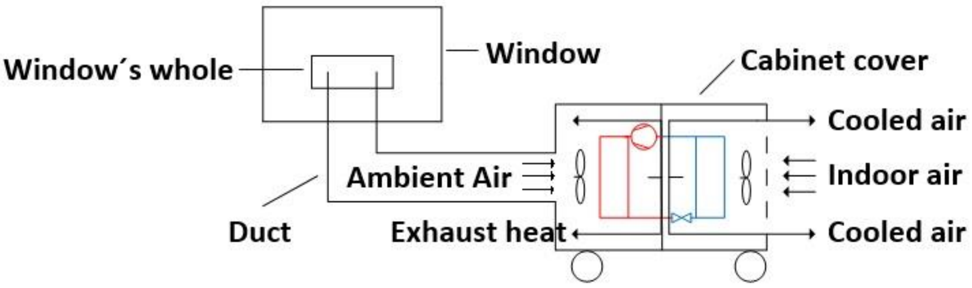

Figure 6 Portable unit system [6]

Rooftop

A rooftop AC system refers to a factory-assembled packaged unit, which is mounted on a building's roof. The rooftop AC system provides a cold air supply by ducts to the conditioned space and ventilation. There is a heat recovery from exhaust and inlet air. Rooftop AC systems can be customised to meet the demands of medium to large buildings. See Figure 7 below:

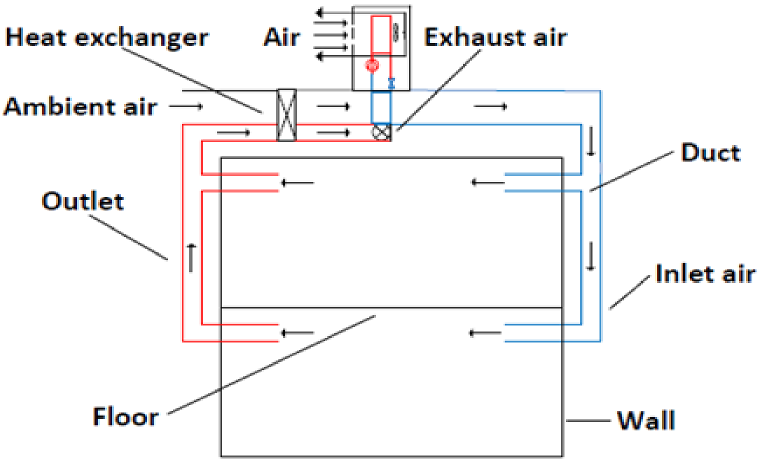

Figure 7 Rooftop system [6]

Chiller

A chiller is a cooling generator of an AC system in which chilled water is distributed to coils (fan-coil units - FCUs), or heat exchangers in air handling units (AHUs), or other types of terminal units. Here the air is cooled and afterward, the chilled water is recirculated to the chilling unit, where it is cooled again. The mentioned SC coils transfer latent heat and sensible heat from air to chilled water, providing SC and dehumidifying air [20] – see Figure 8 and Figure 9.

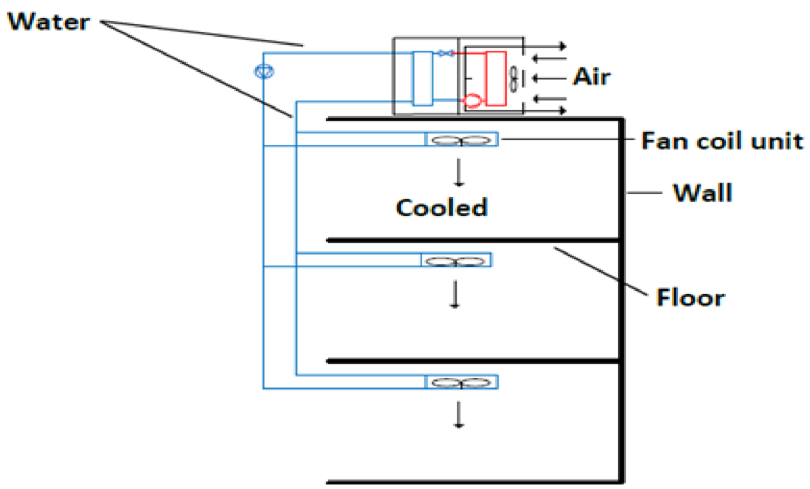

Figure 8 Chiller (e.g. air-to-water system with fan coil terminal units) [6]

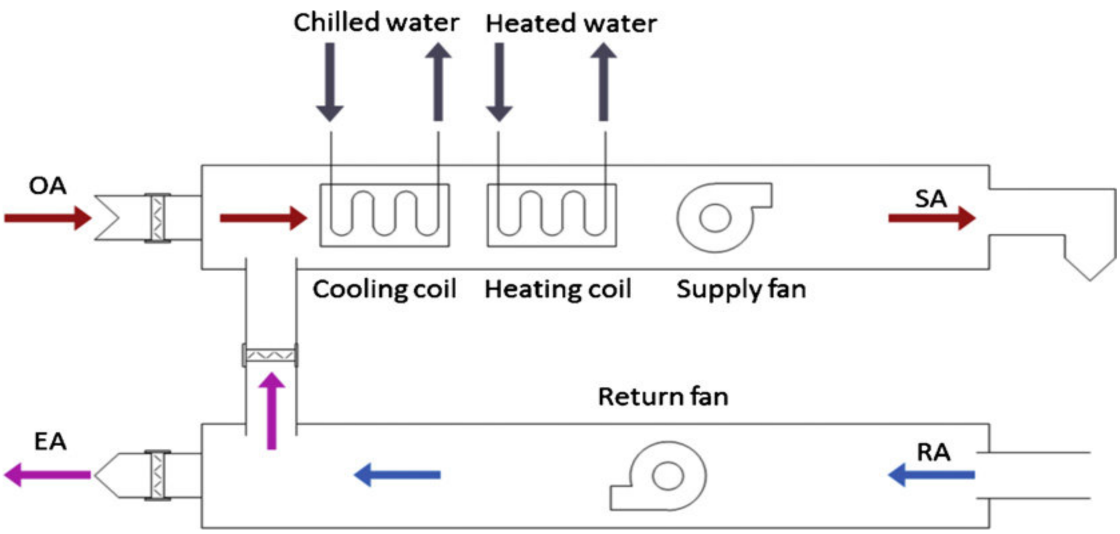

Figure 9 Air handling unit system with a cooling coil integrated

Figure 9 above illustrates the principle of the AHU with a cooling coil, where:

- OA is the outdoor air that is mixed with the return air via a damper.
- SA is the supply of air with airflow, temperature, and humidity allowing it to meet the cooling load.
- RA is the return air that is extracted from the building.
- EA is the exhaust air that is rejected to the environment.

In this type of AHU configuration, the air mixing section of EA and OA, also called economizer, allows to maintain the outdoor air introduction for ventilation purposes and to adjust the airflow on the cooling coil to supply the required cooling capacity. This air mixing section enables to use free cooling to cool the building when OA temperature is lower than EA temperature. This air mixing section is not present in standard AHU ensuring only the ventilation function and the preconditioning of outdoor air.

Cooling AHUs require much larger airflows than ventilation only AHUs for the same building size. For cooling AHUs, the total required airflow is defined by the cooling capacity required to extract the building's maximum heat load. For ventilation AHUs, it depends on the ventilation requirements; a cooling coil may also be present but only to precool outdoor air.

In cooling AHUs, at high outdoor air temperature, most of the return air (RA in Figure 9) is recirculated, as its temperature is lower than outdoor air. The proportion of recycled air can be used as a mean to distinguish ventilation and cooling AHUs. A threshold of 90% recycled air is proposed in the guidelines accompanying Regulation (EU) 1253/2014 [21]. A ratio between total airflow and maximum cooling capacity can also be used with typical values lying between 150 and 250 $m^3.h^{-1}.kW^{-1}$ for cooling AHUs.

Direct evaporative cooling of supply air and indirect evaporative cooling (air-to-air heat exchanger between evaporatively-cooled exhaust air and supply air) are in general implemented in AHUs, although distinct independent cooling devices are also available.

VRF system

A VRF (variable refrigerant flow – also called VRV – variable refrigerant volume) system refers to one outdoor condensing unit delivering chilled water to several indoor units. This kind of system is characterized by the ability to control the quantity of refrigerant flowing to several evaporators (interior units). Thus, the use of many evaporators with different configurations and capacities, connected to an individual condensing unit is possible. This type of arrangement allows individualized comfort control [6]. See Figure 10:

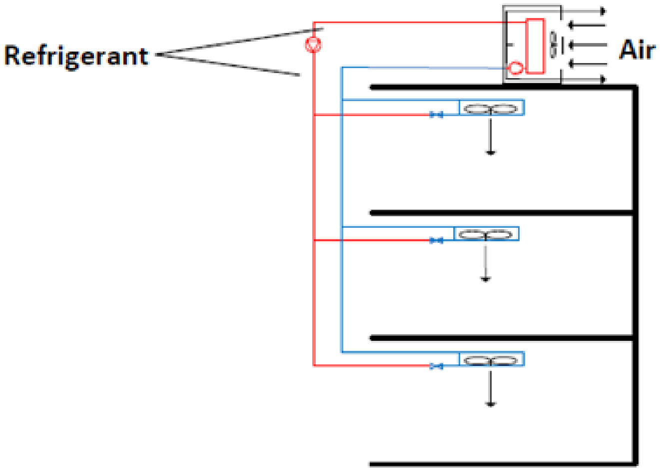

Figure 10 Variable refrigerant flow system [6]

1.2.2. Types of heat rejection systems

The high-temperature refrigerant entering the condenser, which allows heat rejection, is in most cases air-cooled, but can also be evaporatively cooled or water-cooled. These alternatives may allow lowering the temperature of the fluid cooling the refrigerant in the condenser, and thus may increase the cooling generator performance. As the main interest here is the impact on cooling system efficiency, systems are simply classified by heat sink temperature levels:

Ambient air temperature (Figure 11): air-cooled condenser and water-cooled condenser plus dry cooler (water to ambient air heat exchanger).

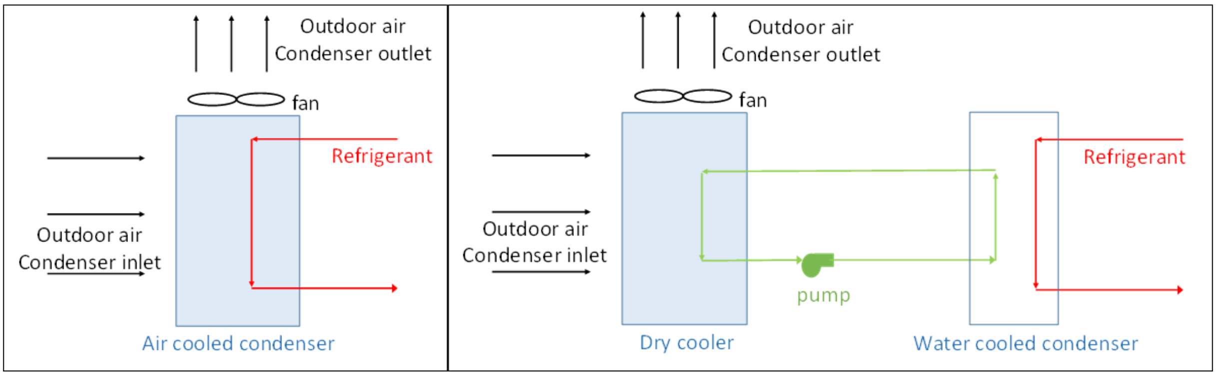

Figure 11 Air-cooled condenser and dry cooler heat rejection systems

Wet-bulb temperature (Figure 12): evaporatively cooled condenser and water-cooled condenser plus cooling tower use an evaporative cooling principle to approach the humid air temperature of outdoor air. Cooling towers can be of direct contact (in that case, water to be cooled is in direct contact with outdoor air) or indirect (in that case, water to be cooled flows inside pipes; evaporation of water in air occurs outside the water pipes).

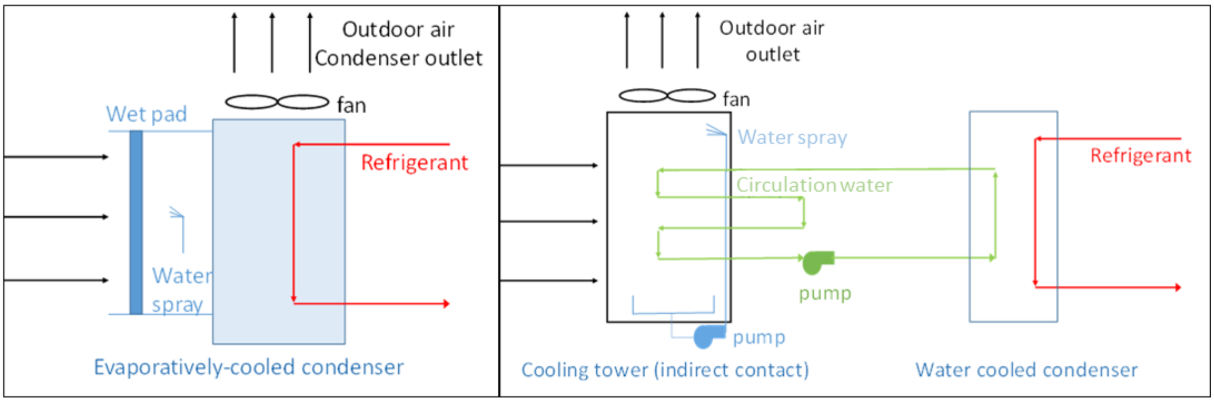

Figure 12 Evaporatively-cooled condenser and cooling tower (closed) heat rejection systems.

Sea/river/lake water temperature (Figure 13): water-cooled condenser plus water-to-water heat exchanger.

Ground (or underground water source) temperature (Figure 13): water-cooled condenser plus ground heat exchanger (or, for the underground water source, water-cooled condenser plus water-to-water heat exchanger). Depending on the type of ground heat exchanger, different temperature levels can be reached.

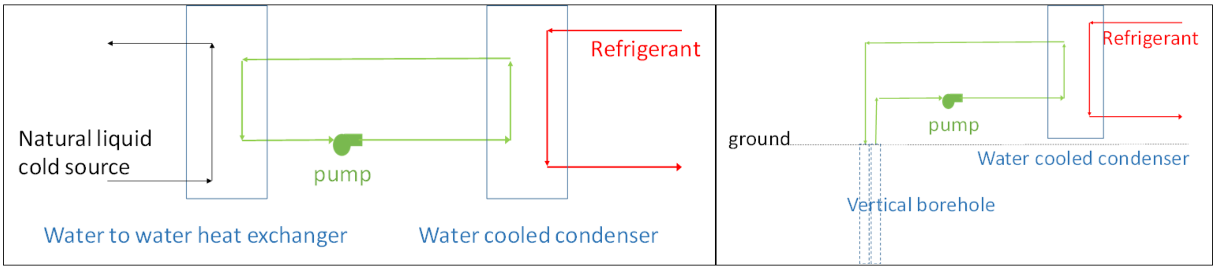

Figure 13 Natural liquid cold source and ground heat rejection system (vertical borehole)

In the case of water-cooled condensers, circulator and fan consumption (for cooling towers and dry coolers) are added to the cooling system's final energy consumption.

1.2.3. Types of chilled water distribution in buildings

There are several types of chilled water distribution in buildings:

- Fan coil unit: the chilled water exchanges its heat through a coil and a fan that circulates the air of the area to be cooled.
- Cooling floor application: the chilled water is distributed in a pipe network placed on the ground of the area to be cooled and absorbs its heat.
- Chilled ceilings/passive cold beams: this is the same principle as for cooling floors except the cold pipes are located close to the ceiling.
- The chilled water distributions have several temperature levels which impact the cooling generator efficiency.

1.3. Process cooling

Following Table 2 displays typical PC applications.

Table 2 Process cooling applications

SECTOR	APPLICATION	TEMPERATURE LEVELS	TYPICAL TECHNOLOGY
Food, beverages, and tobacco	Quick freeze	-45 °C	Vapour compression
Food, beverages, and tobacco	Freezing	-30 °C	Vapour compression
Food, beverages, and tobacco	Cold store	-8 - 3 °C	Vapour compression
Food, beverages, and tobacco	Cooling of products, process streams, and supporting medias	0 – 250 °C	Vapour compression, free cooling
Food, beverages, and tobacco	Drying (humidity control)	-40 – 20 °C	Vapour compression
Food, beverages, and tobacco	Condensation	0 – 200 °C	Vapour compression, free cooling
Food, beverages, and tobacco	Vacuum systems (condensable parts)	-50 – 40 °C	Vapour compression, free cooling. Ejector
Iron and steel	Controlled cooling	100 – 800 °C	Free cooling
Textile and leather	Cooling after wash	30 – 70 °C	Vapour compression, free cooling
Paper, pulp, and printing	Drying (humidity control)	-40 – 25 °C	Vapour compression
Chemical and petrochemical	Cooling of products, process streams, and supporting medias	-40 – 1000 °C	Vapour compression, free cooling. Ejector
Plastic moulding	Hydraulic cooling, mould tempering	-5 – 90 °C	Vapour compression, free cooling

Data centre	Electronic	10 – 35 °C	Vapour compression, free cooling
Fishery	Storage of fresh fish	-25 - 0 °C	Vapour compression
Agriculture	AC and product cooling	0 - 30 °C	Vapour compression, free cooling

1.3.1. Process cooling technologies

Regarding PC there are numerous different setups of the main system configurations and they are not easy to group into unambiguous categories. The main reason is that there are multiple solutions for each component in the system and these can be assembled in any given configuration, depending on the specific site/need/legislation, etc. Process cooling systems are less standardized in terms of cooling generators than SC systems.

In this section, the main variations of the overall setup and components will be described, all focusing on VC. The different variations to be described are:

- Decentralized vs. centralized systems
- Refrigeration stages
- Evaporators
- Condensers
- Free cooling

Decentralized vs. centralized systems

Process cooling can be produced in decentralized or centralized systems. The capacity of the systems is not decisive, but the general tendency is that the largest systems are centralized and serve several PC applications. Decentralized systems can however also have a high-capacity supplying cooling for a single special process.

Production sites may have a mix of both and in certain cases more than one of both. It is not uncommon to have one or two centralized systems and one or more decentralized systems. Reasons to choose a decentralized system include situations where a single consumer is located too far from the other consumers; a single cooling consumer requires cooling at a different temperature level and an existing centralized system does not have the capacity for more consumers.

Refrigeration stages

When the temperature difference, and hence the pressure difference, between a heat source and sink in a VC system, is large, it can be necessary, or economical, to run a 2-stage cycle where two compressors are set in series. This is the simplest form of a multistage system and there are a high number of variations. The main variations and parameters are described below:

- Systems with multiple compressors, and not equal numbers, on the different stages of a PC system.
- Systems with more than two stages.

- Systems with cooling consumers of both pressure stages in the systems. For example, a simple two stages system where the low-stage compressor is running a cold store or process at -25 °C and using the intermediate pressure as a heat sink. The intermediate pressure is also supplying large amounts of cooling at 2 °C to a cold store or process and the high-stage compressor is removing all this combined cooling load (at -25 °C and 2 °C) to the final heat sink. In this case, the compressor capacity is largest for the high stage since it should cover both loads (at -25 °C and 2 °C), while the low stage compressor should cover load at 2 °C.
- In the different compression stages, the same or different refrigerants can be used. If the same refrigerant is used it is necessary to have an interstage cooling system between the stages, cooling the refrigerant before further compression. The main systems for this are an open cooler, closed cooler, or refrigeration injection, which all have different advantages. When two different refrigerants are used, called a cascade system, no inter-stage cooler is needed.
- Screw compressor systems may add an economizer, which enters the compressor at an economizer port on an intermediate pressure. This increases the efficiency of the overall system. Furthermore, it is possible to add an extra cooling load on the economizer port, which is very efficient. This is a semi-2-stage system on one single compressor.

Evaporators

In the evaporator, the refrigerant receives energy and changes phase and it is here that “cooling” occurs. The refrigerant may be distributed directly to the consumer and the evaporation occurs at the place of the cooling needs. In other systems, a cooling medium, e.g. water or brine, is cooled in the evaporator and is then distributed to the cooling consumer. Both systems are widely used and again it is also possible to have a mix of both. Furthermore, you can have one or both setups at different stages.

Condensers

In the condenser, the refrigerant releases the heat extracted from the processes and changes phase. The refrigerant can release the heat directly to the heat sink, e.g. directly in a dry cooler or evaporative condenser, or indirectly via a cooling medium as water, which then carries the energy to the heat sink. Both systems are widely used [5].

Free cooling in PC

A description of free cooling is to utilize natural heat sinks in the refrigeration system without the need of driving mechanical force, i.e. a cooling device’s compressor. This is for example direct use of outside air, seawater, groundwater, etc. The system will still have an energy consumption for driving pumps and/or fans but is significantly less than the mechanical energy needed.

Free cooling can be, and is, implemented in many ways, but all of them increase the overall efficiency. The main system setups are described below:

- When a cooling medium distributes cooling to the consumers, this cooling medium can be free cooled, or partly free cooled before it enters the evaporator. This can be done in a dry cooler, a cooling tower, seawater, groundwater, etc.
- When direct cooling with the use of a refrigerant is given, it can still be combined with free cooling as indicated above.
- Direct use of outside air is also a form of free cooling.

1.3.2. Examples of process cooling

Process cooling can be also divided in terms of cooling setpoints, temperature profile, and cooling media. These criteria can easily be identified from one industry to another and hence the cooling technology can be identical. Notably, three different real-life examples with a free cooling potential are provided below.

Data centre

Process temperature profile: 35 °C extract air from the server chilled to 24 °C inlets to the server. Cooling of critical equipment as servers, storage, and network equipment.

There are typically large potentials for free cooling in data centres. The most efficient data centres in the world (e.g. a Google datacentre with power usage effectiveness as low as 1.07 i.e. using 7% of the electricity consumption for Information Technology (IT) equipment for cooling, losses in power supply, backup power generators, etc. [22]-[23]) are built with direct and/or indirect free cooling as main cooling technologies (CTs) and a certain number have evaporative cooling as back up directly mounted in the AHU. This is typically seen for the newer hyper-scale data centres. For further backup or, for instance, due to a high-temperature climate zone of the location, alternative cooling technologies (CTs) can be present, most likely in the form of VC.

In older and more typical data centres the cooling system is evolved around a VC unit. The main reasons for this are that these data centres operate at a lower set point for the supply air due to older design specifications for the IT equipment requiring lower operating temperatures, inefficient air flows, and mixing of hot and cold air. As for all PC applications, numerous different cooling system setups exist – however, below a typical solution has been indicated.

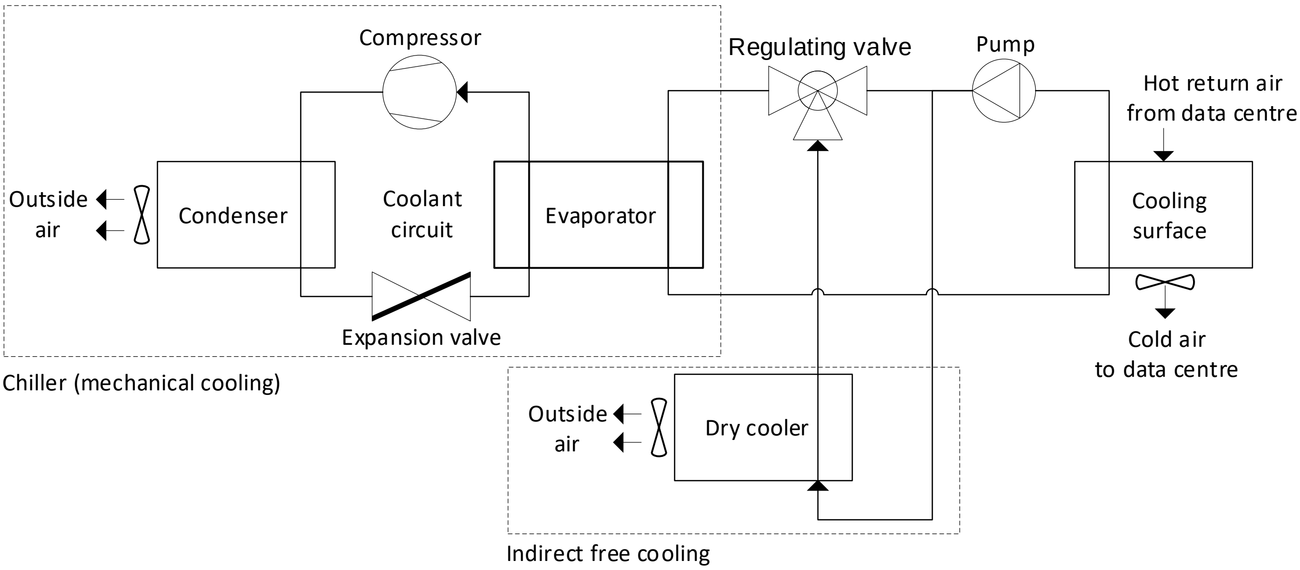

Figure 14 A chiller cools water, used as heat transfer media, which are distributed to units in the data centres where the air is chilled and sent to the IT equipment. In this setup, a dry cooler is added to the water circuit to provide free cooling.

The cooling system setup shown in Figure 14 can run with partial free cooling, meaning that the dry cooler lowers the water temperature as much as possible, and if the setpoint is not met, the chiller handles the rest. Depending on the operating set points and climate zone, the possibility for partial free cooling can increase the EFLHs on the dry cooler by up to 2000 hours. This is calculated by comparing the needed temperature of the cold air delivered to the servers and storage equipment with the number of hours where the outdoor temperature is below the needed temperature for a particular location taking into account the temperature difference in the dry cooler. Direct free cooling is also possible, however, humidity requirements need also to be considered and if dehumidification or humidification is necessary [22]-[23].

Dairy

Process cooling temperature profile: 8 °C water chilled to 0 °C. Cooling of raw milk, after pasteurization, storage, etc.

The use of ice (0 °C water) as heat transfer media is widely used in PC. In this example, we are focusing on a dairy, but the CT could be identical at other productions with the same temperature requirement. Dairies vary greatly in size and product types across Europe and this case is relevant to most medium-sized sites and larger.

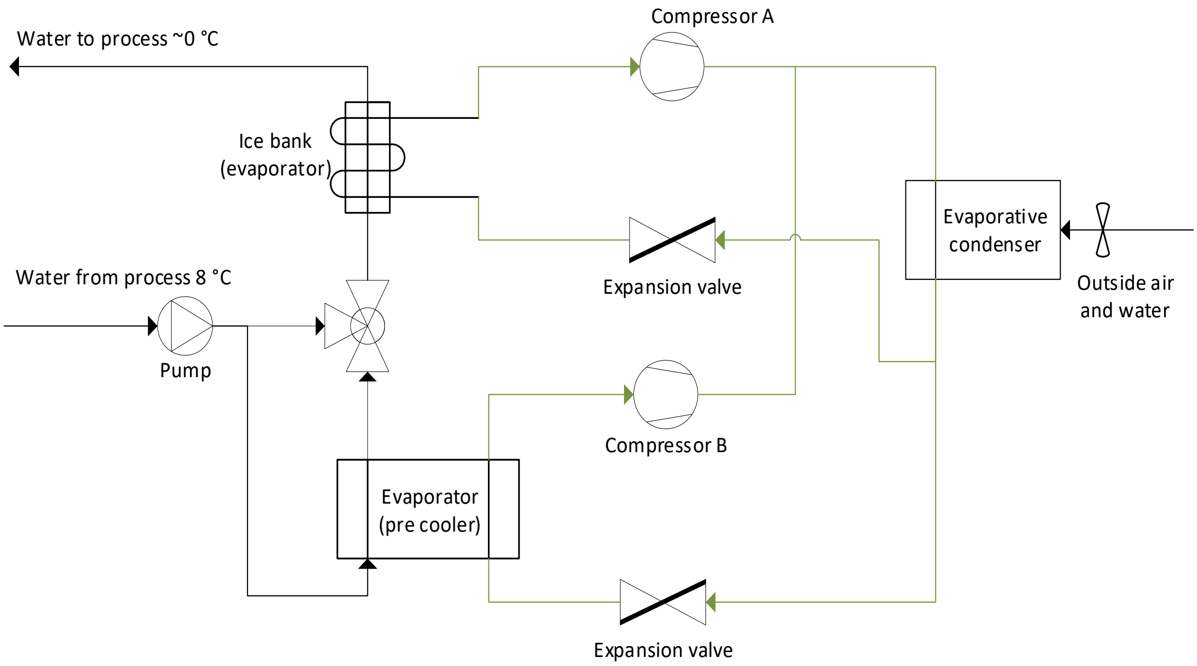

Figure 15 Cooling setup that chills water from 8 to 0 °C. The pre-cooler is important for energy efficiency and the ice bank is typical for dairies and lowers the necessary installed cooling capacity

At several production sites, the cooling setup would be even simpler without the pre-cooler, but the pre-cooler increases the overall system Seasonal energy performance ratio (SEPR) significantly.

The cooling setup can be even more optimized by adding a free cooling unit before the pre-cooler. By doing this the water from the process will firstly be free cooled, then precooled, and in the end, go through the ice bank. The EFLHs on the free cooling unit will mainly depend on the climate zone, the temperature of return water, and the distribution of operating hours over the year.

Plastic moulding

Process cooling temperature profile: 20 °C water chilled to 15 °C. Cooling of plastic in the molds, where cooling time and profile are critical parameters. The moulding process emits large amounts of heat to the factory floor, where the plastic moulding takes place, and often it is necessary to cool it to keep a satisfactory working environment. Therefore, cooling is also used for SC.

At PC all temperatures and temperature profiles are seen, but a 5 K temperature profile and supply temperature of 15 °C is not unusual. In this example, we are looking at the PC of production using plastic moulding. In the actual production, different temperatures are needed at individual moulding machines, hence a shunt unit for mixing cold and hot streams is present at every consumer to ensure the correct temperature.

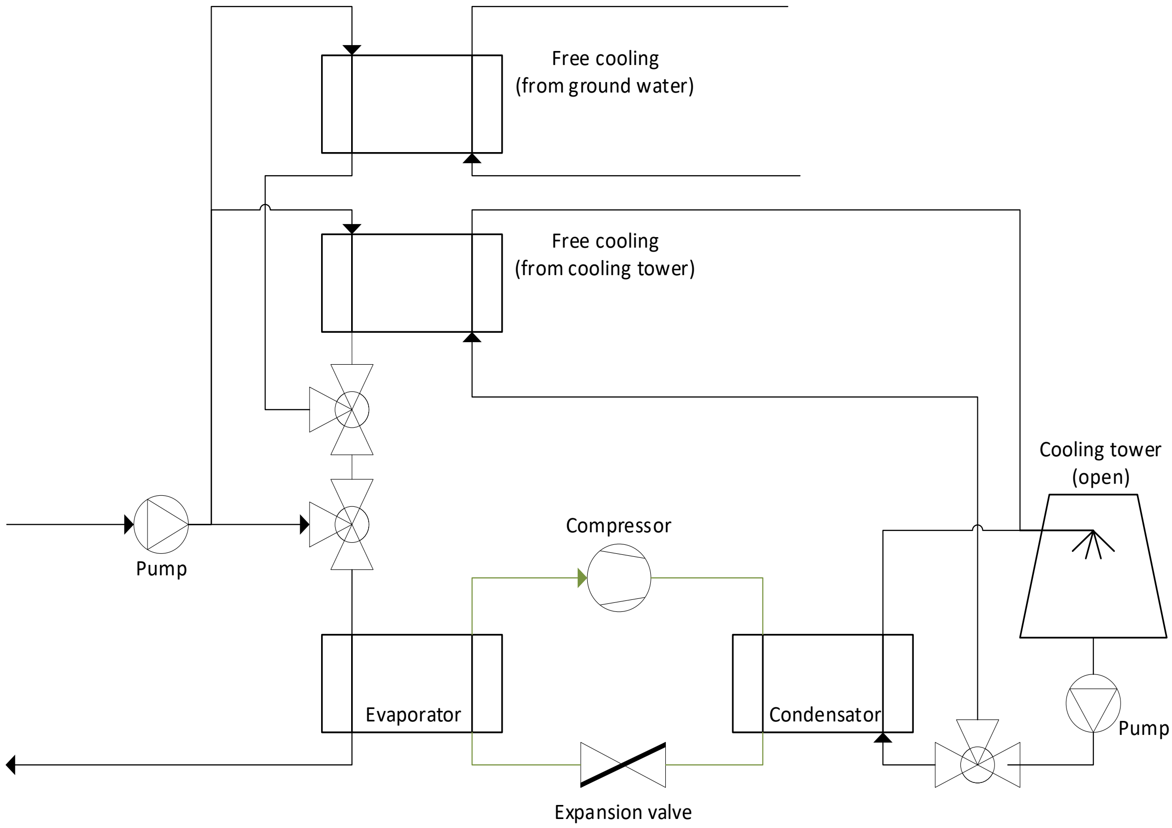

Figure 16 Cooling setup that chills water from 20 to 15 °C. The basic system of operation is without the two free cooling heat exchangers.

In some cases, the cooling setup would be even simpler by not including the free cooling heat exchangers: However, the presence of the latter significantly increases the overall SEPR system.

In this system, two different types of free cooling are shown, one with groundwater and one with the wet cooling tower. A reason for having two systems is that there are capacity limits of the groundwater cooling making it impossible to support the full need for PC for the specific production. With the temperature set point and the climate zone, the EFLHs are highest for the groundwater system.

1.4. District cooling

District cooling refers to the distribution of cold thermal energy in the form of chilled liquids, from central or decentralised sources of production to a network and multiple buildings or sites, for the use of SC and/or PC [24].

District cooling systems consist of three primary components [25]:

- The central plants, where the chilled water is produced by one or more of the followings technologies: absorption refrigeration machines, electric-driven compression equipment, sea and/or ground water-free cooling, gas/steam turbine or engine-driven compression equipment as well as the combination of mechanically driven systems and thermal energy-driven absorption systems.

- The distribution network, where the chilled water is conveyed. The chilled water piping usually consists of uninsulated or pre-insulated directly buried systems. A wide variety of materials is used for DC distribution piping systems and jackets on insulated systems, including steel, copper, ductile iron, polyethylene, polyvinyl chloride, or fiberglass-reinforced plastic. Because the initial cost is high, the piping is the most expensive portion of the configuration of a DC system, and therefore it is important to maximize the use of the distribution-piping network.
- The consumer system or customer's interconnection, which includes all of the in-building equipment. The chilled water may be used directly by the building systems or indirectly by a water-to-water heat exchanger. In general, a substation (a water-to-water heat exchanger and cooling energy accounting system) is installed for each site/customer.

The following figure shows the configuration of a DC system (Figure 17).

Figure 17 District cooling network piping distribution of Climespace, the largest district cooling network in Europe, located in the city of Paris [26]

To cover the capital investment and the thermal loss of the piping distribution, the DC systems are best used in markets where the thermal load density is high.

For the same reason, the DC systems are also best used when the cooling EFLHs are high (each MW of cooling capacity installed should lead to the largest cooling energy supply in MWh). This favours the connection of process cooling or large tertiary building sites with long summer and/or cooling need periods.

It can be said that the successful performance of the DC systems depends on the selection of the three key components (see above), and also how they interact with each other. As such, the compatibility of the different characteristics of one component with the other components plays a crucial role. In addition, as the generation of cooling is separated in time from its use, the combination of thermal energy storage may be needed. Common Thermal Energy Storage (TES) technologies for district cooling system (DCS) applications are [25]:

- Ice TES: thermal storage system, used for chilling processes or for comfort cooling that uses the phase change of ice to water. Ice is formed during periods of low refrigerating demand and delivers cooling by fusion during periods of high-refrigerated demand.

- Chilled water TES: chilled water (CHW) is produced and stored in a tank during periods of low refrigerating demand. Then during periods of high-refrigeration demand, the chilled water delivers its cooling in the DCS.
- Aqueous low-temperature fluid: low-temperature fluid is produced and stored in a tank during periods of low refrigeration demand. Then during periods of intense refrigeration demand, the low-temperature fluid delivers its cooling in the DCS. The principle is the same as the chilled water, except that the medium is a fluid that can operate at inferior temperatures than chilled water.

The characteristics of different TES systems described above are summarized in Table 3.

Table 3 Characteristics of three main thermal energy storage in district cooling systems [25]

CHARACTERISTICS	ICE TES	CHW TES	AQUEOUS LOW TEMP. FLUID TES
Cooling storage density (kJ/kg)	335	4.19	≈4.19
Typical TES specific volume (m^3/kWh)	0.02 to 0.03	0.09 to 0.14	0.06 to 0.09
Discharge temp. from TES (°C)	1 to 7	4 to 6	-1 to 2
Recharge temp. to TES (°C)	-8 to -2	4 to 6	-1 to 2
Recharge chiller plant power (kW electricity in/kW thermal out)	0.23 to 0.31	0.17 to 0.2	0.2 to 0.23

The implementation of a DCS, in general, is most effective in the case of high-density thermal load, which may be the case even in cold climates, within an area of high cooling demand.

1.5. Energy efficiency metrics of state-of-the-art cooling systems

1.5.1. Energy efficiency of electric vapour compression cooling generators

The energy efficiency ratio (EER) can be used to compare the performance of different cooling generators. In the case of an electric VC cooling generator, the EER is calculated as follows (Eq.) 1:

$$EER = \frac{Qcool}{Pelec} \qquad \text{(Eq.) 1}$$

Where:

- Qcool is the cooling capacity of the unit, in kW
- Pelec is the electric power input consumed by the unit, in kW

Both the cooling capacity generated and the electric power consumed by the cooling generator depend on refrigerant condensing and evaporating temperatures.

The Carnot energy efficiency ratio is the energy efficiency ratio defined for a Carnot ideal cooling cycle. This type of cycle is only theoretical but is often used as a reference efficiency. It is built on the hypothesis that the cycle can exchange heat with an ideal heat source and sink whose temperatures remain constant, and on reversible and adiabatic transformations at compression and expansion. The Carnot efficiency in cooling mode can be computed as follows:

$$EER = \frac{Tc}{Th - Tc} \qquad \text{(Eq.) 2}$$

Where:

- Tc is the heat source temperature of the cooling generator in K
- Th is the heat sink temperature of the cooling generator in K

The ratio between the EER of a specific cooling generator and the reference Carnot efficiency for the same source and sink temperatures allows the comparison of the efficiency of different cooling generators without the bias of the differences in source temperatures. This ratio is particularly useful when trying to compare the efficiency of different cooling generators that have been tested at different source temperature conditions [20]; it is called hereafter second law efficiency and is used for the screening of the efficiency of alternative cooling technologies (section 2.1). Note that if Th < Tc, the Carnot cycle cannot be defined. The reference efficiency would theoretically be infinite as the heat flow would naturally flow from the heat source to the heat sink in that case.

EER in standard rating conditions

In real cooling generators, the heat source and sink temperatures vary while exchanging heat at the evaporator and condenser respectively. This is even the main goal of a cooling generator to decrease the temperature of the external fluid at the evaporator. As both the EER and the cooling capacity of VC cycles depend on the average temperature level of the external fluids at the condenser and the evaporator, standard testing conditions are thus used to allow meaningful comparisons.

In Europe, to get comparable EER values, standard rating conditions, as well as testing and accounting methods, are defined in the standard [27], which are reported in Table 4. These temperature levels of external fluids, which are typical of sizing practice (which defines situations with lowest unit capacity and maximal cooling demand), are used to define maximum cooling generator capacity and efficiency in these conditions.

Thermal capacities and electric power consumption are corrected in order EER values may be comparable between different unit configurations (the method is defined in the EN14511 standard [27]):

- Ducted units: for refrigerant-to-air heat exchangers, either located outdoor or indoor, a correction is made not to account for fan power consumption required to distribute the air in distribution ducts. Indeed, some units are ducted - it means that either on the indoor or outdoor side or at both sides, their fan is capable of delivering a high static pressure, and consequently, these units are characterized by larger power consumption. For these units, part of the fan power consumption is deducted using standard fan efficiency; only the consumption necessary to cope with refrigerant-to-air or air-to-refrigerant pressure losses are included. The cooling capacity is also increased for the same quantity. With these corrections, EER values of ducted and non-ducted units are comparable.
- Water-cooled units and chiller: if a pump is integrated into the unit, the same correction as for ducted units is operated; in case there is no pump, the pumping power consumption required to cope with water-to-refrigerant and refrigerant-to-water heat

exchanger are computed and added to the power consumption and the cooling capacity is corrected of this quantity in case of chiller (refrigerant-to-water indoor side heat exchanger).

Table 4 Temperature levels according to the different heat exchanger fluids and applications [20]

FLUIDS	APPLICATION	OUTDOOR HEAT EXCHANGER		INDOOR HEAT EXCHANGER	
Air-to-air		Inlet temp. °C dry bulb	Inlet temp. °C wet bulb	Inlet temp. °C dry bulb	Inlet temp. °C wet bulb
	Comfort (outdoor air / recycled air) (e.g. window, double duct, split units)	35	24	27	19
	Single duct	35	24	35	24
Air-to-water		Inlet temp. °C dry bulb	Inlet temp. °C wet bulb	Inlet temp. °C	Outlet temp. °C
	Fan coil application	35		12	7
	High-temperature cooling application (floor and ceiling panels)	35		23	18
Water-to-air and brine-to-air		Inlet temp. °C	Outlet temp. °C	Inlet temp. °C dry bulb	Inlet temp. °C wet bulb
	Cooling tower application	30	35	27	19
	Ground coupled (water or brine)	10	15	27	19
Water-to-water		Inlet temp. °C	Outlet temp. °C	Inlet temp. °C	Outlet temp. °C
	Fan coil application	30	35	12	7
	High-temperature cooling application (floor and ceiling panels)	30	35	23	18

The evaporating temperature of cooling generators is maintained at a relatively low level to allow dehumidification, with typical values in the range of 10 to 12 °C for split air-conditioners [20]. In addition, it is worth mention that the second law efficiency (noted as Φ) of VC cooling generators in cooling mode is afterward used as an efficiency criteria to select potentially more efficient alternative cooling technologies.

Application for air-conditioners:

- EER in standard rating conditions: 2.5 to 6.5
- Carnot reference efficiency noted as EER_C = (273+10)/(35-10)= 11.3
- Φ thus lies between 22% and 57%

Application for water-to-water chillers:

- EER in standard rating conditions: 3 to 6.5
- Carnot reference efficiency noted as EER_C = (273+7)/(30-7)= 12.2

- Φ thus lies between 24% and 53%

For comparison with other cooling technologies, the Φ value for ACs includes all auxiliary power (such as fans and controls), and that the possibility to supply dehumidification is considered. For water-to-water chillers, auxiliary power for fans and pumps is not included, but chilled water temperature level also allows dehumidification.

If the EER of the most efficient air-conditioners has been increased up to 6.5 by increasing the indoor airflow rate and so with a reduction of the capacity to dehumidify, the evaporating temperature could be higher. For 12 °C instead of 10 °C evaporating temperature, the reference Carnot EER would be 12.3 and Φ would be 53 %.

Given the uncertainties in estimating these figures because of the lack of detailed data, we only use hereafter an approximate Φ range of 25 % to 55 % for VC given comparison with alternative cooling technologies.

Minimum and maximum EER values for SC generators are given in Table 5.

Table 5 Minimum and maximum EER in standard rating conditions for space cooling air-to-air air conditioners (ECC, 2020) [28]

SPACE COOLING ELECTRIC VAPOUR COMPRESSION GENERATOR TYPE	Min. EER (ECC 2020)	Max. EER (ECC 2020)
Split <6kW	2.6	6.5
Split >=6kW and <=12kW	2.6	5.3
VRF, Split>12kW	1.7	6
Rooftop air-conditioners	2.4	5.1
Chiller (A/W) <400kW	1.9	3.9
Chiller (A/W) >=400kW	1.9	4.1
Chiller (W/W) <400kW	2.8	6.1
Chiller (W/W) >400kW	4	6.3

The distribution of the EER for air-to-air air-conditioners has been calculated based on the data of ECC 2020 [28] and is summarized in Table 5. It is important to notice that these data are not sales-weighted average data but give distributions of the number of models offered by manufacturers for each efficiency segment. Sales weighted average EER values are typically lower than model weighted average values. Median EER values based on several models have proven to be closer to sales-weighted average values, even if still higher [29].

Table 6 EER distribution of space cooling generators based on technologies and applications in standard conditions from ECC 2020

TECHNOLOGIES	EER VALUES										MEDIAN	TOT UNITS
	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	4-4.5	4.5-5	5-5.5	5.5-6	6-6.5		
Roof-top		0.86%	22.43%	69.69%	5.14%	1.03%	0.68%	0.17%			3.1	584
VRF, Split >12kW	0.30%	4.16%	16.90%	36.57%	27.39%	10.49%	1.87%	1.16%	0.94%	0.22%	3.4	2669
AC <6kW			7.98%	40.67%	28.48%	14.21%	5.62%	2.25%	0.51%	0.28%	3.5	1787
AC >=6kW and <12kW			20.73%	48.91%	22.13%	7.22%	0.85%	0.16%			3.3	1288
A/W<400kW	0.16%	4.60%	60.79%	34.05%	0.39%						2.9	11470
A/W>=400kW	0.06%	1.17%	45.90%	51.44%	1.38%	0.04%					3	9607
W/W<400kW			0.08%	1.27%	4.13%	30.56%	53.92%	8.46%	1.23%	0.37%	4.7	2448
W/W>400kW						11.68%	21.16%	39.38%	18.47%	9.31%	5.2	2826

SEER for space cooling

Condensing and evaporating temperatures vary in time during the cooling season. On the condenser side, this is mainly due to the heat sink temperature variation. However, when the heat to be rejected is lower, the condensing temperature also decreases. The magnitude of the variation depends on the heat rejection system and cooling generator designs and controls. On the evaporator side, the indoor cooling temperature set point is considered constant. However, when the heat to be extracted decreases, the evaporating temperature may increase. For chillers, the chilled water temperature regime may also vary with the heat to be extracted and with the type of control of the pump (constant or variable speed control).

To take into account these variations of temperatures and required capacity, seasonal performance metrics have been defined for SC in the Regulations (EU) 626/2011 [30], (EU) 206/2012 [31] for air-conditioners with capacities below 12 kW and in Regulation (EU) 2281/2016 [32] for larger air-conditioners, rooftops, and chillers.

A typical building heat load profile (a linear – in that case – the relationship between outdoor air temperature and building cooling need, cooling need equals cooling capacity to be supplied) is defined. Typical fluid temperatures (air and water depending on cooling system configuration) at evaporator and condenser are estimated along that load curve. The EER of the machine is tested for four points along this load curve and interpolated at 1 °C temperature intervals (also called temperature bins) between the test points. Air/water temperature at condenser side and load ratio (ratio of the cooling need at reduced outdoor air temperature to the maximum cooling need/cooling capacity in design conditions) conditions for the four tests are shown in Table 7. The EN14825 standard [33] also defines temperature profiles for dry cooler outdoor heat exchanger (inlet water temperature levels of 50, 45, 40, and 35 °C respectively for A, B, C, and D test points, and ground-coupled application (the specific application, aquifer, ground heat exchanger type is not given; a constant inlet water/brine temperature of 10 °C is used), but these conditions are presently not used in EU regulations.

Table 7 Test conditions for SEER calculation in Regulations (EU) 626/2011 [30], (EU) 206/2012 [31] and in Regulation (EU) 2281/2016 [32]

	Load ratio in %	Outdoor heat exchanger, refrigerant-to-air inlet air temp. in °C	Outdoor heat exchanger, refrigerant-to-water (cooling tower) inlet water temp. in °C
A	100%	35	30
B	74%	30	26
C	47%	25	22
D	21%	20	18

For an average EU climate, the occurrence of each outdoor temperature condition is computed by 1 °C temperature bin and a weighted average efficiency over the cooling season is computed as the ratio of the whole cooling energy supplied divided by the total electricity consumption input to the SC cooling generator during the same period. See (Eq.) 3 below.

$$SEERon = \frac{\sum_j \ h_j \times P_C(T_j)}{\sum_j \ h_j \times \frac{P_C(T_j)}{EER(T_j)}} \qquad \text{(Eq.) 3}$$

Where:

- Tj = the bin temperature
- j = the bin number, with j {1,2,… n} n the amount of bins
- PC(Tj) = the cooling capacity to be supplied for the corresponding temperature Tj
- hj = the number of bin hours occurring at the corresponding temperature Tj
- EER(Tj) = the EER value of the unit for the corresponding temperature Tj

The $SEER_{on}$ value is then corrected to account for the auxiliary power modes, which correspond to electricity consumption when the compressor of the unit is off, to reach the final SEER value (Eq.) 4.

$$SEER = \frac{Q_C}{\frac{Q_C}{SEER_{on}} + APM} \qquad \text{(Eq.) 4}$$

Where:

- Q_C = The reference annual cooling need, expressed in kWh
- APM = the annual final energy consumption of auxiliary power modes (standby, off mode, thermostat-off, and crankcase heater), expressed in kWh

The reference annual cooling need is computed – see (Eq.) 5 - as the product of the capacity of the cooling generator in standard rating conditions ($P_{designc}$) and an equivalent number of full load hours (H_{CE}) to estimate the total cooling energy supplied by the unit over the cooling season. H_{CE} is supposed to be equal to 350 hours for less than 12 kW air-conditioners, which are mostly residential units, and 600 hours for more than 12 kW air-conditioners and chillers.

$$Q_C = P_{designc} \times H_{CE} \qquad \text{(Eq.) 5}$$

Minimum and maximum Seasonal energy efficiency ratio (SEER) values for SC generators are given in Table 8. These SEER values are in general higher than EER values in standard rating conditions.

Table 8 Performance of space cooling generators based on technologies and applications: MEPS (Minimum Energy Performance Standard) in the Ecodesign context is the minimum energy efficiency requirement for a product to be put on the EU market [34].

SPACE COOLING ELECTRIC VAPOUR COMPRESSION GENERATOR TYPE	MIN SEER	MAX SEER	MAX SEER (ECC 2020) [28]
Split <6kW	4.6 (Ecodesign MEPS 2014)	8.5 (Ecodesign benchmark 2012)	10.6
Split >=6kW and <12kW	4.3 (Ecodesign MEPS 2014)	8.5 (Ecodesign benchmark 2012)	9.4
Split, VRF >= 12kW	4.6 (Ecodesign MEPS 2018)	6.5 (Ecodesign benchmark 2016)	10.1
Rooftop air-conditioner	3 (Ecodesign MEPS 2018)	6.5 (Ecodesign benchmark 2016)	6.5
Chiller (A/W) <400kW	3.8 (Ecodesign MEPS 2018)	5.3 (Ecodesign benchmark 2016)	7.2
Chiller (A/W) >400kW	4.1 (Ecodesign MEPS 2018)	5.7 (Ecodesign benchmark 2016)	7.2
Chiller (W/W) <400kW	5.1 (Ecodesign MEPS 2018)	7.0 (Ecodesign benchmark 2016)	9
Chiller (W/W) >=400kW and <1500kW	5.9 (Ecodesign MEPS 2018)	9.0 (Ecodesign benchmark 2016)	9.8
Chiller (W/W) >=1500kW and <=2000kW	6.3 (Ecodesign MEPS 2018)	9.0 (Ecodesign benchmark 2016)	9.8

The distribution of the SEER has been calculated based on the data of the ECC 2020 and is summarized in Table 9. It is important to notice that these data are not sales-weighted average data but give distributions of the number of models offered by manufacturers for each efficiency segment. Sales weighted average SEER values are typically lower than model weighted average values. Median SEER values based on numbers of models have proved to be closer to sales-weighted average values, even if still higher (by 5 to 10 % for instance in the case of less than 12 kW split air conditioners for the year 2016 [17]).

Table 9 Performance partition of space cooling generators based on technologies and applications from ECC 2020 (SEER)

TECHNOLOGIES	SEER								MEDIAN	TOT UNITS
	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11		
Rooftop	54.97%	38.36%	5.82%	0.86%					3.9	606
VRF, Splits >=12kW		3.71%	36.75%	36.87%	15.38%	6.01%	1.26%	0.03%	6.2	3170
AC <6kW		0.73%	21.64%	50.42%	15.85%	9.44%	1.46%	0.45%	6.6	1779
AC >=6kW and <12kW		2.27%	30.56%	56.73%	9.36%	1.02%	0.07%		6.1	1368
A/W <400 kW	33.69%	62.91%	3.13%	0.24%	0.03%				4.1	9324
A/W >=400kW		80.06%	19.38%	0.54%	0.01%				4.4	7192
W/W<400kW			73.19%	23.04%	2.59%	1,17%			5.7	1966
W/W >=400 kW and <1500			12.20%	53.44%	16.67%	11.65%	6.04%		6.5	1656
W/W >=1500kW				25.19%	23.28%	43.13%	8.40%		8.1	262

Then, two important precautions have to be taken when using SEER values, see the following.

Standard and real-life conditions

The present Ecodesign regulations for SC generators only establish SEER for the following cooling generator configurations (see Table 4 for corresponding design temperature conditions):

- air-to-air, comfort conditions.
- air-to-water, fan coil application;
- water-to-water, cooling tower conditions at the outdoor heat exchanger and fan coil application.

So even if a water-to-water chiller rejects heat to a groundwater source resulting in a lower average condensing temperature than with a cooling tower and so with possibly better seasonal performance efficiency, this is not considered in the Regulation 2016/2281 [32].

In addition, using a SEER with an average climate aims at comparing cooling generators on a better basis than with a single point in standard conditions, and this helps to promote efficient units operating better in part-load conditions, operating conditions that are largely dominant for SC application. However, real-life seasonal efficiency may significantly differ, depending on climate, system, controls, and building load profile.

Comparison of SEER values of different space cooling generator types

When trying to compare the SEER of different cooling generator types, above the possible differences in temperature conditions, it should be taken care regarding the boundary conditions.

What is of real interest to a building designer is the performance of the complete cooling system. But the SEER metrics are limited to the cooling generator. Please note that, as the SEER is a weighted average of measured EER values, the pressure loss corrections regarding ducted units and water-based units also apply.

In a typical water-cooled chiller based cooling system, it would be necessary to consider, in addition to the cooling generator electricity consumption, the final energy consumption of the heat rejection system (e.g. cooling tower fan), of the heat rejection system pump (except for the part already included in standard EER measurement), and for the distribution side of the consumption of the chilled water distribution pump (except the part already included in standard EER measurement) and of the terminal units (e.g. fan coils). But the SEER of a water-to-water chiller is a metric for the cooling generator alone. On the contrary, for a non-ducted split system air-conditioner, the SEER metrics include all energy-consuming components of the system.

This difference is partly corrected in Regulation (EU) 2281/2016 [38] as the SEER is translated to primary energy efficiency, noted seasonal SC energy efficiency ($\eta_{S,C}$), and computed following (Eq.) 6 below:

$$\eta_{S,C} = \frac{SEER}{CC} - F(1) - F(2) \qquad \text{(Eq.) 6}$$

Where:

- CC = the conversion coefficient

- F(1) = 0,03. It is a correction that accounts for a negative contribution to the seasonal energy efficiency ratio due to adjusted contributions of temperature controls and applies to all space cooling generators
- F(2) = 0,05. It accounts for the consumption of the pumps of water-cooled systems.

SEPR for process cooling

For process cooling and refrigeration, the heat load is much less dependent on outdoor temperature than for SC. Consequently, the second set of conditions has been defined for evaluating the seasonal performance of process cooling and refrigeration equipment (in Regulations (EU) 1095/2015 [35] and 2281/2016 [32]). An average EU climate is used (Strasbourg climate). The load is highest at 35 °C and above (and matches the standard rating capacity of the unit). It is 80 % of this value at 5 °C and below and evolves linearly between 80 % and 100 % in between. As in the case of the SEER, four test points are defined and shown in Table 10 below:

Table 10 Test conditions for SEPR HT calculation in Regulation (EU) 2281/2016 [32]

	Load ratio in %	Outdoor heat exchanger, refrigerant-to-air inlet temp. in °C	Outdoor heat exchanger, refrigerant-to-water (cooling tower) inlet temp. in °C
A	100 %	35	30
B	93 %	25	23
C	87 %	15	16
D	80 %	5	9

In what follows, only the efficiency of process cooling is discussed as refrigeration has been excluded from the scope of this study.

The process cooling chillers' standard chilled water temperature level is defined in Regulation (EU) 2281/2016 [32] (chilled water temperature regime of 7/12). The metric is named seasonal energy performance ratio (SEPR). Final energy consumption corresponding to auxiliary power modes is not considered and the SEPR is computed as the SEERon in (Eq.) 3.

The reference process cooling (PC) SEPR values are presented in Table 11.

Table 11 Performance of cooling system based on technologies and applications [30]

PROCESS COOLING ELECTRIC VAPOUR COMPRESSION GENERATOR TYPE	Min. SEPR	Max. SEPR	Max. SEPR (ECC 2020) [28]
Chillers (A/W) <400kW	4.5 (Ecodesign MEPS 2018)	8 (Ecodesign benchmark 2016)	7
Chillers (A/W) >400kW	5 (Ecodesign MEPS 2018)	8 (Ecodesign benchmark 2016)	7.4
Chillers (W/W) <400kW	6.5 (Ecodesign MEPS 2018)	8.5 (< 200 kW) 12.5 (≥ 200 kW) (Ecodesign benchmark 2016)	11.6
Chillers (W/W) >=400kW and <=1000kW	7.5 (Ecodesign MEPS 2018)	12.5 (Ecodesign benchmark 2016)	12
Chillers (W/W) >=1500kW	8 (Ecodesign MEPS 2018)	13 (Ecodesign benchmark 2016)	11.7

The distribution of the SEPR for the high-temperature process has been calculated based on the data of the ECC 2020 and is summarized in Table 12 below.

Table 12 Performance partition of process cooling generators based on technologies and applications from ECC 2020

TECHNOLOGIES	SEPR HT									MEDIAN	TOT UNITS
	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13		
A/W <400 kW	17.14%	75.46%	7.40%							5.3	3244
A/W >=400 kW		62.82%	27.40%	9.78%						5.7	1248
W/W<400 kW			46.74%	49.30%	1.16%	0.93%		1.86%		7	430
W/W >=400 kW and <1500 kW				40.74%	13.83%	16.79%	2.96%	24.69%	0.99%	8.2	405
W/W >=1500 kW				4.88%	6.10%	3.66%	1.22%	84.15%		11.3	164

As in the case of the SEER, real-life SEPR values may differ importantly because of climate, load, heat rejection, and chilled water temperatures. The main merit of the SEPR figure is to allow the comparison of the performances on a more representative basis than by using the standard rating conditions EER.

Energy efficiency of absorption cooling generators

The European standard EN12309 [36] describes the calculation of the seasonal performance of gas-fired sorption chillers with a cooling capacity below 70 kW.

As the unit consumes gas and electricity, the seasonal performance is defined by two indicators the SGUE (Seasonal gas utilization efficiency) and the SAEF (Seasonal auxiliary energy factor).

The method for testing and rating is inherited from the EN14825 standard for VC [41].

The calculation of the reference Seasonal Gas Utilization Efficiency ratio in cooling mode (SGUEc) is given by the (Eq.) 7:

$$SGUEc = \frac{\sum_j \ h_j \times Fon \times P_c(T_j)}{\sum_j \ h_j \ \times Fon \times \frac{P_C(T_j)}{GUEc(T_j)}} \qquad \text{(Eq.) 7}$$

Where:

- T_j = the bin temperature
- j = the bin number, with j {1,2,… n} n the amount of bins
- $P_C(T_j)$ = the cooling capacity to be supplied for the corresponding temperature T_j
- h_j = the number of bin hours occurring at the corresponding temperature T_j
- Fon = the fraction of the bin hours during which the appliance is active
- $GUEc(T_j)$ = the GUE value of the unit for the corresponding temperature T_j

The calculation of the reference Seasonal Auxiliary Energy Factor in cooling mode (SAEFc) is the ratio of the reference annual cooling demand divided by the annual electricity consumption.

$$SAEFc = \frac{Q_{refC}}{\frac{Q_{refC}}{SAEFc_{on}} + HTO * Pto + Hsb * Psb + Hoff * Poff} \qquad \text{(Eq.) 8}$$

Where:

- Q_{refC} = The reference annual cooling demand, expressed in kWh
- $SAEFc_{on}$= The Seasonal Auxiliary Energy Factor in cooling mode and active mode
- HTO, HSB, HOFF are the number of hours the appliance is considered to work in respective thermostat off mode, standby mode, and off mode.
- PTO, PSB, POFF are the electrical power consumed during respective thermostat off mode, standby mode and off mode hours, expressed in kW. The measurement of PTO, PSB, POFF shall be made according to EN 12309–4:2014.

The reference annual cooling need is computed – see (Eq.) 9 - as the product of the capacity of the cooling generator in standard rating conditions ($P_{designc}$) and an equivalent number of full load hours (H_{CE}) to estimate the total cooling energy supplied by the unit over the cooling season.

$$Q_{refC} = P_{designc} \times H_{CE} \qquad \text{(Eq.) 9}$$

The SAEFcon is calculated as follows:

$$SAEFc = \frac{\sum_j h_j \times Fon \times (T_j)}{\sum_j h_j \times Fon \times \frac{P_C(T_j)}{AEFc(T_j)}} \qquad \text{(Eq.) 10}$$

With:

- AEFc (T_j) the AEFc values of the appliance for the corresponding temperature T_j.

The European standard determined a calculation example for reference SGUEc and SAEFc in an annex that is presented below for a machine with a cooling capacity of 15 kW, which leads to an SGUEc of 0.74 and to a SAEFc value of 11.6 for an absorption air-to-water chiller whose electric power in standard rating conditions is about 5 % of the cooling capacity.

Table 13 Calculation example of the seasonal performance of a gas-fired sorption chiller in cooling mode

	Outdoor air temperature	Part load ratio	Indoor heat exchanger outlet water temperature	Cooling load	GUEC	AEFC
	°C	%	°C	kW	kW/kW	kW/kW
A	35	100	7	15	0.78	18.6
B	30	74	8.5	11.1	0.76	16.4
C	25	47	10	7.1	0.74	13.2
D	20	21	11.5	3.2	0.71	11.0

Efficiency of internal combustion engine

For chillers and air-conditioners using fuels for an internal combustion engine, the seasonal space cooling energy efficiency $\eta_{s,c}$ is defined in the European standard 16905-5 as:

$$\eta_{S,c} = SPER_c - \sum F(i) \qquad \text{(Eq.) 11}$$

Where:

- SPERc is the seasonal primary energy ratio for cooling
- F(i) is a negative contribution to the seasonal space heating or cooling energy efficiency

The SPERc is estimated by this formula:

$$SPER_c = \frac{1}{\frac{1}{SGUE_c} + \frac{CC}{SAEF_c}} \qquad \text{(Eq.) 12}$$

in which:

$$SGUE_c = \frac{\sum_{j=1}^{n} hj * P_c(T_j)}{\sum_{j=1}^{n} hj * (\frac{P_c(T_j)}{GUE_{c,bin}(T_j)})} \qquad \text{(Eq.) 13}$$

Where:

- T_j = the bin temperature
- j = the bin number, with j {1,2,… n} n the amount of bins
- $P_C(T_j)$ = the cooling capacity to be supplied for the corresponding temperature T_j
- h_j = the number of bin hours occurring at the corresponding temperature T_j
- $GUE_c(T_j)$ = the GUE value of the unit for the corresponding temperature T_j

And the $SAEF_h$ indicator is estimated by this formula:

$$SAEF_h = \frac{Q_{ref,c}}{(\frac{Q_{ref,c}}{SAEF_{c,on}} + (H_{TO} * P_{TO}) + (H_{SB} * P_{SB}) + (H_{CK} * P_{CK}) + (H_{OFF} * P_{OFF}))} \qquad \text{(Eq.) 14}$$

Where:

- $Qref_C$ = The reference annual cooling demand, expressed in kWh
- SAEFcon= is the Seasonal Auxiliary Energy Factor in cooling mode and active mode
- HTO, HSB, HOFF are the number of hours the appliance is considered to work in respective thermostat off mode, standby mode, and off mode.
- PTO, PSB, POFF are the electrical power consumed during respective thermostat off mode, standby mode and off mode hours, expressed in kW. The measurement of PTO, PSB, POFF shall be made according to EN 12309–4:2014.

The reference annual cooling demand is computed – see (Eq.) 15 - as the product of the capacity of the cooling generator in standard rating conditions ($P_{designc}$) and an equivalent number of full load hours (H_{CE}) to estimate the total cooling energy supplied by the unit over the cooling season.

$$Q_{ref,c} = P_{design,c} * H_{CE} \qquad \text{(Eq.) 15}$$

The SAEF con is calculated as follows:

$$SAEF_{c,on} = \frac{\sum_{j=i}^{n} hj * P_c(T_j)}{\sum_{j=i}^{n} hj * (\frac{P_c(T_j)}{AEF_{c,bin}(T_j)})} \qquad \text{(Eq.) 16}$$

Where:

- AEFc, bin (Tj) the AEFc values of the appliance for the corresponding temperature Tj.

Efficiency of district cooling systems

For Europe, an estimate of the characteristics of DC has been carried out by Dittmann et al. 2016 (Horizon 2020 Heat Roadmap Europe 4 - HRE4 - project) [37] based on limited information from network operators.

Efficiency has been modeled using a simple yearly energy balance which accounts for electric-driven VC chillers and free cooling. Other cold generation types have not been considered. System efficiency accounts for a standard SEER of large water-cooled chiller corrected for the impact of free cooling (direct use of cold water for district cooling purpose; indirect use to lower the condensing temperature of water-cooled chillers has not been modelled), of cold losses during distribution and of pumping electricity consumption according to the energy balance scheme in Figure 18.

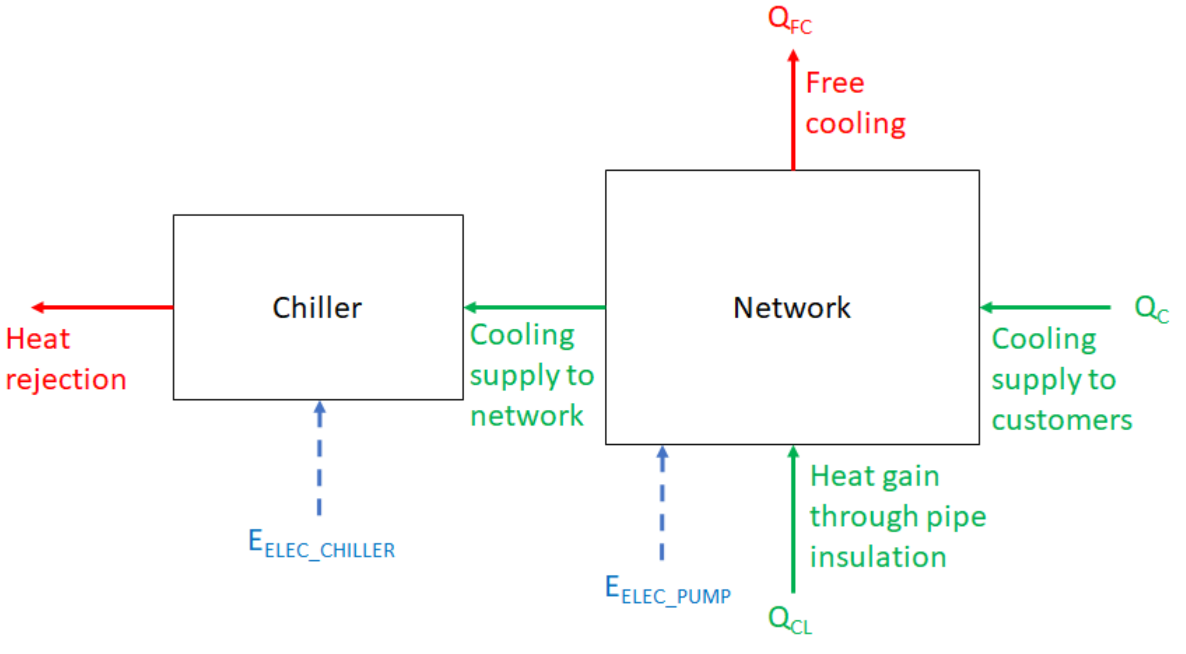

Figure 18 District cooling network functional scheme for SEER computation, adapted from [15] (arrows indicate heat/electricity flows)

The seasonal energy efficiency ratio can then be computed as in (Eq.) 17 (a and b).

$$SEER_{DC} = \frac{Q_C}{\frac{Q_C - Q_{FC} + Q_{CL}}{SEER_{Chillers}} + E_{pump}}$$

(Eq.) 17a

or

$$SEER_{DC} = \frac{1}{\frac{1 - \frac{Q_{FC}}{Q_C} + \frac{Q_{CL}}{Q_C}}{SEER_{Chillers}} + \frac{E_{pump}}{Q_C}}$$

(Eq.) 17b

(Eq.) 17

Where:

- Qc is the cold energy supplied by DC to its customers
- Epump is the required pumping energy
- Q_{FC} is the cold energy supply via free cooling (from river or sea mainly)
- Q_{CL} is the cold loss (heat gain from the environment into the cold pipes during distribution)

The advantage of Eq. 17b is that the terms relative to the cold supply appear so that these can be characterized in some cases for real networks, the ratio of pumping energy ($\frac{E_{pump}}{Q_C}$), ratio of cold supply by free cooling ($\frac{Q_{FC}}{Q_C}$) and ratio of cold losses during distribution ($\frac{Q_{CL}}{Q_C}$).

Parameters and resulting SEER proposed in [37] are indicated in Table 14.

Table 14 Modelled SEER of district cooling in Europe in 2015 [15]

SEER_DC	Cold	Central	Warm
SEERchiller	5.3	5.3	5.3
Free cooling ratio	80%	40%	20%
Network losses ratio	7%	9%	11%
Ratio of pumping energy	5.5%	6.5%	8.0%
SEERglobal	9.4	5.1	4.0

This model was built in the frame of the Heat Roadmap Europe (HRE) H2020 project with a view of modelling the global cooling consumption, including DC, until 2050. In that study, the SEER of chillers was planned to evolve thanks to Ecodesign and other policy measures. The SEER of chillers in DC was thus linked to the stock average value: 5.3 was the estimated SEER of water-to-water based chillers in the EU for the year 2015 in the HRE study [37].

The impact of the climate on chiller efficiency is not taken into account in this simplified model. In real life, the SEER of chillers in DC application is probably higher. As global SEER values are thought to be realistic, the share of free cooling is thus certainly largely overestimated for central and warm climates.

Nevertheless, the data provided in the table above reveal the influence of the cold source availability (seawater is colder in Northern Europe and a larger part of cooling needs can be supplied by free cooling). This approach allowed the projection of district cooling SEER with an increase in chiller SEER and also accounting for a decrease in free cooling potential, due to higher natural source temperatures, and also to the increase of cold losses and of pumping power with the expansion of cooling networks. The results are presented in Table 15.

Table 15 Prospective modelling of SEER of district cooling in Europe until 2050 [15]

	SEER			
Year of operation	2015	2020	2030	2050
Cold Europe	9.4	9.3	9.3	9.2
Temperate Europe	5.1	5.2	5.7	6.2
Warm Europe	4	4.2	4.7	5.3

However, as in section 1.4, the DC systems are also best used when the EFLHs of cooling are high, which depends on the cooling demand shape and consequently on the types of customers connected and on the climate.

In addition, several case studies [25] on DC systems indicated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) have been summarized below in Table 16.

Table 16 Characteristics of several district cooling systems from ASHRAE case studies

APPLICATIONS	BUSINESS BAY EXECUTIVE TOWER	TEXAS MEDICAL CENTER	DISTRICT COOLING SAINT-PAUL
Location	Dubaï, United Arab Emirates	Houston, Texas	Saint-Paul, Minnesota
Year of operation	2009	1969	1993
Number of building	22	43	100
Number of customers	122	18	/
Annual cooling supplied	60 GWh/8 months	≈1000 GWh	118 GWh
Average SEER	3.35	3.95	3.91

The case study of the United Arab Emirates is relevant for the influence of the climate on the operating hours of DC systems (8 months of operation in the year).

The SEER of DC depends on the availability of cold sources and the climate and varies from around 3 to 9.

2. Overview of cooling technologies

A large bibliographical work has been carried out on both cooling technologies mainly existing in the current market and stock of systems as well as possible alternatives. Only the part of this research related to active cooling technologies is presently discussed in the current section.

The following Figure 18 displays a **taxonomy**, according to which a whole list of cooling technologies are categorized by the physical form of energy input, basic working principles, phase of the working fluid, refrigerant/heat transfer medium, specific physical process/device, active/passive solution, and SC/PC application.

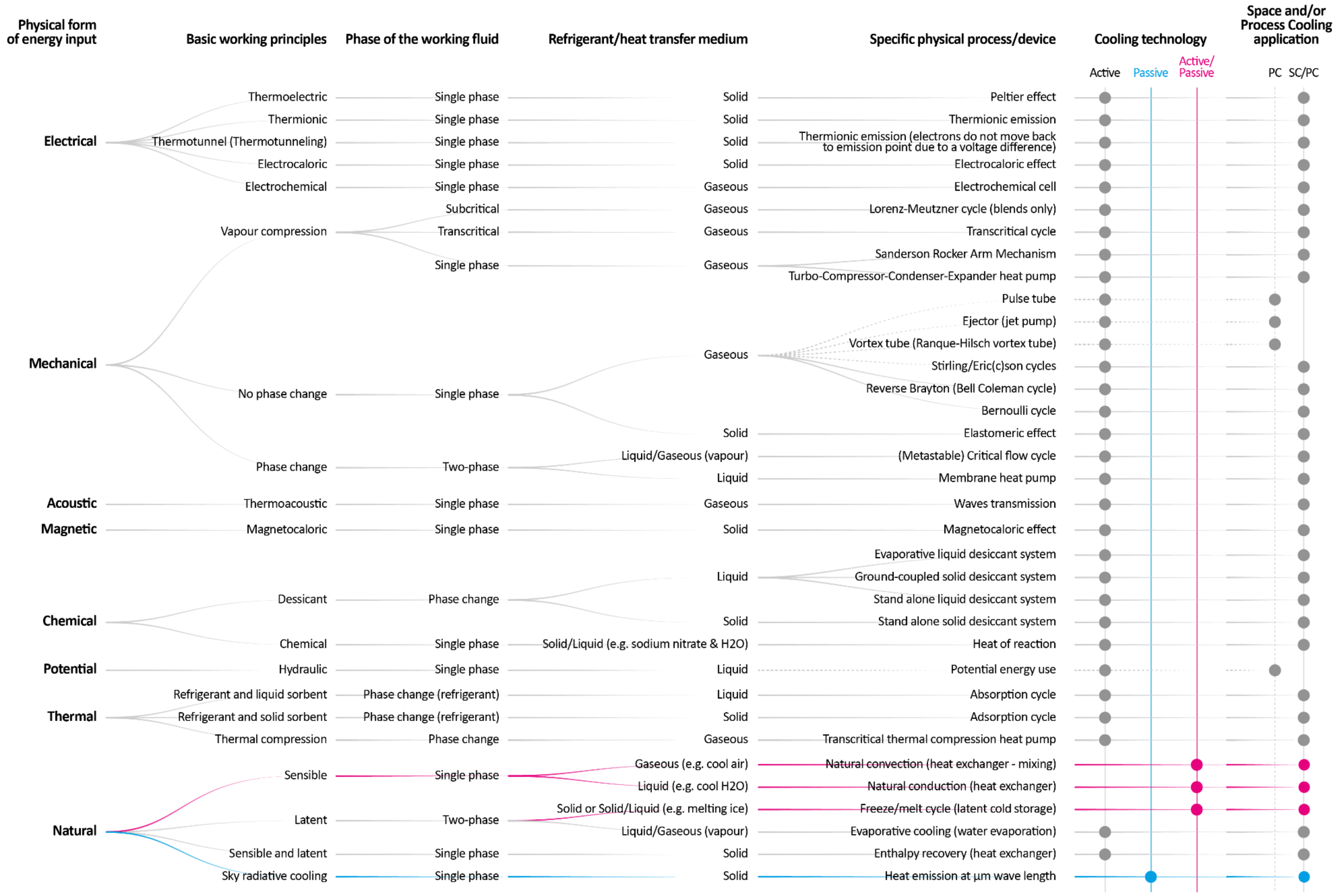
Physical form of energy input
Basic working principles
Phase of the working fluid
Refrigerant/heat transfer medium
Specific physical process/device
Cooling technology
Space and/or Process Cooling application
Active
Passive
Active/ Passive
PC
SC/PC
Electrical
Thermoelectric
Thermionic
Thermotunnel (Thermotunneling)
Electrocaloric
Electrochemical
Single phase
Solid
Gaseous
Peltier effect
Thermionic emission
Thermionic emission (electrons do not move back to emission point due to a voltage difference)
Electrocaloric effect
Electrochemical cell
Mechanical
Vapour compression
Subcritical
Transcritical
Lorenz-Meutzner cycle (blends only)
Transcritical cycle
Sanderson Rocker Arm Mechanism
Turbo-Compressor-Condenser-Expander heat pump
Pulse tube
Ejector (jet pump)
Vortex tube (Ranque-Hilsch vortex tube)
Stirling/Eric(c)son cycles
Reverse Brayton (Bell Coleman cycle)
Bernoulli cycle
No phase change
Elastomeric effect
Phase change
Two-phase
Liquid/Gaseous (vapour)
Liquid
(Metastable) Critical flow cycle
Membrane heat pump
Acoustic
Thermoacoustic
Waves transmission
Magnetic
Magnetocaloric
Magnetocaloric effect
Chemical
Dessicant
Evaporative liquid desiccant system
Ground-coupled solid desiccant system
Stand alone liquid desiccant system
Stand alone solid desiccant system
Solid/Liquid (e.g. sodium nitrate & H2O)
Heat of reaction
Potential
Hydraulic
Potential energy use
Thermal
Refrigerant and liquid sorbent
Refrigerant and solid sorbent
Thermal compression
Phase change (refrigerant)
Absorption cycle
Adsorption cycle
Transcritical thermal compression heat pump
Natural
Sensible
Latent
Sensible and latent
Sky radiative cooling
Gaseous (e.g. cool air)
Liquid (e.g. cool H2O)
Solid or Solid/Liquid (e.g. melting ice)
Natural convection (heat exchanger - mixing)
Natural conduction (heat exchanger)
Freeze/melt cycle (latent cold storage)
Evaporative cooling (water evaporation)
Enthalpy recovery (heat exchanger)
Heat emission at µm wave length

Figure 19 Taxonomy of cooling technologies [5], [14], [15], [16]

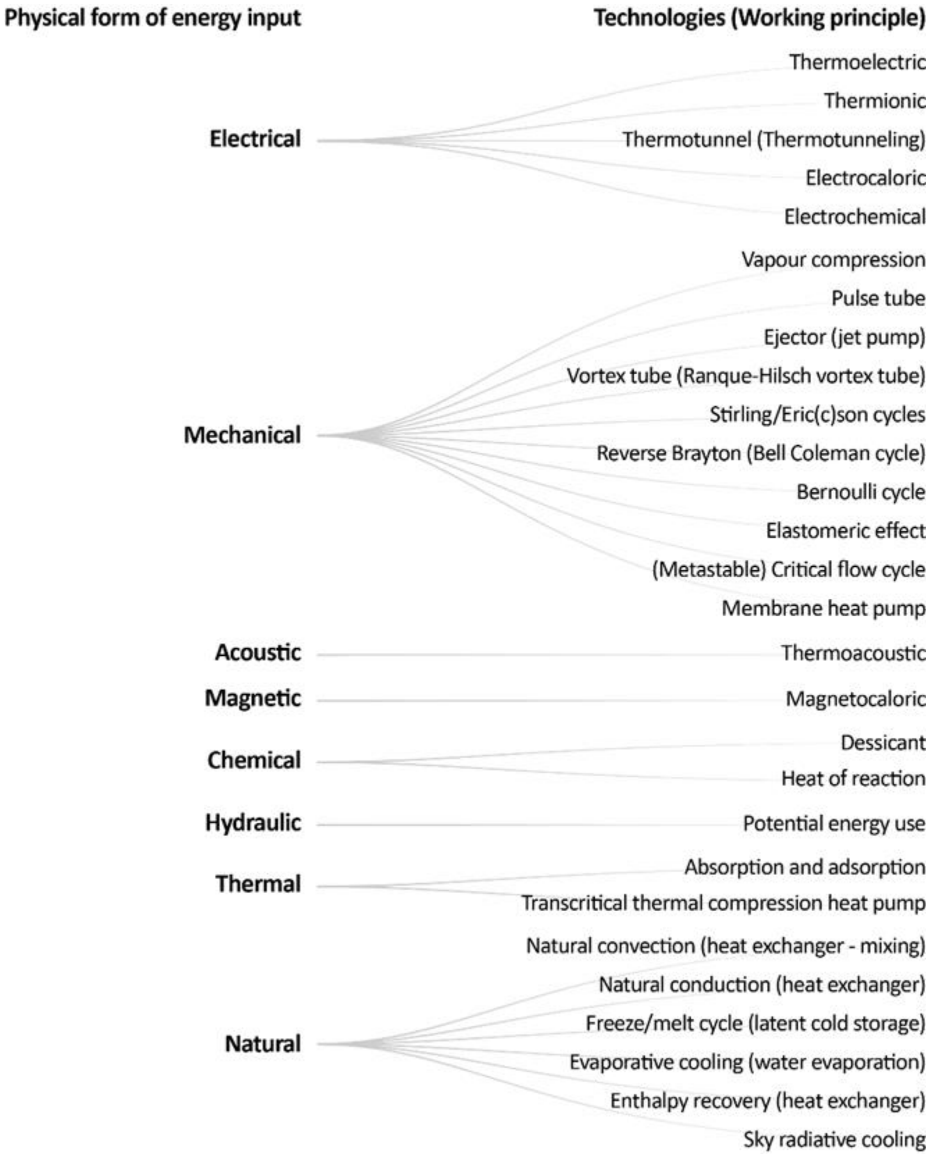

Figure 20 List of cooling technologies identified

Several technologies, mentioned in the previous Figure 19, have been grouped in Figure 20. Vapour compression entails Lorenz-Meutzner cycle (blends only), transcritical cycle, Sanderson Rocker Arm Mechanism, and Turbo-Compressor-Expander heat pump devices. Sterling/Eric(c)son cycles entail reverse Stirling, duplex Stirling, Vuilleumier HP, and reverse Eric(c)son devices. Finally, desiccant cooling devices entail evaporative liquid desiccant systems, ground-coupled solid desiccant systems, stand-alone liquid desiccant systems, and stand-alone solid desiccant systems.

A description of each identified technology follows, indicating wherever possible key technical parameters (e.g. energy efficiency levels), market maturity (e.g. technology readiness levels – TRLs), sales and stock (if available), costs (e.g. purchasing, installation, maintenance, reparation, dismantling), as well as utilization indications (per sector – if available).

Concerning the TRL, it has to be pointed out that the codified TRL system helps to qualify technologies' life stage from the idea/concept to the application on the market and therefore assists major research and development (R&D) actors to manage technologies' development, utilizing a common language. Moreover, regarding the TRLs, the H2020 EU research program definition is used, resulting in the list presented below.

- TRL 1 - basic principles observed;
- TRL 2 - technology concept formulated;
- TRL 3 - experimental proof of concept;
- TRL 4 - technology validated in lab;
- TRL 5 - technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies);
- TRL 6 - technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies);
- TRL 7 - system prototype demonstration in an operational environment;
- TRL 8 - system complete and qualified;
- TRL 9 - the actual system is proven in an operational environment (competitive manufacturing in the case of key enabling technologies; or space)

Within the following section, TRL levels [38] have been assigned either by taking over the most recent literature sources indications or by evaluating the most recent information obtained. In the latter case, the year of assignment is 2019. In the following section, assignment years are indicated in round brackets after the TRL level. It is important to mention that only technologies reaching a TRL of 8 or 9 are available on the market.

2.1. Screening of cooling technologies

2.1.1. Thermoelectric

Thermoelectric devices are electrically (direct current) powered. Modern thermoelectric cooling devices are based on semiconductor materials, which have not been commercialized yet. The commercialization of these materials faces considerable hurdles, and practical devices have not been able yet to surpass the performance of the status quo materials such as bismuth telluride and antimony telluride.

Status quo materials have a maximum theoretical second law efficiency of 0.18 – far lower than a second law efficiency of 0.50, which is achievable by today's VC technologies [20]. Thus, current thermoelectric devices have negative savings (increased energy use) compared to VC systems [39].

Such instruments are characterized by a TRL level of 4 (2016). The technology is not available on the market yet [40]. For the next two decades, thermoelectric cooling will likely remain uncompetitive with VC technology other than in certain specific applications with low cooling requirements and modest temperature lifts (e.g. specific electronic cooling applications, military and space applications, medical applications, recreational cooling, etc.) [20].

Typical applications for such instruments are portable refrigerators, seat conditioning for cars, portable refrigerators, wine cabinets, and spot cooling for electronics. Moreover, such technologies could be implemented to cool individual rooms or parts of rooms. Thermoelectric technology is technically applicable to all SC applications for residential and commercial buildings. This technology is also technically applicable to all climate regions and building types [39]. Moreover, this technology could be utilized also for PC applications.

Thermoelectric systems currently only have an economic advantage over VC systems for applications requiring less than 50 W of cooling, regardless of efficiency. However, costs are likely to decrease as manufacturability improves [39]. The research will likely bring thermoelectric devices to efficiency parity with VC [41].

2.1.2. Thermionic

Thermionic devices are electrically powered. The technical maturity of thermionic cooling devices has not been reached yet. This technology is so far in a very early research and development (R&D) stage. Such instruments are characterized by a TRL level of 2 (2014). It was not possible to identify any prototypes demonstrations or test results. Furthermore, it was not possible to identify any cooling applications currently employing thermionic technology. The company Borealis Exploration Limited (under the name of Cool Chips PLC) is currently developing thermionic cooling solutions.

This technology is technically suitable for all cooling applications both for residential and commercial buildings. Thermionic cooling devices apply to all climate regions and building types. Novel packaging concepts (e.g. localized cooling) could be possible too. Furthermore, this technology could be utilized also for PC applications.

Predictions indicate that thermionic cooling modules could achieve 50 - 55% of the Carnot efficiency. However, this estimation does not take into account the system losses associated with fans and other balance-of-plant components in heating, ventilation, air-conditioning (HVAC) application [39]. Hence, there are no energy savings based on the current performance [42].

Costs are projected to be on par with the costs of thermoelectric systems, which are significantly more expensive than VC above 50 W of cooling. However, these costs may decrease as manufacturability increases [39].

2.1.3. Thermotunnel (Thermotunneling)

Thermotunnel cooling devices are electrically powered too. This technology is still in the early stages of R&D. It was not possible to identify any prototypes for this type of technology or demonstrations beyond basic materials research [43]. Such devices are characterized by a TRL level of 2 (2019).

The predicted efficiency is 55% of Carnot, compared to 40 - 45% of Carnot for typical VC systems in HVAC applications. Thus, there are no energy savings based on current performance [39].

Projected to be on par with the cost of thermoelectric systems [39].

Thermotunneling technology is technically applicable to all cooling applications for residential and commercial buildings. This technology is technically applicable to all climate regions and building types [39]. What’s more, this technology could be utilized also for PC applications.

2.1.4. Electrocaloric

Also, electrocaloric instruments are electrically powered. Electrocaloric cooling technology is in a very early R&D stage. Recent laboratory experimentation and theoretical analyses suggest the potential for high efficiency in space conditioning applications, but this requires further demonstration before considering it as a viable alternative to VC technology. The understanding of electrocaloric cooling devices needs to be further investigated. Furthermore, promising areas of further development need to be identified. It was possible to identify solely documentation of two proof-of-concept breadboard prototypes. It was not possible to identify any applications, HVAC or other, which currently employ electrocaloric technology. Moreover, it was not possible to find any private companies that are currently developing electrocaloric technologies, nor is it clear whether electrocaloric R&D is ongoing at the moment. Electrocaloric devices are characterized by a TRL level of 2 (2019) [39].

Laboratory testing and simulations have shown electrocaloric cooling systems to have capacities too small for building cooling or freezing applications. However, if successfully developed, electrocaloric technology would likely be technically applicable to all cooling applications for residential and commercial buildings. It would also likely be technically applicable to all climate regions and building types [39]. This technology could also be applied to PC applications.

Electrocaloric cooling instruments are characterized by relatively high (projected) energy efficiency values, such as projected CFCs ranging from 3.7 to 4.9. These projected COPs are 16 - 53% higher than the overall system COP of baseline air-conditioners [39]. Thus, if successfully developed as a product, electrocaloric cooling systems could offer high COPs without the use of high global warming potential (GWP) refrigerants [42].

Costs are largely unknown - the technology will use advanced materials that likely have high incremental costs [42].

2.1.5. Electrochemical

Electrochemical HPs are electrically powered too. HPs using electrochemical compressors are still undergoing laboratory R&D and initial prototype testing, but face many significant challenges before commercial introduction.

The most significant barrier to market adoption is the development of a commercially available and cost-effective product. Electrochemical compressors themselves are smaller than conventional compressors, but the size required for other system components to accommodate alternative refrigerants is unknown. The introduction of new working fluids to the HVAC industry requires significant R&D efforts. In addition, the use of hydrogen gas may pose issues with public acceptance.

Similarly, electrochemical HP systems are expected to operate as conventional systems. However, the full system’s size, weight, reliability, and other characteristics are still unknown [42]. This technology is characterized by a TRL level of 3 - 4 (2017) [42].

Electrochemical HPs could technically replace most VC-type HVAC systems, but their development for different applications will depend on the technology's advantages in specific markets. Initial product development has focused on packaged AC systems [42]. This technology could be applied for SC as well as PC applications.

Current efforts focus on developing a room air-conditioner with a COP greater than four [42]. Goetzler et al. 2017 estimate energy savings of 20% for commercial AC systems. Moreover, electrochemical HPs can use zero-GWP refrigerants for reduced direct greenhouse gas (GHG) emissions [42].

The incremental cost of the electrochemical compressor itself is expected to be modest, but it is uncertain how the cost for an entire system would appear if compared to conventional equipment. Costs are expected to be modest, so that quick payback can be achieved [42].

2.1.6. Vapour compression

Vapour compression using electrically driven compressors has become the dominant cooling technology due to several reasons. Among others, the most important ones are its scalability, reliability, costs, non-toxic and non-flammable refrigerants, use of electricity, and relatively compact size. Depending on environmental conditions and equipment configuration, different types of VC systems can nearly always supply cooling, with relatively high efficiency and moderate costs [44]. Vapour compression systems provide the absolute majority (nearly 100%) of Europe’s cooling needs - for SC as well as PC applications [6], [15], [45]–[52].

A huge R&D effort is devoted to meliorate such systems. An important part of R&D on vapour compression cooling systems is dedicated to further higher energy efficiency levels. Furthermore, a large amount of private and public R&D funding is currently devoted to developing environmentally friendly refrigerants. While hydrofluorocarbons (HFC) refrigerants facilitated the successful phase-out of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), HFCs can contribute to global climate change when released to the atmosphere. For example, refrigerants HFC-134a and HFC-410A have significant GWPs. To curb human-influenced climate change, several countries and institutions like the EU endorsed an agreement to reduce HFC consumption by roughly 80% until 2030. Meeting these agreements will require significant actions within the HVAC industry to balance the phase down of high GWP refrigerants with the rising consumer demand for HVAC and other refrigeration systems. Researchers have so far identified several low GWP alternatives. However, many of these refrigerants suffer from other undesirable characteristics such as flammability, which poses a significant concern under current safety standards. Moreover, alternatives for HFCs may have lower volumetric capacities, while options such as CO_2 require complete system redesign due to their transcritical cycle properties. Furthermore, design changes required to address the characteristics of low GWP refrigerants may significantly raise the costs of VC systems and could affect overall system efficiency. Because the energy consumed during system operation accounts for the majority of an HVAC system's carbon emissions, maintaining or improving the efficiency of HVAC equipment relative to current technology is an important consideration when developing equipment with low GWP refrigerants [45]. Vapour compression technologies are characterized by a TRL level of up to 9 (2019).

The main system configuration variations for SC are given among different types of RACs and CACs. Regarding these, please see section 1.2 and their respective description. Regarding the main system configuration variations for PC, please see section 1.3. RACs are mainly to find in the residential sector but are used also in the tertiary sector (in particular in offices/office buildings). In contrast, CACs are to find mostly in the tertiary sector but are applied also in households [6]. Concerning the SEER per RAC and CAC type, please see figures Figure 55 and Figure 60 in section 3.2. Concerning costs, please find Table 17, Table 18, and Table 19 below which refer to average installation costs (€/kW), average purchasing costs (€/unit), and average operation and maintenance (O&M) costs (fixed) (€/unit/year) respectively. Following values have been derived from source [6], which provides respective cost indications from 2015-2050, by simply computing the yearly costs increase and thus obtaining numbers, which refer to 2016. Moreover, indicated values have been rounded.

Table 17 Mean installation costs per air-conditioning type (€/kW), the reference year 2016 [43] - indicated values for moveables plus window units include 20% value-added tax (VAT)

TECHNOLOGIES	MEAN INSTALLATION COSTS (€/kW)
ROOM AIR-CONDITIONERS	
Movables	164
Small split (<5 kW)	300
Big split (>5 kW, inclusive ducted)	226
CENTRALIZED AIR-CONDITIONERS	
Variable refrigerant flow systems	789
Rooftop + Packaged	279
Chiller (air-to-water) < 400 kW	260
Chiller (air-to-water) > 400 kW	181
Chiller (water-to-water) < 400 kW	173
Chiller (water-to-water) > 400 kW	117

Table 18 Mean purchasing costs per air-conditioning type (€/unit), the reference year 2016 [48]

TECHNOLOGIES	MEAN PURCHASING COSTS (€/unit)
ROOM AIR-CONDITIONERS	
Movables	409
Small split (<5 kW)	1051
Big split (>5 kW, inclusive ducted)	1692
CENTRALIZED AIR-CONDITIONERS	
Variable refrigerant flow systems	19720
Rooftop + Packaged	18135
Chiller (air-to-water) < 400 kW	20768
Chiller (air-to-water) > 400 kW	111370
Chiller (water-to-water) < 400 kW	1676
Chiller (water-to-water) > 400 kW	88033

Table 19 Mean operation and maintenance costs per air-conditioning type (€/unit/year), the reference year 2016 [48]

TECHNOLOGIES	MEAN O&M COSTS (fixed) (€/unit/year)[2]
ROOM AIR-CONDITIONERS	
Movables	/
Small split (<5 kW)	42
Big split (>5 kW, inclusive ducted)	68
CENTRALIZED AIR-CONDITIONERS	
Variable refrigerant flow systems	789
Rooftop + Packaged	725
Chiller (air-to-water) < 400 kW	830
Chiller (air-to-water) > 400 kW	4455
Chiller (water-to-water) < 400 kW	787
Chiller (water-to-water) > 400 kW	3521

Indicative running costs are estimated at 11 €/m² y [14]. As an indicative disposal cost, a typical price of approximately 33€ is mentioned (for equipment up to 100 kg weight) [6], [14].

Finally, please find in Table 20 indications concerning the average lifetime of various VC typologies.

Table 20 Average lifetime per air-conditioning type (years) [44]

TECHNOLOGIES	MEAN LIFETIME (Years)
ROOM AIR-CONDITIONERS	
Movables	10
Small split (<5 kW)	12
Big split (>5 kW, inclusive ducted)	12
CENTRALIZED AIR-CONDITIONERS	
Variable refrigerant flow systems	15
Rooftop + Packaged	15
Chiller (air-to-water) < 400 kW	15
Chiller (air-to-water) > 400 kW	20
Chiller (water-to-water) < 400 kW	15
Chiller (water-to-water) > 400 kW	20

Moreover, there are several further technologies, which belong to VC devices (see Figure 19).

Lorenz-Meutzner cycle (blends only)

Also because of the fact this technology is not on the market yet, data/information found concerning this technology is very limited. These devices are electrically driven. A relatively recent publication [54] indicates that with a refrigerant mixture of R290/R600 instead of using R600a, a gain of 11% can be obtained. The experiment carried out relates to a large-size

[2] The indicated operation and maintenance costs do not include energy costs.

refrigerator freezer appliance. However, the indicated gain has been evaluated solely at one outdoor temperature condition. Moreover, no information could be found that such a design development is going on. The TRL for the Lorenz–Meutzner cycle has been assessed at 4 (2019).

Lorenz-Meutzner cycle devices could be applied to SC as well as PC applications.

Transcritical cycle

Such devices are electrically powered. Concerning the transcritical cycle, it has to be pointed out that transcritical CO_2 AC and refrigeration has been a very active R&D area over the past 20 years. Since the mid-1990s, there have been hundreds of articles published on this topic. There has been a large number of application areas investigated for transcritical CO_2 – among others: residential air-conditioners and HPs as well as automotive air-conditioners [55]. The application which received the most interest is automotive AC, including the possibility of its near-term commercial use.

The CO_2 transcritical cycle was proposed in the 1990s - partially to reduce the global warming impact from HFC-based AC and refrigeration systems. However, there has been considerable debate whether the use of the CO_2 transcritical cycle instead of conventional HFC-based VC equipment reduces the impact on the climate for individual applications. This debate focused on the fact that the impact on the climate strongly depends on the system efficiency in addition to the refrigerant's GWP and its leak rate [20]. The TRL for the transcritical cycle has been assessed at up to 9 (2016) [56].

Regulations aiming to phase down the use of high GWP refrigerants will further increase interest in applying transcritical CO_2 in comfort cooling and refrigeration applications. This technology can be applied for SC and PC applications. For the next 20 years period, the transcritical CO2 cycle will likely continue to be an area of research interest with a possible larger-scale commercial introduction, which would help to reduce the system costs to a more competitive level. If large-scale commercialization is realized, it is likely to be for small size, small capacity applications benefiting from the large volumetric cooling capacity of CO_2.

Considering the thermodynamic disadvantage compared to the subcritical vapour compression cycle, for the transcritical CO_2 cycle to be more widely applied, it is likely that external factors will play a role - e.g. taxes, regulations, legislation, or public perception. Among others, many issues that still need to be addressed are efficiency at high ambient temperatures and costs [20].

Sanderson Rocker Arm Mechanism

Sanderson Rocker Arm Mechanism (S-RAM) devices are electrically driven. The S-RAM technology does not appear to have undergone any benchtop or full prototype testing as an HP, and the projected performance is based on modelling. The likely performance, efficiency, reliability, manufacturability, costs, as well as other attributes, are unknown at this time. If successfully developed at reasonable costs, the S-RAM HP could operate like conventional rooftop HVAC units and have solely minor barriers for the market introduction [42]. The TRL level of S-RAM technology has been indicated to be 3 - 4 (2017) [42].

The target market for this technology is packaged rooftop units for commercial buildings. The US Army is also funding the development of an S-RAM mobile refrigeration system using CO_2 as a refrigerant [42]. This technology could be utilized for SC and PC applications.

The likely efficiency of S-RAM technology is unknown at this time. The technology developers predict that the S-RAM HP could provide 30 - 50% energy savings for commercial rooftop units through the coupled compressor/expander and variable capacity capabilities [42].

Turbo-Compressor-Condenser-Expander HPs

Turbo-Compressor-Condenser-Expander HPs are electrically powered. Several prototypes have been developed so far and testing of these is going on. If testing proves successful, it is planned to conduct field tests to demonstrate performance in various relevant conditions.

Turbo-Compressor-Condenser-Expander HPs are characterized by a TRL level of 3 - 4 (2017) [42].

From a technical-fit standpoint, the technology could be used in any type of air-cooled packaged air-conditioning system meant for commercial buildings. This technology could be utilized for SC and PC applications.

The performance of the current design is estimated at a SEER of 20 (for split system prototypes), to be comparable to high-efficiency residential products on the market today. Other self-contained designs could achieve higher efficiencies, but these designs have not been tested yet.

There is limited information on performance and costs. The unique heat exchanger assemblies require specialized joining methods with uncertain manufacturability and long-term reliability. By combining several components into a single assembly on a common shaft, it is believed that the fully developed turbo-compressor-condenser-expander will have lower manufacturing costs [42].

2.1.7. Pulse tube

Pulse tube instruments are electrically driven. Technical maturity for pulse tube cooling devices is currently not reached yet. This technology is currently utilized for cryocooling applications. However, it has not been developed for space conditioning yet due to low cooling efficiency [39]. It has been identified a TRL level of 6 for this technology (2014) [57].

Pulse tube devices are currently used for cryocooling applications. Such devices can achieve very low temperatures (-270 to -170 °C) for cryocooling applications (e.g. gas liquefaction, cooling of sensors, superconductors, and medical specimens). This technology is currently not developed for space conditioning [39]. Thus, so far this technology can be utilized solely for PC applications.

For cryocooling applications, COP levels range values from 0.01 to 0.10. Hence, pulse tube devices offer no energy savings compared to current VC systems, and there is little research into its potential for space conditioning applications [39], [58].

2.1.8. Ejector (jet pump)

Ejector HPs are mainly driven by natural gas but can utilize boiler, solar water heater, or waste heat stream [39]. No recent research on this technology could be found. Greenblatt 2011 [59] explains that refrigerator manufacturers in the USA did not consider it a proven concept to the higher energy efficiency of refrigerators/freezers. Ejector HPs are characterized by a TRL level of 3 (2014) [40].

Ejector cooling devices are employed in mobile AC. There are no ejector SC applications available. However, ejector HVAC applications are under development [39]. So far this technology can be utilized solely for PC applications.

Cooling COPs range from 0.2 - 0.4. Furthermore, this technology ejector devices can use benign refrigerants [39].

Compared to electrically driven systems, ejector HPs could provide a cost advantage due to the lower cost of natural gas [39].

2.1.9. Vortex tube (Ranque-Hilsch vortex tube)

Vortex tube devices utilize a compressed air source. These devices are characterized by a high technical maturity - these are widely utilized throughout industrial processes and settings. Costs of such a technology appear to be relatively low as well as result in being compact, light, and adjustable. Market maturity appears to be moderate - if compressed air is available, such applications are inexpensive and a convenient way to provide spot cooling for machines, electronics as well as people. Stakeholders' support is missing for this technology due to its low applicability for building conditioning [39].

Vortex tube instruments are characterized by a TRL level of 4 (2014) [60].

This technology is widely utilized throughout industrial processes and settings [39]. So far, this technology is utilized solely for PC applications.

Energy efficiency levels of this cooling technology are very low: COP values result to be 0.1 and less [61].

Purchasing prices are approximately one to several hundred euros (€) per vortex tube. If compressed air is available, it is an inexpensive and convenient way to provide spot cooling to machines, electronics, and people [39].

2.1.10. Stirling/Eric(c)son cycles

Some technologies have been assigned to Sterling/Eric(c)son cycles, due to being characterized by similar principles:

Reverse Stirling

Reverse Stirling instruments are powered by gas, gasoline, wood, waste heat, etc. The technical maturity of reverse Stirling devices for cooling is moderate. Currently, low temperature, niche refrigeration as well as cryocooling applications have been developed [39]. The TRL level of reverse Stirling devices is 4 (2017) [40].

To date, minimal development for SC has been carried out. Products have been developed for low-temperature refrigeration applications. There are no commercialized products for SC - HVAC reverse Stirling applications that are under development [62]. Reverse Stirling cooling devices are utilized for cryogenic applications/refrigeration: e.g. cooling of electronic sensors and microprocessors [63]. Moreover, a company located in Taiwan (MSI) developed a miniature Stirling engine cooling system for personal computer chips, which utilizes waste heat from the chip to run a fan [39]. Reverse Stirling devices could be utilized for SC as well as PC applications.

Reverse Stirling cycle cooling types of machinery are characterized by low energy efficiency levels – the estimated COP is approximately 1.0 [64].

Duplex Stirling

Such devices are powered by natural gas (and potentially other high-temperature heat sources) [39]. Duplex Stirling HPs for space conditioning applications have been already investigated for several decades. However, system performance is lower than conventional and other thermally activated HPs. Estimated COPs for cooling are around 1.0. Because cooling COPs are low, even compared to other gas-fired HPs, energy savings during the cooling season are not expected [39]. Duplex Stirling devices are characterized by a TRL level of 3 - 4 (2017) [42].

Currently, no products on the market utilize duplex Stirling HPs for space conditioning. For heating-dominated climates, the higher heating efficiency and cost savings may offset the low cooling efficiency.

The cost for duplex Stirling HPs is unknown at this stage. As a sealed system, installation and operation could be simpler than several VC systems by requiring only water connections to heat exchangers [39].

Such devices have been developed for low-temperature freezing applications: low temperature and niche refrigeration as well as cryocooling applications. Duplex Stirling HPs would be suitable for most residential and commercial applications. Duplex Stirling HP’s development for space conditioning applications is going on. Such devices have not been commercialized yet [39]. This technology could be applied to SC as well as PC applications.

Vuilleumier HP

Vuilleumier HPs are natural gas driven. Although several efforts have been undergone to study the Vuilleumier HP (since decades) and its potential for gas-fired space conditioning, no products currently exist on the market. Researchers are currently developing prototype systems for residential space conditioning. Currently, no products on the market utilize Vuilleumier HPs. Because cooling COPs are low, energy savings are not expected during the cooling season. The estimated COP for cooling is 0.8 [43]. For heating-dominated climates, the higher heating efficiency and cost savings may offset the lower cooling efficiency [39], [42]. This technology is characterized by a TRL level of 3 - 4 (2017) [42].

The Vuilleumier HP would be technically suitable for most residential and commercial applications once developed. Compact size devices are under development [39]. This technology could be utilized for SC and PC applications.

By utilizing natural gas as an energy source, Vuilleumier HPs would have lower operating costs in space and service water heating mode, and potentially in cooling mode. The sealed design could allow for easy installation, requiring only water connections and exhaust vents in the field [39].

Reverse Eric(c)son cycles

Reverse Eric(c)son cycles are powered by gas, gasoline, wood, solar, etc. Technical maturity, as well as market availability, is limited so far. The technology is characterized by relatively high complexity. However, there are also several positive aspects regarding reverse Eric(c)son cooling devices: among others - low emission values. Many R&D efforts are performed on this technology [39], [65]. Reverse Eric(c)son is characterized by a TRL level of 4 (2019).

Such devices are used for freezing and AC [65], [66]. This technology can be utilized for SC and PC applications.

Second law efficiencies of approximately 3% have been achieved so far [67].

2.1.11. Reverse Brayton (Bell Coleman cycle)

This technology is electrically driven. Although Bryton cycle devices are common for SC in aircraft and trains due to their high reliability and low maintenance requirements, Brayton cycle HPs have limited potential for building SC due to their low COP levels. Cooling COPs of reverse Brayton HPs range from approximately 0.5 - 0.8. With cooling COPs below that of conventional VC systems, Brayton HPs are not expected to provide energy savings [39], [43]. This technology is characterized by a TRL level of 5 - 9 (2011).

The Brayton cycle has achieved market success in applications where VC systems pose significant issues. Because of its simple design, high reliability, and ability to achieve very low temperatures, the Brayton cooling cycle has been used for decades throughout various industries, including:

- Transportation space conditioning (e.g. aircraft, train, ship)
- Commercial and industrial refrigeration and freezing (e.g. cold storage, blast freezing, cryocooling)
- PC (e.g. natural-gas liquefaction)

Moreover, this technology could be applied also for building space conditioning (not available yet).

2.1.12. Bernoulli cycle

Bernoulli cycle devices are electrically driven. Concerning Bernoulli HPs' technical maturity, it has to be pointed out that the core technology has been demonstrated, but it is far from a production-ready prototype. Concerning market maturity, Bernoulli cycle devices for the cooling application are still in an early stage development phase, being several years away from a production-ready prototype. The current proof-of-concept prototype has a very low COP, but it is expected to improve in future iterations. Bernoulli HPs are characterized by a relatively simple design with the potential for compact size [39]. Bernoulli cycle devices are characterized by a TRL level of 3 - 4 (2017) [20].

Because of the relatively simple design, the Bernoulli HP would be applicable for most vapour compression cooling applications. The first applications would be expected to use air as a secondary working fluid and more easily replace split and packaged system designs, rather than chillers [68]. The Bernoulli HP is an early-stage technology whose prospects for building cooling cannot be assessed without further product development. Scaling the technology to the capacities required for residential and commercial building applications is the largest challenge [39]. This technology could be applied for SC as well as PC applications.

Current prototypes have very low COPs (around 0.1) but are expected to improve in future iterations (COPs of 2 - 3) [39]. There are no energy savings based on current performance, projected to have some savings if developed [42]. The current proof-of-concept prototype has a very low COP, but it is expected to improve in future iterations [39].

The Bernoulli HP is expected to have comparable costs to VC systems, but additional product development is needed to make credible projections [39].

2.1.13. Elastomeric effect

Cooling devices being characterized by an elastomeric effect are electrically powered too. The supposed maximum efficiency of this technology appears to be the highest of all-solid-state technologies. It is characterized by a maximum COP of 83.7% [69]. In contrast, the vapour compression cycle has a COP of about 60%. The projected SC savings are over conventional packaged commercial AC systems [42]. Additionally, this cooling technology has the advantage to be a low-cost solution. R&D is at the design stage, including material choice, reliability, and heat exchanger design. Elastomeric devices are characterized by a TRL level of 2 (2016) [40].

It was not possible to find any applications, HVAC or otherwise, that currently employ elastomeric technology. However, such cooling devices could replace conventional, compressor-driven air-conditioning and HP systems. This technology is technically applicable to all cooling applications for residential and commercial buildings [39]. Such devices could be applied for SC as well as PC applications.

2.1.14. (Metastable) Critical flow cycle

Also (Metastable) critical flow cycle devices are electrically driven. Regarding the technical maturity of (Metastable) critical flow devices, it has to be stressed that the core technology is still in an early stage R&D phase. (Metastable) Critical flow cycle devices are characterized by a TRL level of 3 - 4 (2017) [42]. Concerning market maturity, it is worth noting that an initial prototype is several years away. A compact design is expected after additional development. The novel cooling cycle is expected to utilize low GWP and low ODP (Ozone depletion potential) refrigerants – however, this is still unproven [39].

Such technology has the potential to replace most vapour compression cooling systems. The technology is potentially applicable for a wide range of SC applications. Large commercial chillers represent one of the clearest applications of the technology, due to the requirement of a secondary working fluid to transfer heat with the nozzle assembly [42].

An analysis of the results of current laboratory testing showed an estimated COP of 1.7 [42]. Researchers suspect that the critical flow refrigeration cycle could achieve efficiencies higher than current vapour compression systems, potentially nearing a COP of 10, but additional development is required to develop a full prototype [39].

Costs for such systems are unknown so far [42].

Recent developments demonstrate the technology’s promising potential for commercial HVAC applications, but challenges remain to determine the performance, efficiency, and operational attributes of a complete system [42]. This technology could be applied for SC as well as PC applications.

2.1.15. Membrane heat pump

Membrane HPs are electrically driven. Concerning technical maturity, it has to be said that this technology is in the second generation prototype stage, and uses a membrane already commercialized for energy recovery ventilators. However, membrane HPs have not yet been commercialized. Prototypes have approximately the same size as VC systems having an equivalent capacity. Finally, stakeholder’s support is given - electric utilities are likely to support membrane HP technology due to its potential for peak demand reduction[39], [43]. This technology is characterized by a TRL level of 5 - 6 (2017) [42].

Membrane HP technology is technically applicable to all cooling applications for residential and commercial buildings. This technology is also technically applicable to all climate regions and building types. Moreover, membrane cooling systems are a promising technology for improving the comfort and efficiency of commercial buildings [42]. This technology could be applied to SC as well as PC applications.

For SC, researchers claim that the EER is twice that of VC, resulting in energy savings of 50% [43].

This technology is likely to cost approximately the same as VC. Furthermore, this technology is characterized by easy installation as well as easy maintenance [42].

2.1.16. Thermoacoustic

Thermoacoustic devices are powered by solar heat, waste heat, or other heat sources [20]. Measured second law efficiencies for thermoacoustic cooling prototypes have typically valued ranged from about 0.03 to 0.21, which is significantly below contemporary VC values, which range from about 0.3 to 0.5. Most early development works were based in the USA:

Los Alamos Laboratory, Purdue University, as well as Penn State University. In 2004, a consulting company was created (ThermoAcoustics Corporation), which developed thermoacoustic cycle-based prototypes for NASA, the U.S. Navy, and Ben & Jerry's. This technology is characterized by a TRL level of 4 (2016) [40].

Thermoacoustic technology is technically applicable to all SC applications for residential and commercial buildings. This technology is also technically applicable to all climate regions and building types. Several institutions have developed patents and prototypes for a variety of refrigeration applications and some HVAC applications. Applications such as portable coolers might be possible. Supermarket chillers for commercialization are under development [39]. This technology could be applied to SC as well as PC applications so far.

Thermoacoustic efficiency in HVAC applications has not been publicly documented. However, models predict that, at typical SC conditions, the maximum theoretical efficiency of thermoacoustic technology is lower than the maximum theoretical efficiency of VC. There are no energy savings based on current performance levels [42]. However, this technology may save energy in refrigeration applications. The maximum efficiency achieved by current supermarket chiller prototypes is 37% of Carnot efficiency, which is higher than the efficiency of equivalent VC refrigeration systems (27% of Carnot).

Costs are projected to be approximately equal to the cost of VC systems from a high production volume perspective [39].

2.1.17. Magnetocaloric

Magnetocaloric devices are electrically driven. In the past two decades, a considerable increase in R&D activities indicated by a large number of scientific papers and patents from various research groups occurred. By the end of the 1990s, a significant discovery was made - Pecharsky and Gschneidner 1997 [70] discussed the discovery of the so-called giant magnetocaloric effect with an approximately 50% greater magnetocaloric effect than that of pure gadolinium. Afterward, the number of scientific papers treating the topic increased significantly, reaching over 250 per year in 2007. Moreover, Yu et al. 2010 [71] report that the number of European patents issued for magnetic refrigerators and HPs during the period 1997 - 2009, totals an amount 135. The research activity noted above, as well as other activities, continues. For example, extensive materials R&D is ongoing - among others on intermetallic compounds [72]. In addition to materials research, prototypes continue to be designed, developed, and tested. Most of the working prototypes use gadolinium. Despite the presence of more than 40 working prototypes and the ongoing work, the literature lacks reliable experimental data for comparing magnetic refrigeration and VC technology [20]. Magnetocaloric devices are characterized by a TRL level of 3 - 4 (2016) [40].

Magnetocaloric technology is technically applicable to all cooling applications for residential and commercial buildings. This technology is also technically applicable to all climate regions and building types [39]. Typical applications include among others, SC and PC applications like a wine cooler, residential refrigerator, medical and commercial refrigeration [42].

Past prototypes have had COPs of approximately 2 [45], [68], [72], [73]. Such devices use working fluids with zero GWP for reduced direct GHG emissions. There are estimated 20% energy savings for AC applications and savings up to 40 - 50% projected for refrigeration applications (compared to conventional systems) [42].

Costs are so far unknown for AC applications, but supermarket refrigeration technology developers project 1 - 5 years paybacks in Europe [42]. The costs of magnets might be an issue [39].

2.1.18. Desiccant

Several different desiccant cooling systems have been identified: evaporative liquid desiccant system, ground-coupled solid desiccant system, stand-alone liquid desiccant system, and stand-alone solid desiccant system.

Evaporative liquid desiccant system

This technology is natural gas-powered. Moreover, the heat used to regenerate desiccants can be supplied also via a boiler, waste heat, or solar heat. Performance simulations for the evaporative liquid desiccant cooling process, comparing it to high-efficiency VC systems have been carried out. These models have been tested through lab testing of breadboard systems. There are many significant market barriers that evaporative cooling faces: low applicability to humid climate zones, increased on-site water consumption, the potential for freezing damage, and the poor reputation of older direct evaporative coolers. Evaporative liquid desiccant air-conditioners face similar market barriers due to their water consumption (which is approximately equal to that of evaporative coolers) and potential for freeze damage. Evaporative liquid desiccant air-conditioners also face the market barrier associated with the corrosiveness of liquid desiccants. This technology is characterized by a TRL level of 3 - 4 (2019).

So far, cost estimations are based on breadboard design concepts that do not include complete bills of material. As a result, these cost projections are highly uncertain. Evaporative liquid desiccant cooling systems do not require the use of any particularly expensive raw materials or components.

Evaporative liquid desiccant cooling technology is technically applicable to all SC applications for residential and commercial buildings. This technology is also technically applied to all building types in all climate regions [39]. Evaporative liquid desiccant cooling technology could be applied for SC as well as PC applications.

Simulations indicated a reduced source energy consumption by 39 - 84% compared to a traditional VC system. Moreover, because evaporative liquid desiccant AC systems can use fossil fuels or waste heat to regenerate the desiccant, they can provide a reduction in electricity demand that is disproportionate to their efficiency improvement over VC. Furthermore, it has to be underlined that evaporative liquid desiccant AC systems deliver 30 - 100% outdoor air, thus maintaining high indoor air quality while obviating the need for supplementary ventilation [39], [74].

This technology has the potential to reach cost parity with VC. However, current projections estimate that systems will cost 25% more than VC systems [75].

Ground-coupled solid desiccant system

Ground-coupled solid desiccant systems are powered by natural gas - heat can be supplied via a gas burner, waste heat, or solar heat. The core components of ground-coupled solid desiccant air-conditioners are widely available, but a complete system has not been commercialized yet. Solid desiccant wheel sand ground loop systems have been utilized for decades in both residential and commercial applications as energy recovery ventilators and geothermal HPs, respectively. However, ground-coupled solid desiccant air-conditioners have not yet been commercialized. Such systems are characterized by a TRL level of 3 - 4 (2019).

Ground coupling significantly increases the complexity and installation costs of space conditioning systems, due to the need for drilling equipment and potentially challenging piping systems to conduct the cooling fluid from the ground-coupled loop to the solid desiccant system. Thus, it is likely that such systems would be more expensive than air-source VC air-conditioners.

Ground-coupled solid desiccant air-conditioners are technically suitable for SC applications for residential and commercial buildings in hot-humid climate zones [39]. Such systems could be applied to SC and or PC applications.

A ground-coupled solid desiccant AC prototype shows a measured COP of 1.85, which is higher than the source COP of baseline residential and commercial VC cooling equipment (1.05). Typical VC systems sometimes overcool the air to remove humidity and then reheat it to reach desired interior conditions. In contrast, a ground-coupled solid desiccant air-conditioner provides greater independent control of latent and sensible loads, making it potentially more energy-efficient to achieve desired indoor air conditions. Ground-coupled solid desiccant air-conditioners offer significant energy savings only in hot-humid climates with large latent loads.

Stand-alone liquid desiccant system

This technology is powered by natural gas - heat used to regenerate desiccants, which can be supplied via a boiler, waste heat, or solar heat. Advanced (stand-alone) liquid desiccant systems that use higher effect regenerators are not yet commercially available. R&D is ongoing for such systems [39]. This technology is characterized by a TRL level of 3 - 4 (2019).

The corrosiveness of many liquid desiccants poses a barrier to market adoption. In the past, systems have encountered conditions that acidified the desiccant, causing it to foam or precipitate solid salts, although residential and commercial applications are typically much more controlled and thus should be less likely to experience unfavorable desiccant air interactions.

Liquid desiccant AC technology is technically applicable to all cooling applications for residential and commercial buildings, but only in hot-humid climate zones [39]. This technology could be applied for SC and PC applications.

Unless coupled with waste or solar heat, the thermal COP of such systems is much lower than that of VC systems, although stand-alone liquid desiccant systems use much less electricity and therefore reduce demand [39]. Typical VC systems must address latent loads by overcooling the air to remove humidity and then reheating it to reach optimum interior temperatures. In contrast, the stand-alone liquid desiccant system significantly reduces the latent load experienced by a cooling system by directly removing humidity, making it easier to achieve ideal indoor air conditions. Consequently, such systems offer significant energy savings only in hot-humid climates with large latent loads.

First-generation prototypes are estimated to cost 65% more than VC systems. However, costs are uncertain because production-oriented designs have not been yet developed [39].

Stand-alone solid desiccant system

Stand-alone solid desiccant systems are powered by natural gas - heat can be supplied via a gas burner, waste heat, or solar heat [39]. This technology is characterized by a TRL level of 3 - 4 (2019).

Unless coupled with waste or solar heat, standalone solid desiccant systems have COPs lower than 1, because they consume at least as much thermal energy to expel the moisture they capture to regenerate the desiccant in addition to electrical fan energy and other losses [76].

Solid desiccant AC technology is technically applicable to SC applications for residential and commercial buildings in hot-humid climate zones [39]. However, this technology could be applied also to PC applications.

Except in hot and humid climates and buildings with high moisture loads (e.g. ice rinks and supermarkets) or specialized indoor air quality loads, stand-alone solid desiccant air-conditioners typically pose unfavourable cost and complexity relative to energy or cost savings [39], [77].

2.1.19. Heat of reaction

The technical maturity of this technology is relatively limited so far. Several R&D efforts are carried out concerning related devices [74], [76]. No commodities utilizing this technology could be found on the market, as well as no companies could be identified developing related products. This technology is characterized by a TRL level of 2 (2019).

Possible applications relate to the cooling of mobile phones, tablets, cameras, two-way radios, global positioning systems (GPS), laptop computers, power tools, portable electronic devices (e.g. beverage cooling system) [78], [79].

2.1.20. Potential energy use

Technical maturity is relatively high so far. The technology is characterized by relatively low complexity. Several R&D efforts are carried out concerning this technology [77], [79]. This technology is characterized by a TRL level of 6 - 9 (2019).

A typical application of hydraulic cooling refers to hydraulically powered fans. In this case, a hydraulic fan drive creates airflow through the engine cooling radiator and the charge air cooler. A hydraulic fan motor directly drives the engine. The modulated fan speed depends on the amount of oil flowing through the fan motor. A pump creates the oil flow necessary to operate the hydraulic fan drive system. The more oil passes through the motor, the faster the fan rotates [81]–[83]. Such devices have been applied for PC applications only.

Such devices are characterized by a rather low payback time [81].

2.1.21. Absorption and adsorption

Sorption cooling devices (also called thermally driven heat pumps – TDHPs) are powered by natural gas – or also other heat sources such as process steam, solar thermal, and waste heat stream can be used. In contrast to the EU, where sorption cooling covers solely around 1% of the cooling market per capacity installed sorption chillers continue to represent a large fraction of cooling types of machinery sold in markets like in Japan or China.

Since two decades apart, perhaps the two most important innovations in absorption cooling have been the introduction of triple effect chillers and the introduction of generator absorber heat exchanger (GAX) technology. Triple effect chillers were commercially introduced in 2005. Smaller, single effect, gas-fired ammonia/water absorption systems for residential and light commercial applications were commercially introduced too, which was made possible by the commercial development of the GAX technology. The GAX technology can improve the COP by 10 - 40% compared to conventional ammonia/water absorption systems.

For large commercial applications, several manufacturers (e.g. Carrier, Trane, York, Broad, Yazaki, Hitachi, etc.), offer lithium bromide (LiBr) absorption chillers ranging from several hundred to several thousand tons nominal cooling capacity. Most offerings are single or double effect systems, although some triple effect systems are available after years of development.

With an increased societal emphasis on energy recovery and alternative energy sources, in addition to direct-fired absorption chillers, both absorption and adsorption systems have seen greater commercial application and increased R&D efforts for applications involving waste heat recovery (e.g. industrial processes, fuel cells, and gas turbines), low-temperature sources (e.g. solar and geothermal), and tri-generation (cooling, heating, and power). In addition to technical advancements, regulations and incentives have begun to be implemented that support and promote the use of sorption cooling. For example, Rowe and White 2014 list several incentive schemes for solar cooling in several of EU MS [20], [49], [52], [84]–[86].

Absorption and adsorption cooling devices are characterized by a TRL level of 3 - 9 (2014) [87].

Manufacturers commonly offer products for both residential and commercial (commercial buildings) markets [39]. This technology is also deployed at district cooling (DC) systems. Absorption and adsorption can be applied for SC as well as PC applications.

Cooling COP values range from approximately 0.5 - 0.7 [39]. For cooling, no source energy savings are expected compared to residential and light commercial air-conditioners or large commercial chillers [39].

Upfront costs are up to about 300% more than conventional cooling equipment [39]. Moreover, please find here specific cost concerning water-LiBr absorption chiller [19]:

- Mean installation costs (€/kW): 170
- Mean purchasing costs (€/unit): 85000
- Mean O&M costs (€/unit/year): 3400

Following Figure 21 visualizes a process diagram of a solar cooling system.

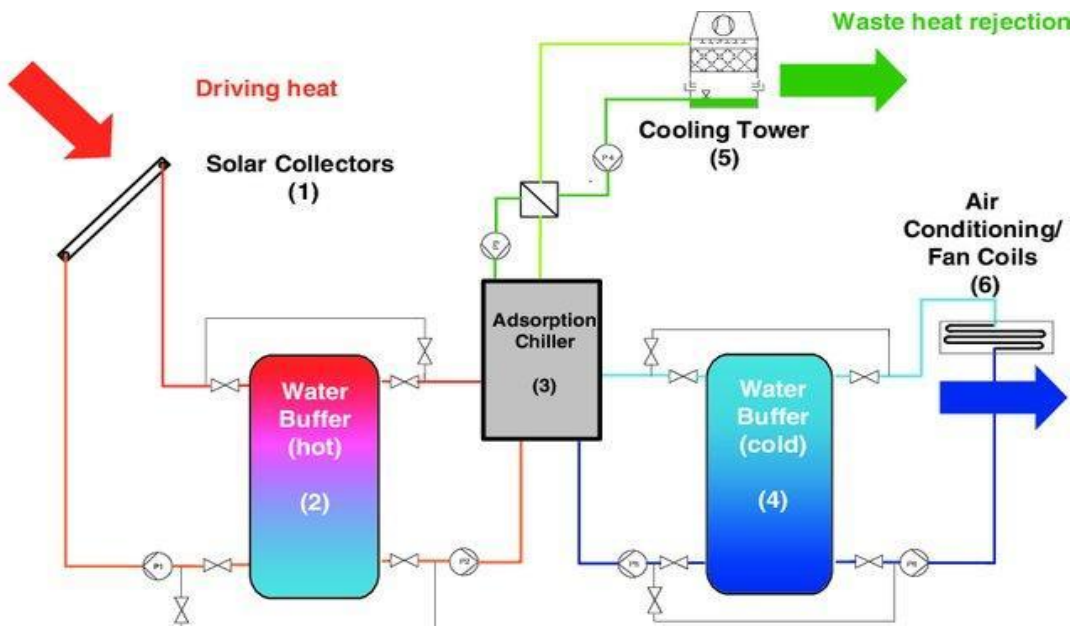

Figure 21 System components of a solar cooling system [92]

2.1.22. Transcritical thermal compression heat pump

Transcritical thermal compression HPs are gas-powered [88]. The concept of this technology has been designed by the boostHEAT company [89]. So far, a model of the thermal compressor has been developed and validated. This technology is characterized by a TRL level of 4 (2019).

Such technology can be utilized for residential as well as service sector applications like hotels, offices, and shopping malls [88]. Transcritical thermal compression HPs could be utilized for SC as well as PC applications.

The COP results to be more than 2 [90].

Purchasing prices are around 365 €/kW. The payback time has been calculated to be between 4 - 6 years [90].

There are ongoing efforts to bring this technology to the market in near future.

2.1.23. Natural convection (heat exchanger – mixing)

While before mentioned technologies are active solutions (see Figure 19), this technology can be an active (in the case of heat exchanger applications, energy - electricity, is consumed to drive air through the heat exchanger) or a passive system (heat exchanges between ambient air and air inside buildings) and can be utilized for SC as well as PC (e.g. air cooling cars' engines) applications.

The current technology presents a relatively high technical maturity and market availability. This technology is characterized by a TRL level of up to 9 (2019). Such natural cooling systems (passive as well as active ones) have been commercially available for decades - especially for use in hot, dry climates. However, so far these systems have achieved quite low market penetration. Many R&D efforts have been and are carried out (e.g. on design, implementation, performance, etc.) concerning these technologies [6], [20], [91]–[93].

Due to utilizing freely available cold sources (free cooling) and external energy input is not required in the case of passive natural convection systems, considerable energy savings can be achieved.

2.1.24. Natural conduction (heat exchanger)

Also, this technology can be an active (in the case of heat exchanger applications energy – electricity, is consumed to drive the medium through the heat exchanger) or a passive system (heat exchanges between building structures and air inside buildings) and can be utilized for SC (e.g. water loops cooling the ambient via air to water heat exchanger) as well as PC (e.g. water intake from a river/lake to cool down industrial processes applications).

The technical maturity of such natural cooling systems is relatively high and market availability is given too. This Technology is characterized by a TRL level of up to 9 (2019). Also, in this case, commercial availability is given as well as low market penetration. A number of R&D activities are ongoing [6], [20], [91], [92].

Once again, due to utilizing freely available cold sources (free cooling) and external energy input is not required in the case of passive natural conduction systems, considerable energy savings can be achieved.

2.1.25. Freeze/melt cycle (latent cold storage)

Also, this technology is an active/passive system and can be utilized for SC/PC applications (e.g. phase change materials integrated into mechanical ventilation cycles or integrated into a building envelope). In the case of active solutions electricity is utilized (e.g. use of mechanical ventilation systems).

Market availability for such technologies is given [94], [95]. However, market penetration is low. This technology is characterized by a TRL level of up to 9 (2019).

Also, in this case, due to utilizing freely available cold sources (free cooling) and external energy input is not required in the case of passive systems, considerable energy savings can be achieved.

2.1.26. Evaporative cooling (water evaporation)

Evaporative cooling devices are electrically powered. This technology achieved so far a very low market penetration, because of its inability to meet moisture removal requirements at all times (even in hot-dry climates), as well as high water consumption, the installation complexities of supplying water to equipment, and maintenance concerns [43]. This technology is characterized by a TRL level of up to 9 (2019).

Advanced evaporative cooling technology is technically applicable to all SC applications for residential and commercial buildings. This technology is technically applicable to all building types, but only in hot-dry climate regions [39]. The described technology can be utilized for SC (e.g. evaporative cooling devices - spray distribution - used in stadiums to cool down ambient air) and PC applications.

Such devices have a typical water utilization efficiency of 50% – thus on average, these systems consume nearly 4 litres of water per 3.5 kW of capacity installed in one hour of operation [39].

Advanced evaporative cooling systems currently cost approximately as much as equivalent VC systems [39].

2.1.27. Enthalpy recovery (heat exchanger)

This technology refers to building integrated heat and moisture exchange panels, which require an electrical input to activate fans being part of such systems. Concerning building-integrated heat and moisture exchange panels, it has to be underlined that such systems are on the market and currently the manufacturability and production capability of such systems is undergoing an improvement process. A widespread launch of this technology is planned. This technology is characterized by a TRL level of 7-8 (2017) [42].

The implementation of building-integrated heat and moisture exchange panels presents challenges for existing buildings because of the need for building envelope changes. In addition, the technology requires greater coordination between contractors who work with the building envelope and those who focus on HVAC.

The target market of such devices is offices and education buildings. However, this technology could be applied for SC as well as PC applications.

This technology could be cost-competitive with conventional energy recovery ventilator systems for new constructions and major renovation projects, where the product’s cost can be offset by the reduced size of HVAC equipment and ductwork, as well as savings on building cladding. Nevertheless, this technology will present challenges for existing buildings because of the need for building envelope changes.

It has been estimated that this technology could reduce 25 - 50% of AC final energy consumption and allow HVAC system downsizing by 7 - 10%. The technology could provide energy savings beyond traditional energy recovery ventilators by separating the space conditioning duties of outside air and recirculating air, lowering the pressure drop across the energy recovery ventilator for reduced fan consumption, and delivering outside air directly into the room or zone, rather than through the building’s ductwork [42].

2.1.28. Sky radiative cooling

Sky radiative cooling is the only pure passive solution identified (see Figure 19). Such devices emerged from a discovery at Stanford University in California in 2014. Afterward, a start-up has founded, developing such products [96]. Several materials, including films, spray paints, and treated wood, are under development. R&D concerning Sky radiative cooling technologies is carried out also from the side of universities, such as Arizona State University. However, there are doubts about the materials' ability to work in a wide variety of climates and places. The cooling effect works best in dry climates and with clear skies. When it is cloudy or humid, water vapour traps infrared radiation. Furthermore, the super cool materials might not last in all weathers or fit easily to all buildings. Another unknown is whether consumers will embrace the idea. Even the simple measure of replacing worn-out roofs with reflective white ones to cool houses has not been widely adopted by homeowners. There are already several related patents registrations and an effort to market Sky radiative cooling technologies is going on [97]. This technology is characterized by a TRL level of 3-4 (2019).

Sky radiative cooling can be utilized for SC of buildings (residential and tertiary sectors) as well as for PC applications (e.g. in greenhouses, keeping the indoor temperature low enough to not damage vegetables, etc.).

It is thought that this technology could remove heat at a rate of around 100 W/m^2 (currently the best performing materials remove heat at a rate of around 100 W/m^2).

So far, costs are largely unknown. However, another challenge is that radiative cooling systems might increase heating costs in winter.

It has been estimated that this technology could save 20 - 35% of cooling energy [97]–[99].

2.2. Present and future cooling technologies

In the previous section 2.1, the screening of the cooling technologies has been presented. The objective of the current section is to determine which cooling technologies, could allow a higher renewable energy content than VC, as well as their potential development, and competitiveness against VC in the target period, which has been set as 2020 - 2030.

The RED II directive already indicates what should be considered renewable. Notably, several cooling technology systems are either more efficient than the present VC systems or allow a renewable energy input to the cooling generator (in substitution of a part of electricity or gas). Moreover, a number of cooling technology systems entail both the characteristics mentioned above.

By starting from the extensive list of various cooling technologies presented in the previous section 2.1, the most promising technologies are selected by considering the period of interest for the study, 2020-2030. Subsequently, concerning the selected technologies, functional diagrams, energy balances, and key information are provided to enable the inclusion of these technologies in the following part of this work (definitions, impacts, and calculation methodologies).

2.2.1. Cross-technology comparative overview

The following Table 21 below summarizes the main technical and market-related features of the cooling technologies identified.

Table 21 Main feature of cooling technologies (regarding the description of mentioned technologies and respective sources please see section 2.1)

	TRL and year of assign-ment	Market share	Apply-able in sector SC/PC	Efficiency compared to VC	Fuel type used/ energy input	Option to use more RES than VC?	Costs compared to VC
Thermoelectric	4 (2016)	/	SC/PC	Lower	Electricity		Equal (assumption)
Thermionic	2 (2014)	/	SC/PC	Higher (assumption)	Electricity	Y	Equal (assumption)
Thermotunnel	2 (2019)	/	SC/PC	Higher (assumption)	Electricity	Y	Equal (assumption)
Electrocaloric	2 (2019)	/	SC/PC	Higher (assumption)	Electricity	Y	Unknown
Electrochemical	3 - 4 (2017)	/	SC/PC	Higher (assumption)	Electricity		Unknown
Vapour compression: RACs and CACs	Up to 9 (2019)	~ 99%	SC/PC	-	Electricity		-
Lorenz-Meutzner cycle (blends only)	4 (2019)	/	SC/PC	Higher (assumption)	Electricity		Not identified
Transcritical cycle	Up to 9 (2016)	/	SC/PC	Unknown	Electricity		Higher
Sanderson Rocker Arm Mechanism	3 - 4 (2017)	/	SC/PC	Unknown	Electricity		Unknown
Turbo-Compressor-Condenser-Expander HPs	3 - 4 (2017)	/	SC/PC	Higher (assumption)	Electricity		Unknown
Pulse tube	6 (2014)	/	PC	Lower	Electricity		Not identified
Ejector (jet pump)	3 (2014)	/	PC	Lower	Natural gas (also boiler, solar water, waste heat stream)	Y	Lower (assumption)
Vortex tube (Raque-Hilsch vortex tube)	4 (2014)	/	PC	Lower	Com-pressed air		Lower (if compressed air is available)

	TRL and year of assign-ment	Market share	Apply-able in sector SC/PC	Efficiency compared to VC	Fuel type used/ energy input	Option to use more RES than VC?	Costs compared to VC
Stirling/ Eric(c)son cycles: Reverse Stirling	4 (2017)	/	SC/PC	Lower	Gas, gasoline, wood, waste heat	Y	Unknown
Duplex Stirling	3 - 4 (2017)	/	SC/PC	Lower	Natural gas (and potentially other high-temp-erature heat sources)	Y	Unknown
Vuilleumier HP	3 - 4 (2017)	/	SC/PC	Lower	Natural gas		Lower (assumption)
Reverse Eric(c)son cycles	4 (2019)	/	SC/PC	Lower	Gas, gasoline, wood, solar	Y	Not identified
Reverse Brayton (Bell Coleman cycle)	5 - 9 (2011)	/	SC/PC	Lower	Electricity		Unknown
Bernoulli cycle	3 - 4 (2017)	/	SC/PC	Lower	Electricity		Equal (assumption)
Elastomeric effect	2 (2016)	/	SC/PC	Higher (assumption)	Electricity		Not identified
(Metastable) Critical flow cycle	3 - 4 (2017)	/	SC/PC	Lower	Electricity		Unknown
Membrane HP	5-6 (2017)	/	SC/PC	Higher (assumption)	Electricity		Equal (assumption)
Thermoacoustic	4 (2016)	/	SC/PC	Lower	Solar heat, waste heat, other heat sources	Y	Equal (assumption)
Magnetocaloric	3 - 4 (2016)	/	SC/PC	Higher (assumption)	Electricity		Unknown

	TRL and year of assign -ment	Market share	Apply -able in secto r SC/P C	Efficiency compared to VC	Fuel type used/ energy input	Option to use more RES than VC?	Costs compared to VC
Desiccant: Evaporative liquid desiccant system	3 - 4 (2019)	/	SC/PC	Higher (assumption)	Natural gas (also boiler, waste heat, solar heat)	Y	Equal (assumption)
Ground-coupled solid desiccant system	3 - 4 (2019)	/	SC/PC	Higher	Natural gas (also gas burner, waste heat, solar heat)	Y	Higher (assumption)
Stand-alone liquid desiccant system	3 - 4 (2019)	/	SC/PC	Lower	Natural gas (also boiler, waste heat, solar heat)	Y	Higher (assumption)
Stand-alone solid desiccant system	3 - 4 (2019)	/	SC/PC	Lower	Natural gas (also gas burner, waste heat, solar heat)	Y	Higher
Heat of reaction	2 (2019)	/	PC	Unknown	None		Not identified
Potential energy use	6 - 9 (2019)	/	SC/PC	Not identified	Potential energy		Not identified
Absorption and Adsorption	3 - 9 (2014)	~ 1%	SC/PC	Lower	Natural gas (also process steam, solar thermal, waste heat stream)	Y	Higher
Transcritical thermal compression HP	4 (2019)	/	SC/PC	Lower	Gas		Higher
Natural convection (heat exchanger - mixing)	Up to 9 (2019)	/	SC/PC	Not identified	Electricity (for active solutions)		Not identified

	TRL and year of assign-ment	Market share	Apply-able in sector SC/PC	Efficiency compared to VC	Fuel type used/ energy input	Option to use more RES than VC?	Costs compared to VC
Natural conduction (heat exchanger)	Up to 9 (2019)	/	SC/PC	Not identified	Electricity (for active solutions)		Not identified
Freeze/melt cycle (latent cold storage)	Up to 9 (2019)	/	SC/PC	Not identified	Electricity (for active solutions)		Not identified
Evaporative cooling (water evaporation)	Up to 9 (2019)	/	SC/PC	Not identified	Electricity		Equal (when used as an independent system)
Enthalpy recovery (heat exchanger)	7 - 8 (2017)	/	SC/PC	Not identified	Electricity		Not identified
Sky radiative cooling	3 - 4 (2019)	/	SC/PC	Not identified	None		Unknown

As visible in Table 21, there are no cooling technologies available on the market, which prove to be more energy-efficient and less expensive than VC devices.

Case of freezing applications

Absorption, Stirling cycle, and thermo-acoustic freezing are heat-driven possible competitors to the dominant VC technology [40]. Absorption refrigerators/freezers have long been available on the market; they are commonly used for hotels or mobile-home applications; they use gas as energy input. However, they remain niche market products because of their high costs. There has been little development on Stirling technologies for these applications in the recent past [40]. Thermo-acoustic technology is still being developed but the terms of the competition with absorption are not clear yet.

The electricity-driven competitors to VC identified are magnetic freezing, electrocaloric, and elastocaloric freezing [40]. If efficiency levels might reach similar efficiency levels to VC in the future, it would remain based on electricity input. The refrigeration/freezing load is nearly constant all year long - there is no product-specific PV development. Therefore, it is proposed to leave freezing applications out of the scope of the study.

2.2.2. Selection of promising cooling technology in the context of this study

Since the EU cooling market is dominated by electric VC, cooling technologies (CTs) entering the cooling market have to compete with its technical and economical characteristics.

Currently, the data/information availability does not allow to indicate reliable future developments, nevertheless, scientific literature on CTs provides pieces of information on present and expected efficiency levels, costs, and technical barriers that still need to be overcome for a technology to be able to reach the EU cooling market.

As stated above in section 2, the specific period defined for this study is 2020-2030. As a requirement to make a difference during the selected period, the emerging CTs need to be ready to reach the EU cooling market, which corresponds to TRL levels of 5 to 9. As already mentioned, only TRL levels of stages 8 and 9 correspond to systems already available on the EU cooling market.

Furthermore, it has been observed that if a CT requires 5 years to reach the market, it means that sales could increase from 2025 to 2030. In any case, the impact on the stock of cooling devices will still be very low in 2030.

Regarding the period 2020-2030, the RED II directive could support the development of an alternative technology, which may thus reach a significant share in the cooling stock by 2030 with the conditions that the selected CTs are mature enough with limited additional costs.

Shortlist of cooling technologies for the 2020-2030 period

The selection of CTs based on renewable cooling criteria and TRL of 5 or higher results in the technologies presented in Table 22 below.

Table 22 Shortlist of potential renewable cooling technologies competing over the period 2020 – 2030

Cooling technology	Mature CT ?	SC	PC	Efficiency/ renewable cooling	Costs	Applicability limitations	Hybridization required?
VC	y	x	x	Reference	Reference	None	No
VC transcritical[3]	y		x	Depends on climate	Higher	Mainly refrigeration/free-zing PC for central and Northern EU	No
VC + PV	y	x	x	Higher	PV addition	Space constraints	PV coupling to grid necessary if the battery is not large enough
Solar thermal absorption cooling	TRL 7-8 (2017)	x	x	Higher electrical efficiency	Higher	Space constraints	Yes
Waste thermal absorption cooling	y	x	x	Higher electrical efficiency	Higher	Mainly for DC	Yes

[3] Regarding VC improvement, such as transcritical cycles, it is not necessary to treat those CTs separately from VC. Indeed, if the technology enters the market it means that costs and performances are comparable to VC. For transcritical cycles, it is a solution that allows to limit the direct CO_2 emissions due to leakage of refrigerant with high GWP. Nevertheless, efforts are made by manufacturers in order to reduce these impacts (use of fluids with lower GWP, improved containment, use of nearly zero GWP fluids, etc.) that will significantly affect the global GHG emissions of VC technology over the period 2020-2030. This trend could be modelled globally without to have to model all VC individual improvement options.

Membrane HP	TRL 5-6 (2017)	x	x	Higher	Equal	Regarding PC: only for air cooling application	No
Cold recovery in AHU/Rooftop	y	x	x	Higher	Lower	Load reduction only. Requires AHU/rooftop	Yes
Cold recovery in building panels	TRL 7-8 (2017)	x	x	Higher	Lower	Load reduction only. In newly built only for this period.	Yes
Direct ambient air free cooling	y	x	x	Higher	Lower	Requires AHU/rooftop	Yes
Indirect ambient air free cooling	y	x	x	Higher	Lower	Requires chilled water loop.	Yes
Use of liquid natural/waste cold source	y	x	x	Higher	Lower	Mainly DC	Yes
Evaporative cooling, direct, indirect, or indirect + direct	y	x	x	Higher	Lower	Climate limitations Requires large air flows so limited to buildings of large height if used as standalone. Direct evaporative not adapted to SC/PC with humidity constraints.	Yes
Cold storage (centralized)	y	x	x	Higher	Higher	Requires chilled water loop. Mainly for large buildings and DC.	Yes

It is important to state that the CT - Potential energy was discarded from the shortlist of potential cooling technologies presented in the table above. It has been observed that, currently, the latter is only developed for fans, and not for compressors.

Overall, as can be observed from Table 22 above the shortlist of the CTs for the 2020-2030 period, based on the TRL threshold of 5/or above entails the following selection: vapour compression, vapour compression transcritical, vapour compression + photovoltaics, solar thermal absorption cooling, waste thermal absorption cooling, membrane heat pump, cold recovery in air handling units/rooftop, cold recovery in building panels, direct ambient air free cooling, indirect ambient air free cooling, use of liquid natural/waste cold source, evaporative cooling, which could be direct, indirect, or indirect + direct, and cold storage (centralized).

3. Evaluation of final energy consumption for cooling in 2016

In this chapter, the state of final energy consumption for cooling in Europe (for the year 2016[4]) is described by distinguishing the following sectors:

- Residential,
- Service,
- Residential plus service, and
- Industry.

Moreover, a comparison between residential, service (space cooling - SC) and industrial final energy consumptions (process cooling - PC) has been provided as well.

Furthermore, an investigation of the district cooling (DC) sector in Europe (country-by-country) has been carried out too.

A summary and comparison of the main results identified are also provided.

3.1. Methodology

To assess final energy consumption for cooling purposes per technology and country (EU27+UK), the breakdown of VC technologies proposed by [53] - (Horizon 2020 Heat Roadmap Europe 4 - HRE4 – project [37]) has been taken over, due to resulting as the most precise found among scientific literature sources. Moreover, the latter mentioned source provides data for the residential, service, and industrial sectors. The only difference of this study, compared to the breakdown of VC technologies provided by the HRE4 project, regards the moveables and window units[5] part, where the windows units have been removed due to being negligible in terms of sale numbers as well as stock installed.

Hence, the classification for the present investigation is as follows for the SC part:

- RACs:
  - Moveables
  - Small split (<5 kW)
  - Big split (>5 kW, inclusive ducted systems)

- CACs:
  - VRF system
  - Rooftop system + Packaged
  - Chiller (air-to-water) < 400 kW
  - Chiller (air-to-water) > 400 kW

[4] 2016 has been selected as a reference year due to reasons of data/information availability for this specific year, which allows to draw a complete picture on Europe’s final energy consumption for cooling.

[5] Window units are the simplest form of an AC system. Such equipment is mounted on windows or walls. It is a single unit that is assembled in a casing, where all the components are located [29].

- Chiller (water-to-water) < 400 kW
- Chiller (water-to-water) > 400 kW

While for PC, we distinguish:

- Chiller (air-to-water) < 400 kW
- Chiller (air-to-water) > 400 kW
- Chiller (water-to-water) < 400 kW
- Chiller (water-to-water) > 400 kW

According to data availability, different CAC types have been assembled in a joined section: rooftop systems plus packaged units. Moreover, concerning split systems, data and information collected enabled to distinguish sales by capacity, but not by different types: split or multi-split systems.

Vapour compression systems provide the absolute majority (nearly 100%) of Europe's cooling needs [6], [15], [45]–[52]. Concerning thermally driven HPs (TDHPs), it has to be underlined that the current market penetration is negligible compared to VC technologies. However, EUROVENT data suggest TDHPs account for approximately 1% of the EU's cooling market [52]. Further cooling technologies find just very little space in Europe's SC market and thus have not been considered in the present investigation.

Based on the provided VC technologies breakdown, an analysis of the cooling market has been performed. Among others, the authors researched mainly the following data per technology and country:

- Amount of cooling units installed
- Equivalent full load hours (EFLHs)
- Capacities installed
- Energy efficiency levels (SEER for SC and SEPR for PC)

Moreover, the work input (electricity) per cooling type has been calculated. To obtain these values, the average capacities per SC type have been divided through their respective SEER means. In the case of PC, the average capacities per equipment type have been divided through their respective SEPR means.

To retrieve reliable values, within the indicated bottom-up approach, an extensive literature analysis has been performed. Only scientific literature sources have been utilized for data collection. All collected information has been filtered and evaluated statistically. As far as the number of sources allowed, data that lie outside a range of plus or minus one standard deviation around the average of the respective data pool have been discarded. The filtered values have then been used to compute a more robust average. Unfortunately, it was not always possible to assemble two or more data per researched value and thus in these cases, no statistical elaboration has been performed.

Conclusively, the final energy consumption (FEC, electricity) by SC/PC type and the country has been calculated. To obtain the yearly final energy consumption per technology and country, the quantity (number - Nr.) of SC/PC units has been multiplied by their average equivalent full load hours (time - T) within a year and its work input (W electricity) – see (Eq.) 18.

$$FEC_{cooling} = Nr._{Units} * \ T_{equivalent\ full\ load\ \ hours} \ * \ W_{electricity} \qquad \text{(Eq.) 18}$$

Moreover, the following text explains in detail how the EFLHs, to perform the calculations mentioned above, have been calculated. The EFLHs have been carried out with two different approaches - one for the residential/tertiary sectors (SC) and a different one for PC.

3.1.1. Residential and service sectors (space cooling) – Calculation of equivalent full load hours

Space cooling processes mainly aim at achieving defined thermal comfort levels for the occupants of different buildings in the residential and tertiary sectors. In this regard, it can be assumed that SC needs are mainly impacted by environmental factors such as ambient temperature (indoor & outdoor dynamics), occupancy density at building and district level as well as population density at the city and regional level. Thus, to calculate the EFLHs for SC in the residential and tertiary sectors, it was decided to use normalized load curves, as they mirror resulting changes in electricity need and as such transform the annual hourly consumption structure.

The cooling load in residential, service, and process cooling sectors is considered linearly dependent on the outdoor temperature, and calculations are performed based on the typical hourly Meteo file[6]. Simplified sizing assumptions are also considered.

Based on the Meteonorm file, the calculation of the Cooling Degrees Day (CDD) has been implemented with a temperature reference of 18°C. The results are summarized in Table 23 below.

Table 23 Weather data calculations by climate zones

City	Country	CDD18
Wien	Austria	282
Brussels	Belgium	107.9
Sofia	Bulgary	303.15
Zagreb	Croatia	623.55
Nicosie	Cyprus	1424.7
Praha	Czech Republic	117.95
Copenhagen	Denmark	65.6
Tallin	Estonia	35.6
Tampere	Finnalnd	30.1
Lyon	France	230.25
Marseille	France	695.95
Paris	France	410.9
Frankfurt	Germany	213
Athens	Greece	964.85

[6] Weather files of typical years from the Meteonorm software version 7.1 with a period reference going from 2000 to 2009.

Debrecen	Hungary	321.8
Dublin	Ireland	0.7
Milano	Italy	714.45
Palermo	Italy	1011.85
Roma	Italy	734.35
Riga	Latvia	83.6
Vilnius	Lithuania	76.5
Luxembourg	Luxembourg	130.85
Valletta	Malta	1037.6
Amsterdam	Netherlands	78.2
Warszawa	Poland	147.3
Lisboa	Portugal	538.4
Bucharest	Romania	477.15
Bratislava	Slovaquia	322.3
Ljubjana	Slovenia	293.4
Barcelona	Spain	666.45
Madrid	Spain	707.45
Seville	Spain	1414.15
Stockholm	Sweden	70.9
London	United Kingdom	120.85

As several climates are selected for France, Italy, and Spain, the climate in this country has been weighted by their climate zones by their different building floor areas for the residential/process cooling and tertiary (service) sectors. The results are summarized in Table 24 below.

Table 24 Climate weight for France, Italy, and Spain by sectors and city

Sector	Country	City	Weight
Tertiary	Spain	Barcelona	0.34
Tertiary	Spain	Madrid	0.30
Tertiary	Spain	Sevilla	0.36
Tertiary	France	Lyon	0.28
Tertiary	France	Marseille	0.11
Tertiary	France	Paris	0.61

Tertiary	Italy	Milano	0.46
Tertiary	Italy	Palermo	0.24
Tertiary	Italy	Roma	0.29
Residential	Spain	Barcelona	0.34
Residential	Spain	Madrid	0.32
Residential	Spain	Sevilla	0.34
Residential	France	Lyon	0.29
Residential	France	Marseille	0.11
Residential	France	Paris	0.60
Residential	Italy	Milano	0.47
Residential	Italy	Palermo	0.24
Residential	Italy	Roma	0.29
Process cooling	Spain	Barcelona	0.34
Process cooling	Spain	Madrid	0.30
Process cooling	Spain	Sevilla	0.36
Process cooling	Italy	Milano	0.28
Process cooling	Italy	Palermo	0.11
Process cooling	Italy	Roma	0.61
Process cooling	France	Lyon	0.46
Process cooling	France	Marseille	0.24
Process cooling	France	Paris	0.29

Moreover, monthly CDD and Heating Degree Day (HDD) by the meteorological station (ASHRAE 2017 Climatic Design Conditions[7]) were used to evaluate the cooling season length for each location. Months in the cooling period are:

Residential sector: CDD18 ≥ 10 and HDD18 ≤ 81 (and at least 2 months, July and August, for Estonia and Ireland)

Tertiary sector: CDD10>HDD10 The tertiary cooling season has been established by the number of months where the CDD is superior to the HDD with a reference temperature of 10°C based on the ASHRAE Meteo file.

Process cooling: it is assumed to operate all the year 365 days per year at 24 hours per day. The length of the cooling season according to different climates is presented in Table 25.

[7] Most stations of the ASHRAE are sourced through the Integrated Surface Database (ISD) from NOAA (www.ncdc.noaa.gov) for a period of 1990-2014 except for Berlin, period of 1982-2003,1996-2014 and 1990-2013 with a temperature reference of 18,3°C.

Table 25 Length of the cooling season according to different climates

Countries	Number of months for the residential cooling season	Number of months for the tertiary cooling season
Austria	5	7
Belgium	3	7
Bulgary	4	7
Croatia	5	7
Cyprus	7	12
Czech Republic	3	6
Denmark	2	5
Estonia(*)	2	5
Finland	2	5
France	4	7
Germany	3	6
Greece	6	12
Hungary	4	7
Ireland(*)	2	6
Italy	6	9
Latvia	2	5
Lithuania	2	5
Luxembourg	2	6
Malta	7	12
Netherlands	2	6
Poland	3	5
Portugal	7	12
Romania	5	7
Slovakia	4	7
Slovenia	4	7
Spain	5	9
Sweden	2	6
United Kingdom	2	5

Residential sector

To assess the cooling load in the residential sector, the outdoor temperature, where the cooling need starts (also called the thermal balance point of the building, which is the average outdoor temperature below which cooling is not needed and above which heating is not needed) was assumed to be of 20°C [100]. The cooling load was assumed to be 100% at the maximum temperature encountered in the typical year. These maximum temperatures are given in Annex I Tmax values in Meteonorm data files.

The cooling load / outdoor temperature relationship is presented in Figure 22 for three different climates.

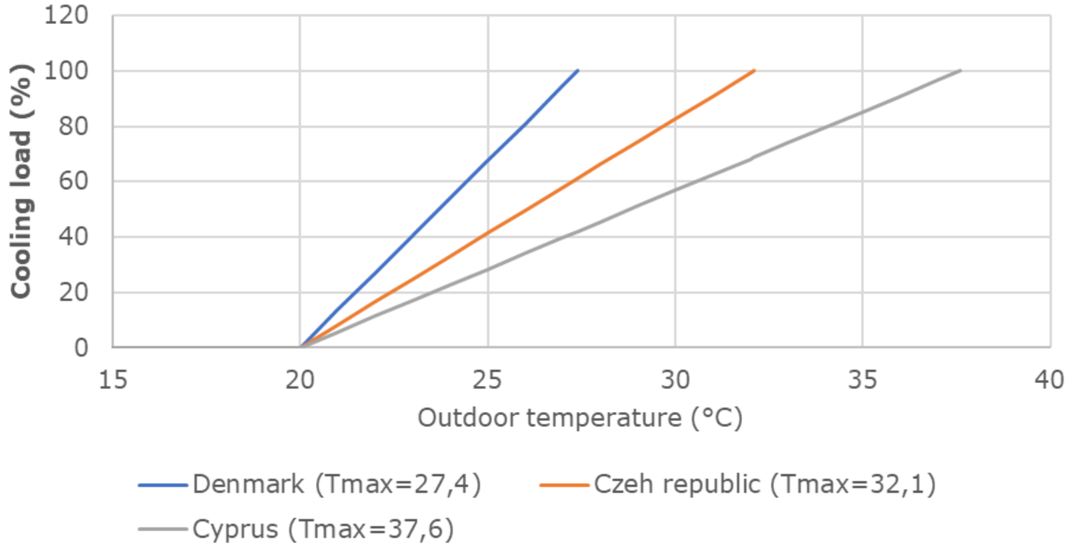

Figure 22 Estimation of the residential cooling load according to the outdoor temperature

In the residential sector, the cooling system was assumed to be switched on for the whole cooling season. Therefore, the yearly number of EFLHs in the residential sector is evaluated by (Eq.) 19 below.

$$EFLHs = \sum_{i,season} \frac{Ti - 20}{Tmax - 20}, Ti > 20 \qquad \text{(Eq.) 19}$$

Service sector

The current section presents the method used to simulate the air-conditioning needs (W/m² at 30 minutes time step) of the commercial building stock for each country in the EU27+UK. The method is close to the one used for the residential sector. However, a complete parameterization was carried out to respect the particularities of the commercial sector. The main adaptations concern the size and geometry of the buildings, the internal loads, the ventilation rate, and the thermal model.

For each climate, the commercial building stock was represented by 2000 individual buildings for each sector of activity: offices, trades, hospitals, hotels, and restaurant buildings simulated with Smart-E the simulation platform of Mines ParisTech [101]. Each simulated building had a specific cooling surface, geometry, occupancy, and thermal parameters. Table 26 summarizes the hypotheses for building stock parameterization.

Table 26 Hypotheses for building stock parameterization

Parameters	References	Hypothesis validation scale	Diversity inside the building stock
Size of buildings (m²)	Office, Trade: INSEE Others : Metadata,CH-SIA-2014	France Switzerland	yes
Geometry and heat exchange surface	ENTR Lot 6 Study Own assumptions	Europe	yes
Occupancy	Office building: ENTR Lot 6 Study Other buildings: Metadata,CH-SIA-2014	Europe Switzerland	no
Internal loads	NF EN 13790 Metadata,CH-SIA-2014 Own assumptions	Europe Switzerland	no
U values	HotMaps	Europe	yes
Years of construction	HotMaps	Europe	yes
Cooling setpoint	Nf EN 13790 Own assumptions	Europe	no
Weather data	Meteonorms v7.2	Europe	yes
Solar shading	Own assumptions	France	no
Ventilation	NF EN 16798	Europe	no
Inertia	Own assumptions	France	yes
Cooling season	Own assumptions	Europe	no

Sector definition

Buildings have been divided into four different categories: offices, hotels and restaurants, hospitals, and trade buildings base on the statistics from the French institute INSEE[8] . The office buildings are all the tertiary buildings with a high proportion of office employees in metropolitan France. The trade buildings are all the buildings associated with the activity of the wholesale and retail trade. The hotels and restaurant buildings are all the buildings associated with food and accommodation. The hospital buildings are all the buildings associated with hospital activity.

Number of occupants

For each building in France, the INSEE records the number of employees of the buildings by a range as presented in Table 27.

[8] All of the office in the activities with a proportion of 90% or more of office employees are considered as office buildings, the activities concerned are: Information and Communication, financial and insurance activities, real estate activities, professional, scientific and technical activities, administrative and support service and public administration with compulsory social security activities. The database for the inventory of the stock is available in [102].

Table 27 The number of employees according to the number of employees of the building in the INSEE statistic [103]

Number of employees	Proportion in the INSEE databases (%)
[3;5]	41
[6;9]	23
[10;19]	18
[20;49]	11
[50;99]	4
[100;199]	2
[200;249]	>1
[250;499]	>1
[500;999]	>1
[1000;1999]	>1

The buildings with less than 3 employees were excluded from the study since it has been assumed that most of them were integrated into the residential sector (town doctor, lawyers, independent contractors, etc.). The buildings with more than 1999 employees were also excluded from the representative building stock for two reasons.

Firstly, for these specific ranges, the occupants are often split into several buildings with a common address (which was not mentioned in the databases). Secondly, business owners tend to sum all the employees at the company headquarter, even if they are distributed around the country.

To determine the number of employees, a number inside a uniform distribution between the minimal and maximal number of employees has been drawn. As only 21% of the employees in the trade sector do not work in offices, solely 21% of the number of employees of the database has been taken into account to determine the number of workers in the trade sector with a minimum of 1 employee.

Thus, it was assumed that in the trade sector for each employee there are 5 customers per hour, which means that there are 6 occupants per hour for one employee in the building. As each customer stays for 30 minutes in the building, it was considered that there are 3 occupants per employee in the building.

For the hotels and restaurants building categories, it has been assumed that there were 4 clients for each employee for each sector.

With regards to the hospital buildings, it has been assumed that there were 521 hospital beds for 1000 employees based on the European Hospital and Healthcare Federation for the year of 2014 [104] with an occupation rate of the bed of 0.77 [105].

Then, the total surface of the office building was estimated by a coefficient of the surface per employee according to the work of Marty et al. (2018) [106]. The coefficients are presented in Table 28 below.

Table 28 The surface area per employee according to the number of employees in the office buildings [106]

Number of employees	Surface per employee (m^2/employee)
<45	22
[45;217]	23
>217	32

Concerning trade buildings, the total surface area for trade buildings in France in 2013 was determined [107] and it has been divided by the total number of employees in the trade sector in France in 2013 [108]. Based on that method, the total surface area resulted to be 33.2 square-meter per employee for trade buildings.

Regarding the other buildings (Hotels, Restaurants, Education, and hospitals), the estimation of the surface area was based on the occupation density given by the City Energy Analyst [104]. Respective data are given in Table 29 below.

Table 29 The surface area per employee according to the City Energy Analyst [104]

Type of building	Density (m²/occupant)
HOTEL	15
RESTAURANT	2
SCHOOL	3
HOSPITAL	9.28
UNIVERSITY	10

Vertical walls surface

Outside vertical walls surface

The estimation of the outside vertical walls has been estimated based on the modelling of offices, trade, hospital, hotels, and restaurant building sectors according to the ENTR Lot 6 study [110]. The source provides a ratio of outside vertical walls and glazed vertical surfaces per total surface area according to the type of building. The ratios are presented in Table 30 and Table 31 below.

Table 30 Estimation of the outside vertical walls by type of buildings according to the ENTR Lot 6 study [110]

Type of buildings	Total surface area (m²)	Ratio of all vertical walls (opaque and glazed) per total surface area (%)	Ratio of glazed (vertical) surfaces per total surface area (%)
Large office building	5001-15000	58	26
Medium office building	1001-5000	42	9
Small office building	0-1000	54	21
Hypermarket	1001 - 6000	37	4
Shopping mall	6000 - 13000	63	4.8
Small trade building	0-1000	37	21
Health buildings	Any	30	8
Hotels buildings	Any	50.4	9.3
Restaurant buildings	Any	78.3	9.3

Table 31 Estimation of the outside vertical walls by type of buildings according to the ENTR Lot 6 study [110]

	Total surface area (m²)	Ratio of all vertical walls (opaque and glazed) per total surface area (%)	Ratio of glazed (vertical) surfaces per total surface area (%)
Large office building	5001-15000	58	26
Medium office building	1001-5000	42	9
Small office building	0-1000	54	21
Hypermarket	1001 - 6000	37	4
Shopping mall	6000 - 13000	63	4.8
Small trade building	0-1000	37	21
Health buildings	Any	30	8
Hotels buildings	Any	50.4	9.3
Restaurant buildings	Any	78.3	9.3

Adjacent vertical surfaces

The adjacent surfaces were supposed to be dependent on the total surface area of the buildings. Therefore, we assumed that 75% of the vertical walls were adjacent surfaces for small tertiary buildings (less than 100 m² of the usable surface) and that large tertiary buildings do not have adjacent surfaces (more than 1000 m² of surface area).

With regards to the other buildings, it has been assumed that the buildings have a linear interpolation of the share of adjacent surfaces between these values (Figure 23).

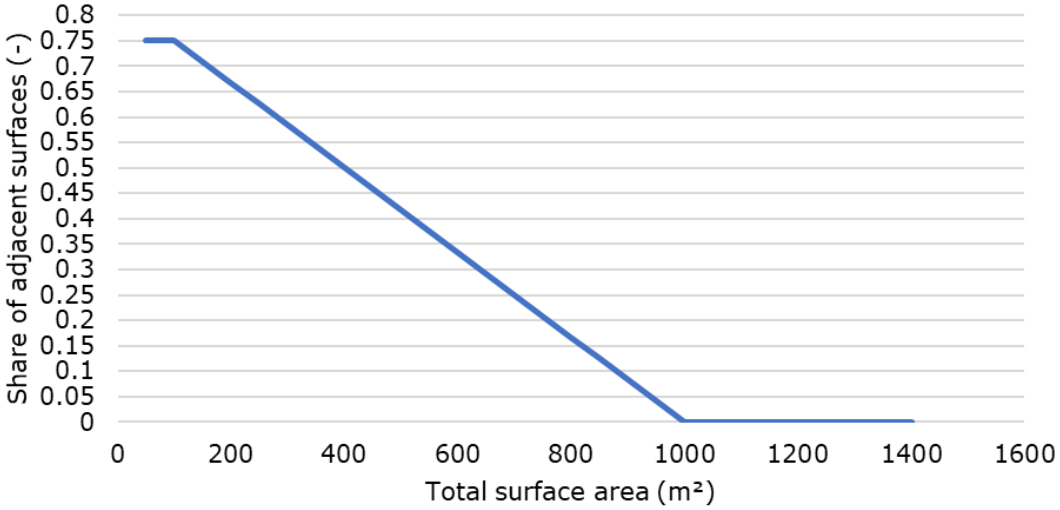

Figure 23 Share of adjacent surfaces based on the total surface area

This hypothesis aims to better represent small tertiary surfaces inside large built-up areas: shops at the foot of a building, offices occupying a single floor of a tower. For example, it has been assumed that a shop of less than 100 m² has only 25% of its vertical surface area is in contact with the outside part.

Height and number of floors

The height and the number of floors of the tertiary buildings were estimated according to the ENTR Lot 6 study [110] (modified for 0 to 1000 m² buildings), as presented in Table 32 and Table 33 below.

Table 32 Estimation of height and number of floors based on the total surface area on European office buildings

Office buildings surface total are	Height of floor	Number of floors
0-1000	2.7	1
1000-3000	2.7	2
3001 - 7500	3	4
>7500	3	12

Table 33 Estimation of height and number of floors based on the total surface area on European office buildings

Trade buildings surface total are	Height of floor	Number of floors
0-1000	3	1
>1000	7	1

Concerning the other buildings, the ENTR Lot 6 study [110] estimates the height and the number of floors according to Table 34, some other assumptions have also been implemented.

Table 34 Estimation of height and number of floors based on the total surface area on European tertiary buildings

Type of buildings	Height of floor	Number of floors
Health	3	5
Hotels[9]	2.5	4
Restaurants	2.2	1
School[10]	2.2	2
University	4.2	2

Floor and roof surfaces

The floor and roof surfaces were estimated by the formula below:

$$S\_fr = \frac{St}{Nb_{floor}} \qquad \text{(Eq.) 20}$$

[9] For a medium size hotel according to the ENTR Lot 6 Study [110].

[10] The height of the school and university are assumed to be equal while the university has lecture halls that tends to increase the height of the floors, therefore we assumed a lower height for school buildings at 2.2 meters.

Where:

- S_fr is the surface of the floor and the roof of the building
- S_t is the total surface area of the building

U values

Based on the H2020 HotMaps project [111], the U coefficients for the roof, the floor, the walls, and the windows of the building are determined for each country, each sector, and each range of years of construction.

The estimation of the range of years of construction has been determined by the ratio of the total area of buildings constructed by country and by sectors from the H2020 HotMaps project [111].

The presentation of the repartition of the years of construction is presented in

Annex III Years of construction.

Ventilation

All of the buildings own a mechanical ventilation system and it is turned on when there is an occupant in the building. A single flow system was assumed for each building.

Based on the NF EN 16798, the fresh air flow is estimated at 1.68 vol/h when there is one occupant and more. Besides that, it has been assumed that the airflow is equal to 0.5 vol/h.

Occupancy

The occupancy scenario for office buildings is presented in a semi-hour period from one week by Figure 24:

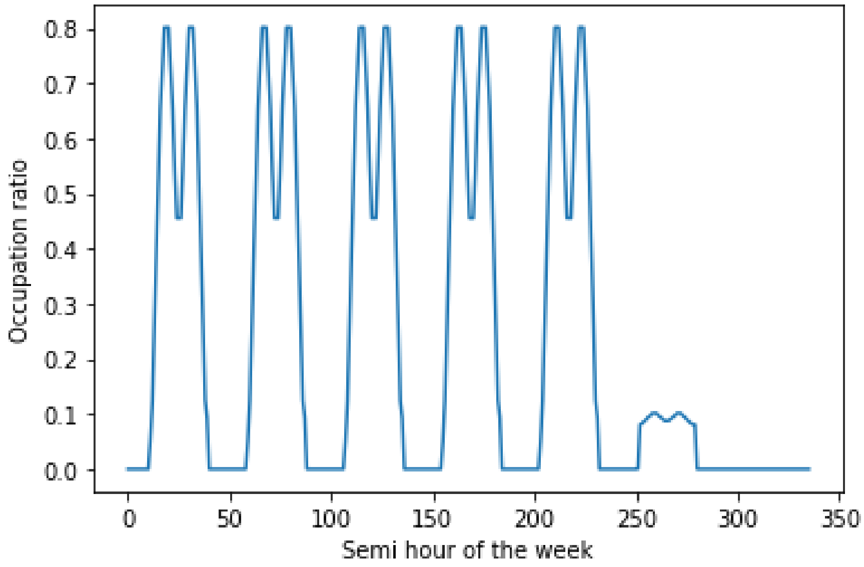

Figure 24 Presentation of the occupancy scenario for office buildings

The scenario for office buildings is based on the hourly occupancy ratio estimated in the ENTR Lot 6 study [110] with a range of variation of maximum ±10% (draw independently at each time step). We also assumed that on weekend days the occupancy is equal to 10% of the occupancy of the weekdays. Finally, we assumed that there is at least one occupant in the building if the occupancy ratio is superior to 0.

As the occupancy scenario of the office buildings has been introduced, the occupancy scenario for trade buildings is presented in a semi-hour period from one week by Figure 25 below.

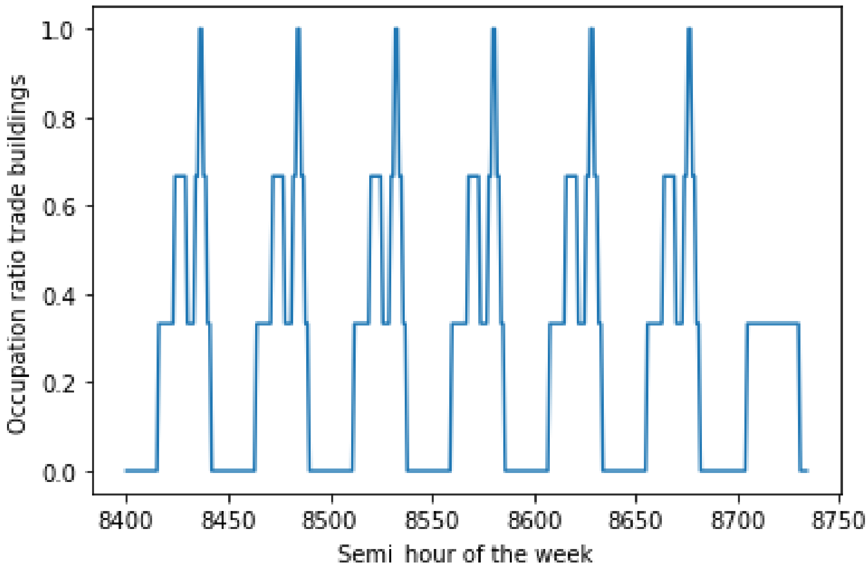

Figure 25 Presentation of the occupancy scenario for trade buildings

The occupancy scenario for trade buildings was estimated based on the referential scenario developed by the City Energy Analyst [104] with a range of variation of maximum ±10% (draw independently at each time step). Also, it has been assumed that on weekend days the occupancy is equal to 30% of the occupancy of the weekdays with a limit of 40% occupancy and that there is at least one occupant in the building if the occupancy ratio is superior to 0.

As the occupancy scenario of the trade buildings has been introduced, the occupancy scenario for hotel buildings is presented in a semi-hour period from one week by Figure 26.

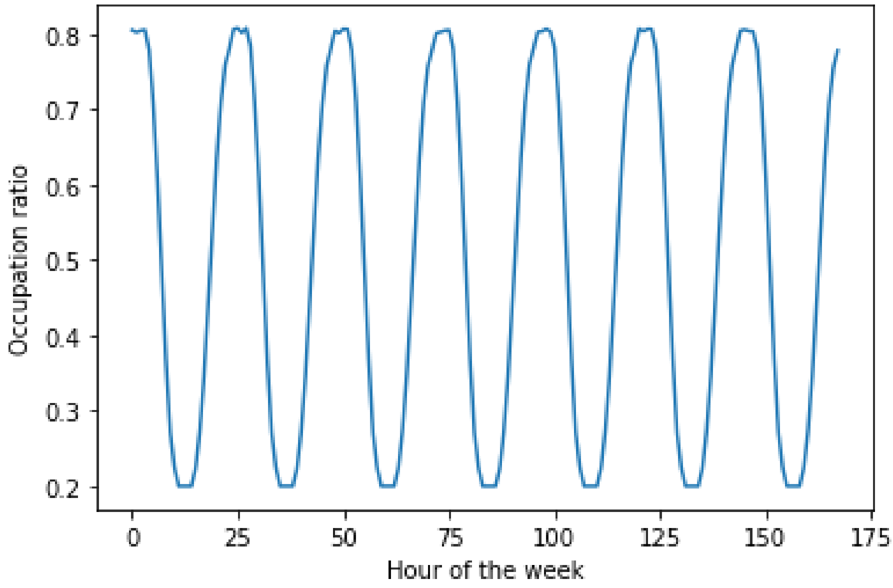

Figure 26 Occupation scenario for hotel buildings

The occupancy scenario for hotel buildings was estimated based on the referential scenario developed by the City Energy Analyst [104] with a range of variation of maximum ±10% (draw independently at each time step). Also, it has been assumed that the hotels' sector enlists one employee for four visitors during all seasons.

Moreover, it has been assumed that in the daytime, there are only the employees in the room and at nighttime, there are only the customers.

As the occupancy scenario of the hotel buildings has been introduced, the occupancy scenario for restaurant buildings is presented in a semi-hour period from one week by Figure 27.

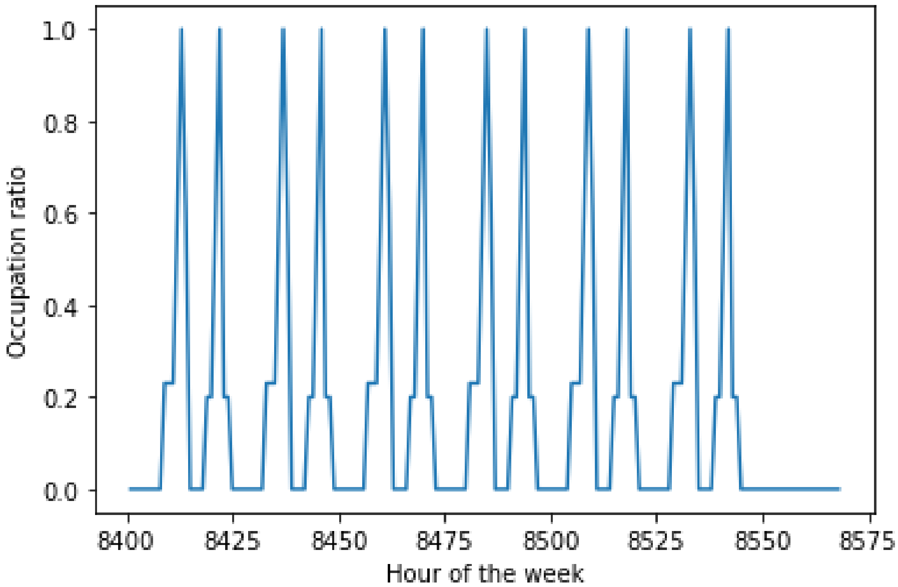

Figure 27 Occupation scenario for restaurants buildings

The occupancy scenario for restaurant buildings was estimated based on the referential scenario developed by the City Energy Analyst [104] with a range of variation of maximum

±10% (draw independently at each time step). Besides that, it has been assumed that the restaurant sector enlists one employee for four visitors during all seasons.

The City Energy Analyst also assumed that the restaurants are closed on Sundays.

As the occupancy scenario of the restaurant buildings has been introduced, the occupancy scenario for hospital buildings is presented in a semi-hour period from one week by Figure 28.

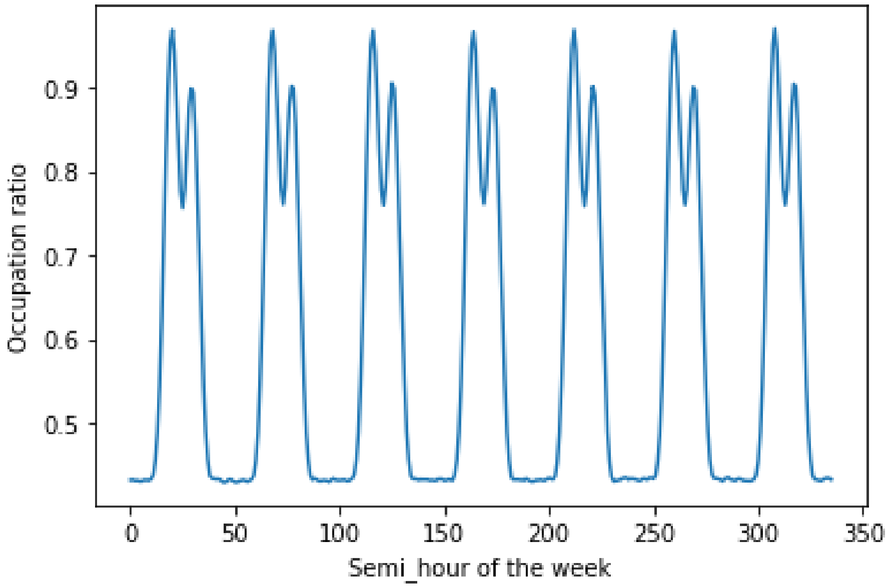

Figure 28 Occupation scenario for hospital buildings

The occupancy scenario for hospital buildings was estimated based on the referential scenario developed by the City Energy Analyst [104] with a range of variation of maximum ±10% (draw independently at each time step). Besides that, it has been assumed that for each employee staff, there is a nurse-patient ratio of 0,40. It is assumed that at nighttime the occupancy of hospital buildings is at 43%.

Internal Loads

The light transmission of the windows and the solar heat gain are estimated at 60% according to the ENTR Lot 6 study [110].

Based on the NF EN 13790, the parameter of the estimation of the internal load was estimated below:

- The metabolism load is estimated at 80 watts per occupant for office and hospital buildings, 90 watts per occupants for trade buildings (client and employees included), and 100 watts per occupants for hotels and restaurants buildings.

The electrical appliances loads were also estimated by the NF EN 13790, the assessments are shown in Table 35 below.

Table 35 Electrical appliances load based on the type of buildings

Type of buildings	Electrical appliances (W/m²)
Offices	15
School	5
Hospital	15
Restaurant	10
Trade	10
Hotel	4

The thermal power of the lighting equipment was assumed to be at 5 W/m².

Examples of electrical appliances gain and the internal loads' gains for the different types of buildings are shown in the charts below from Figure 29 to Figure 38:

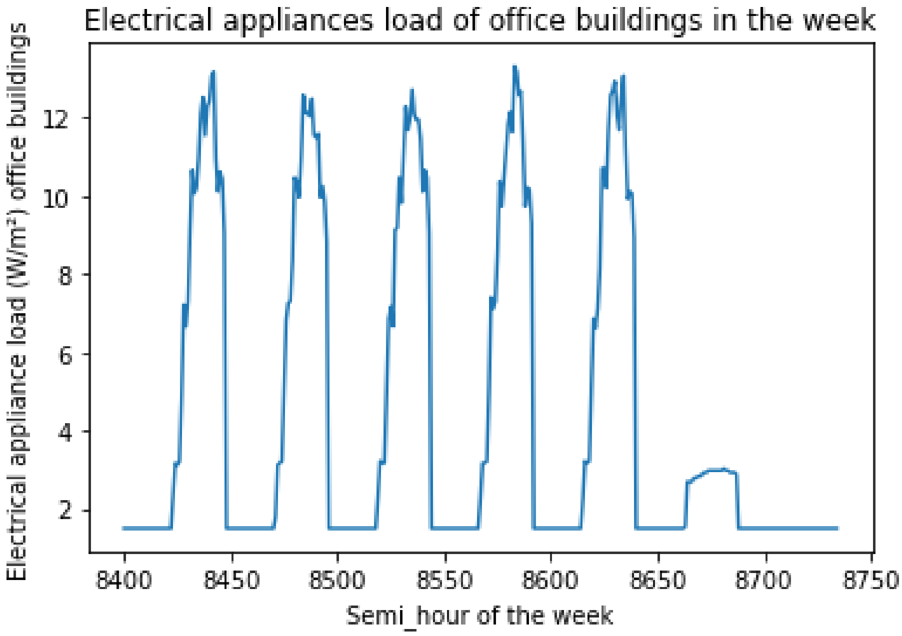

Figure 29 Electrical appliances load of office buildings during the week

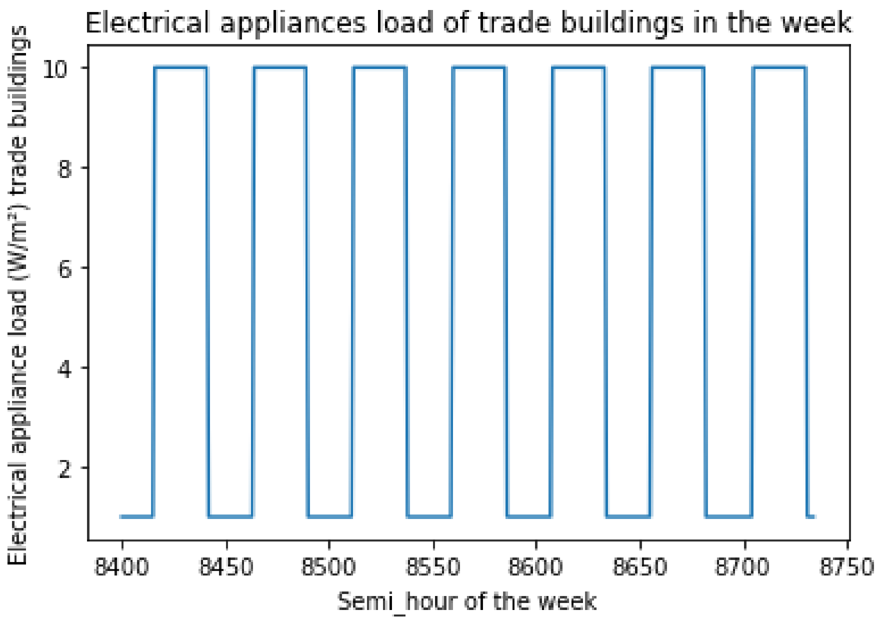

Figure 30 Electrical appliances load of trade buildings during the week

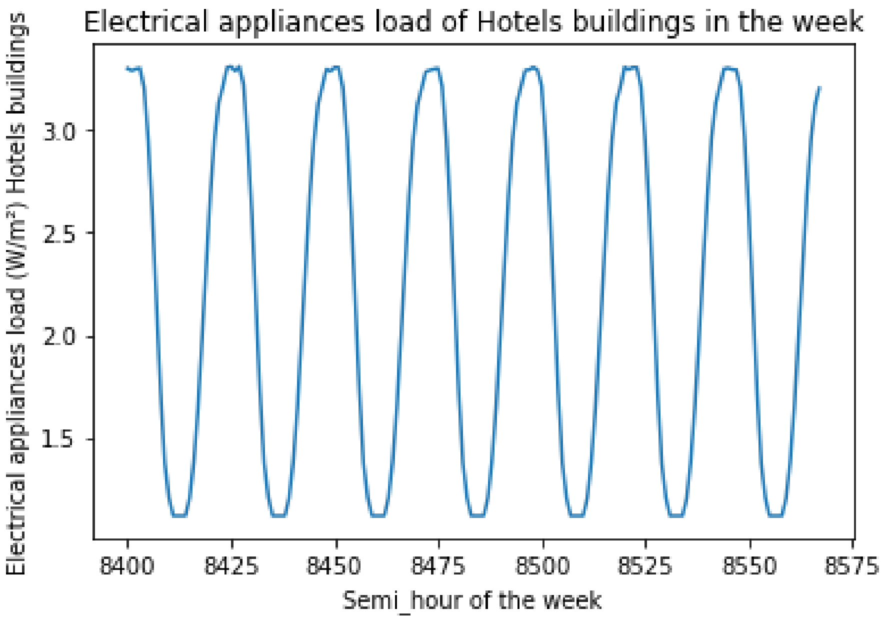

Figure 31 Electrical appliances load of hotel buildings during the week

As can be seen, the space cooling needs in hotels buildings are mostly present at night time due to the occupation of the customers during that period.

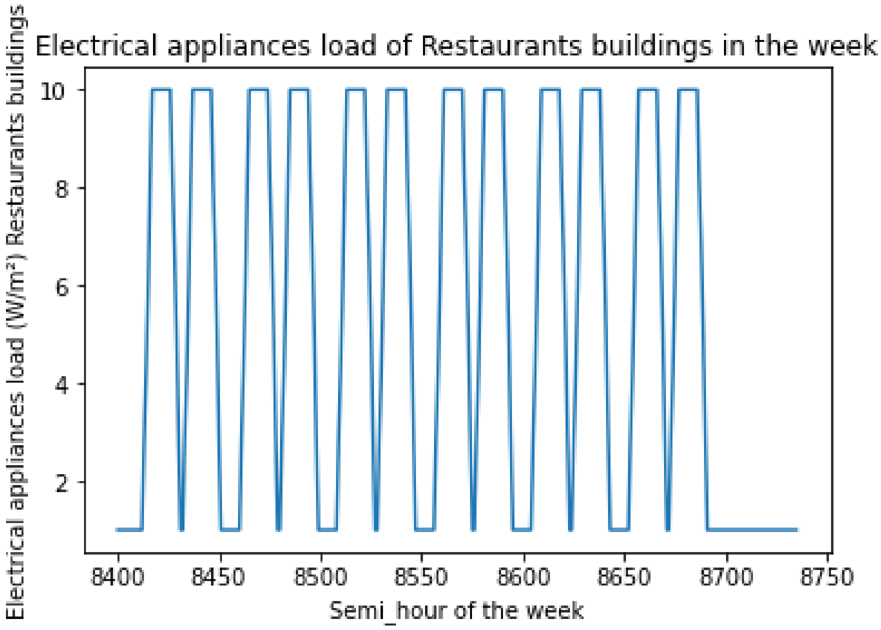

Figure 32 Electrical appliances load of restaurants buildings during the week

As shown, the space cooling needs in restaurant buildings are mostly present at lunchtime and dinnertime due to the occupation of the customers during that period.

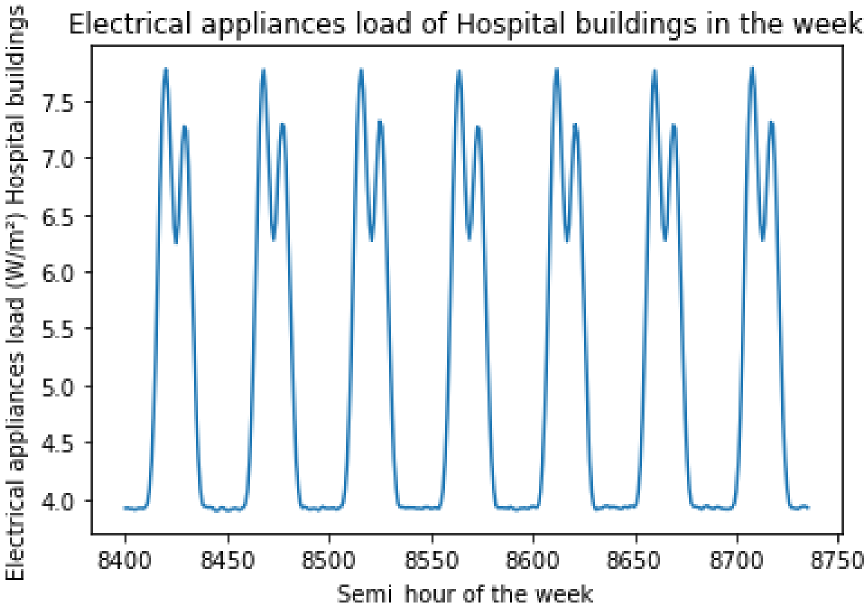

Figure 33 Electrical appliances load of hospital buildings during the week

Then the internal loads are presented from Figure 34 to Figure 38 below:

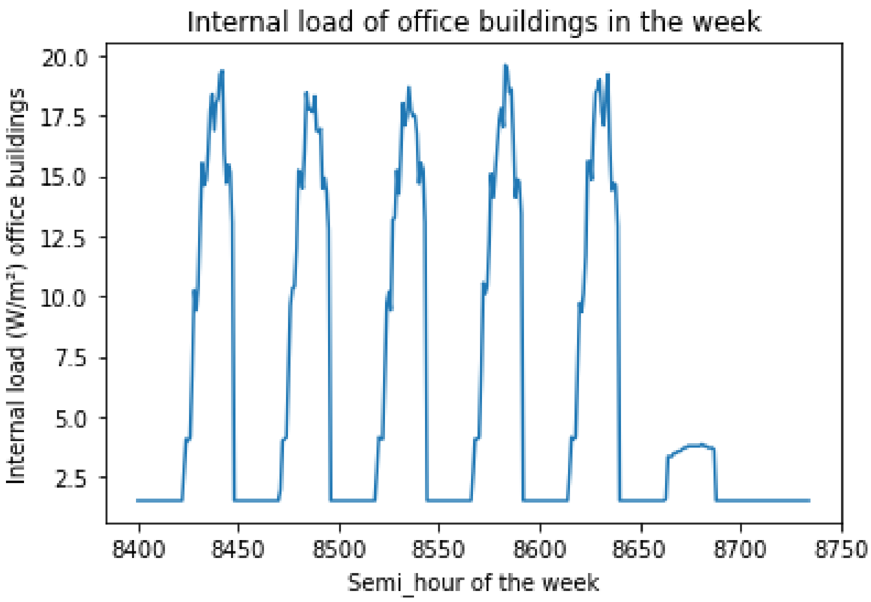

Figure 34 Internal load of office buildings during the week

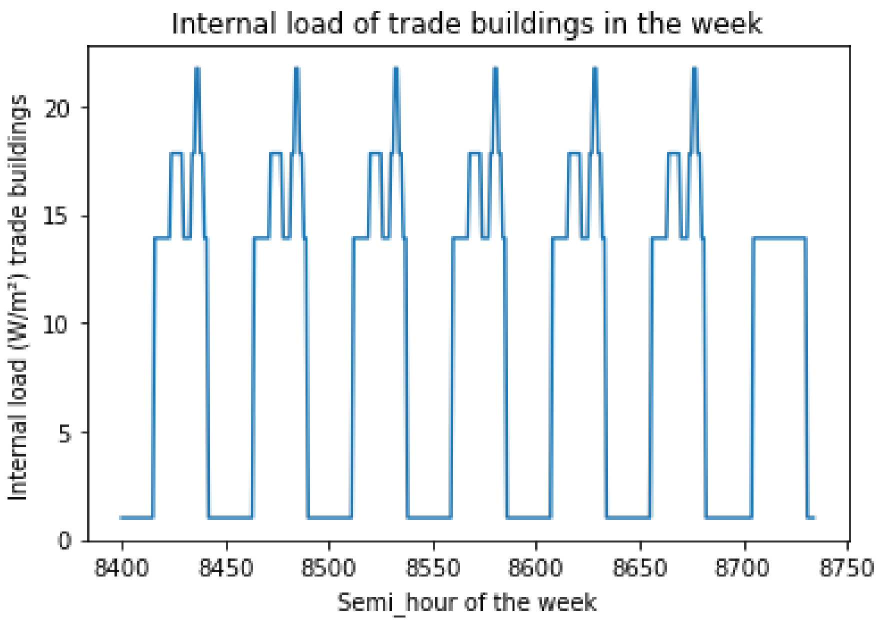

Figure 35 Internal load of trade buildings during the week

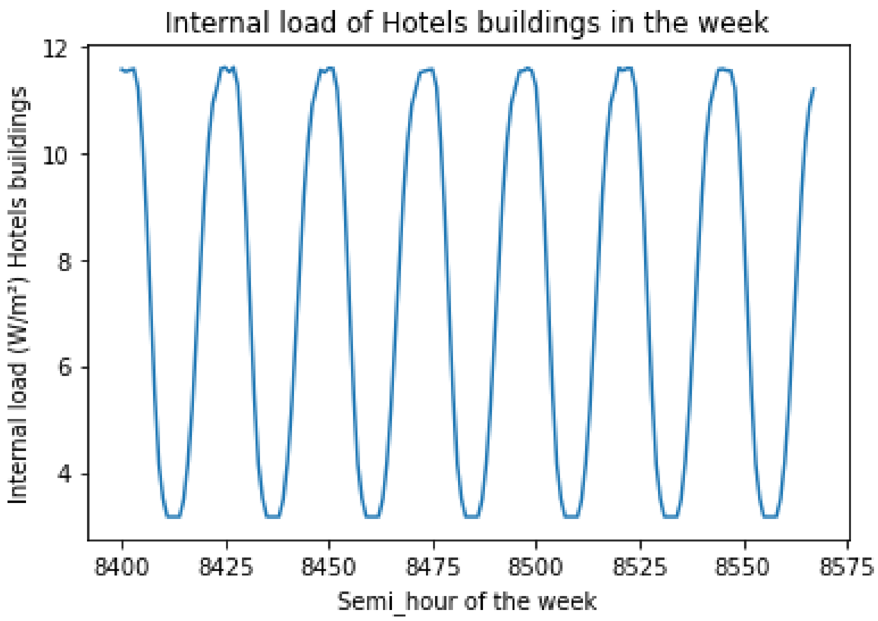

Figure 36 Internal load of hotel buildings during the week

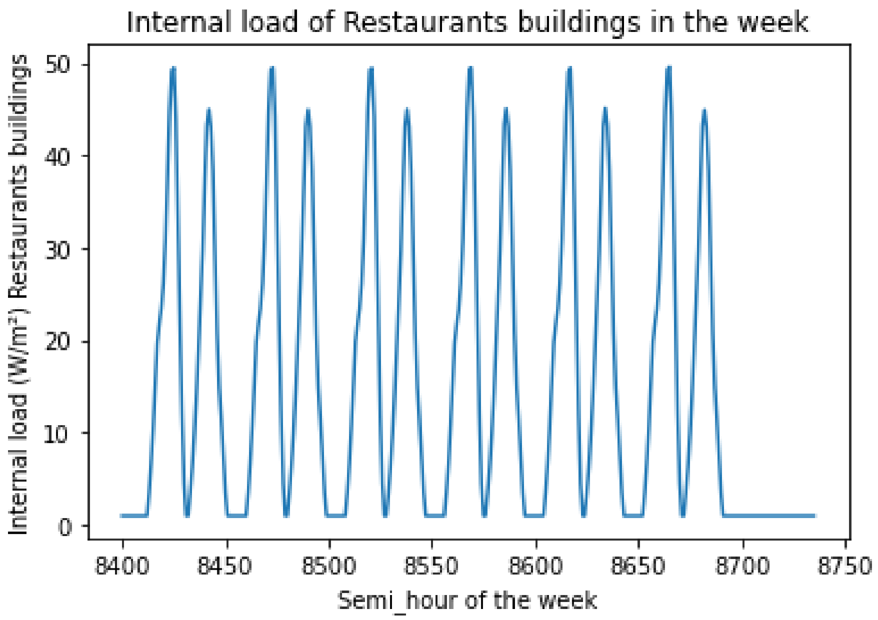

Figure 37 Internal load of restaurants buildings during the week

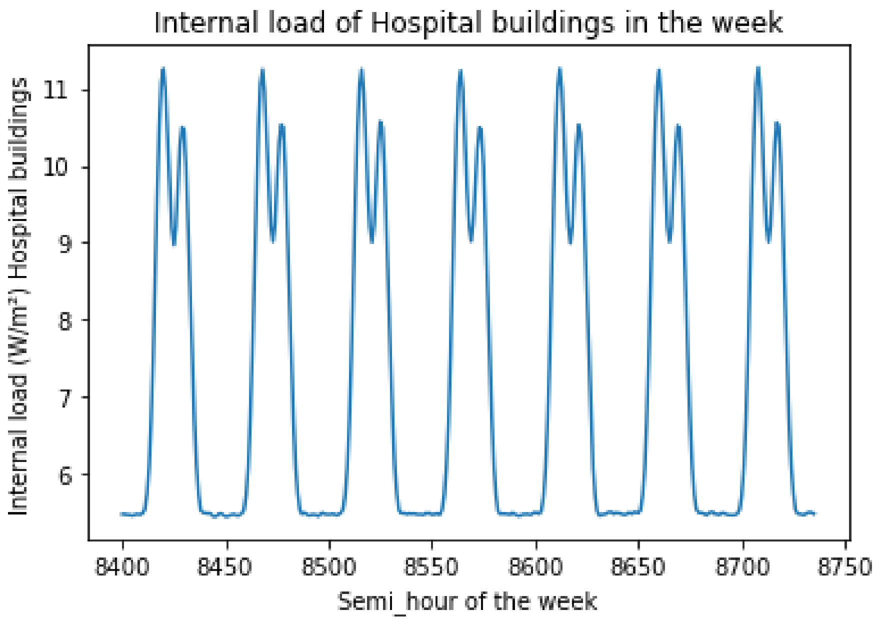

Figure 38 Internal load of hospital buildings during the week

The internal loads of restaurants buildings are higher due to superior density inactivity and a larger device gain in this type of building.

Cooling set-point

The set-point temperature of the buildings was assumed to be at 23°C in summer. If there is no occupant, the set-point cooling temperature of the building is increased by 7°C.

Thermal zone

To be more realistic, the surface area of the buildings has been divided into two distinct zones. The zone "south" receives the integrality of the solar gain and the "north" zone where there is no solar gain. Each zone represents 50% of the total surface area. The simulation time step is 30 minutes for control purposes, even if the final results are analyzed at 60 minutes time steps.

Results

The next figures show one-week simulation outputs for the climate of Greece.

- Office buildings

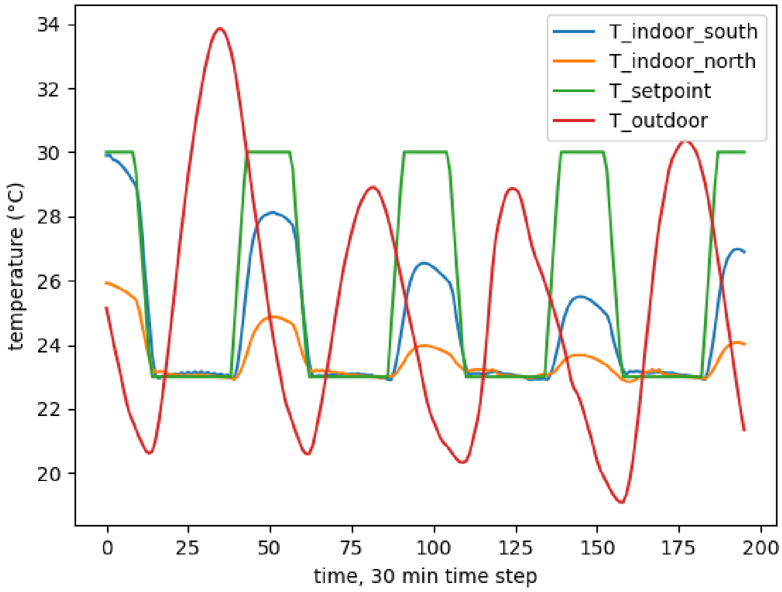

Figure 39 Example of outdoor temperature with set-points and indoor temperature of the two thermals zones for one office buildings in Greece in 4 days

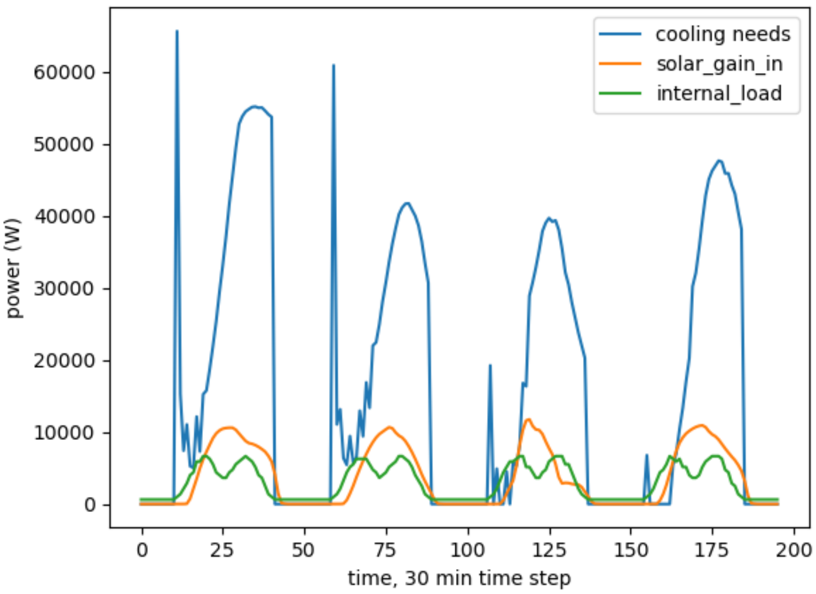

Figure 40 Example of space cooling needs compared to solar gain and the internal load of one office building in Greece in 4 days

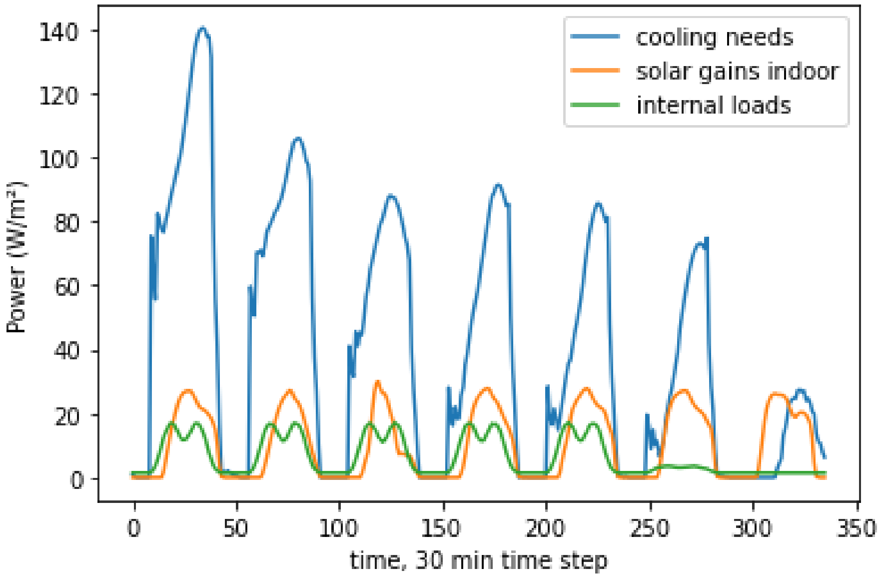

Figure 41 Space cooling demand compared to solar gain and the internal load of one office building in Greece in one week

- Trade buildings

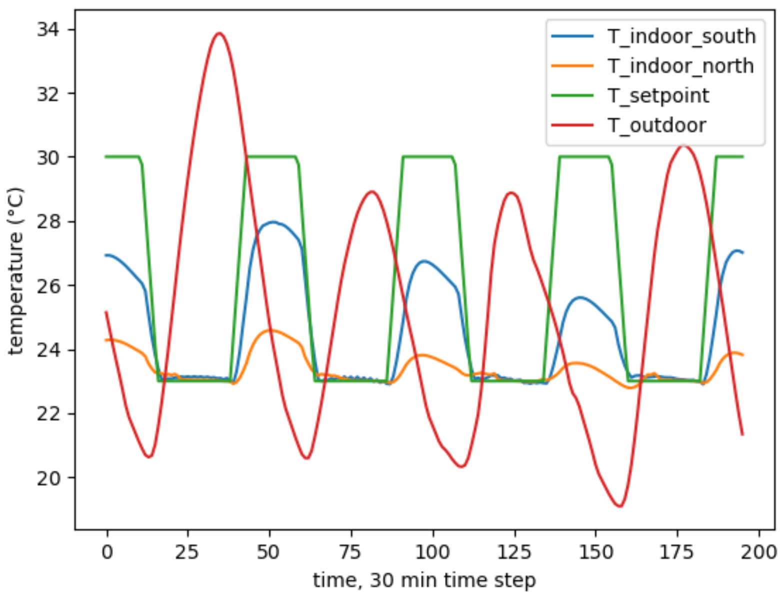

Figure 42 Example of outdoor temperature with set-point and indoor temperature of the two thermals zones for one trade buildings in Greece in 4 days

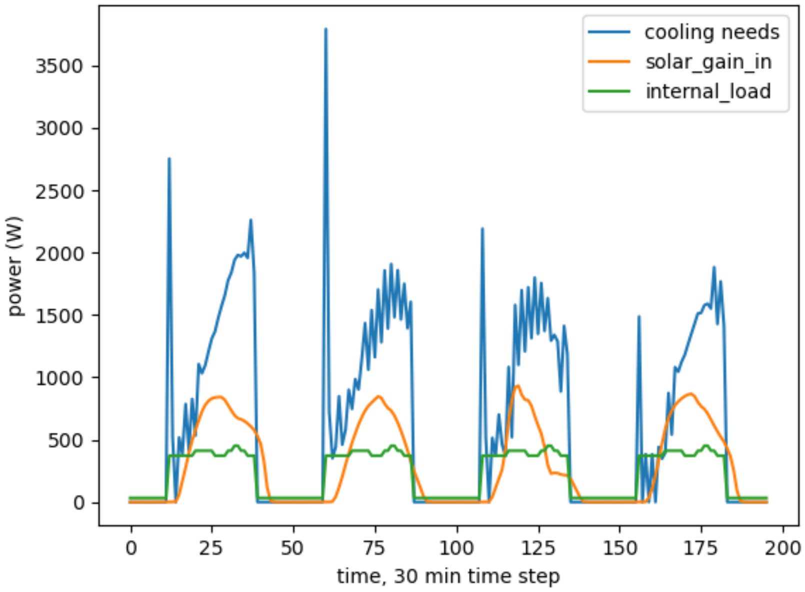

Figure 43 Example of space cooling needs compared to solar gain and the internal load of one trade building in Greece in 4 days

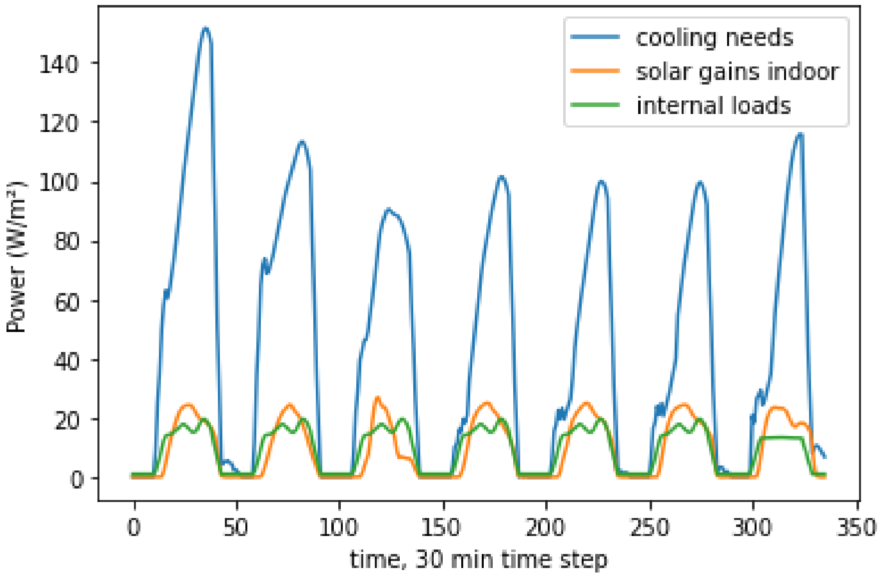

Figure 44 Space cooling demand compared to solar gain and the internal load of one trade building in Greece in one week

- Hotel buildings

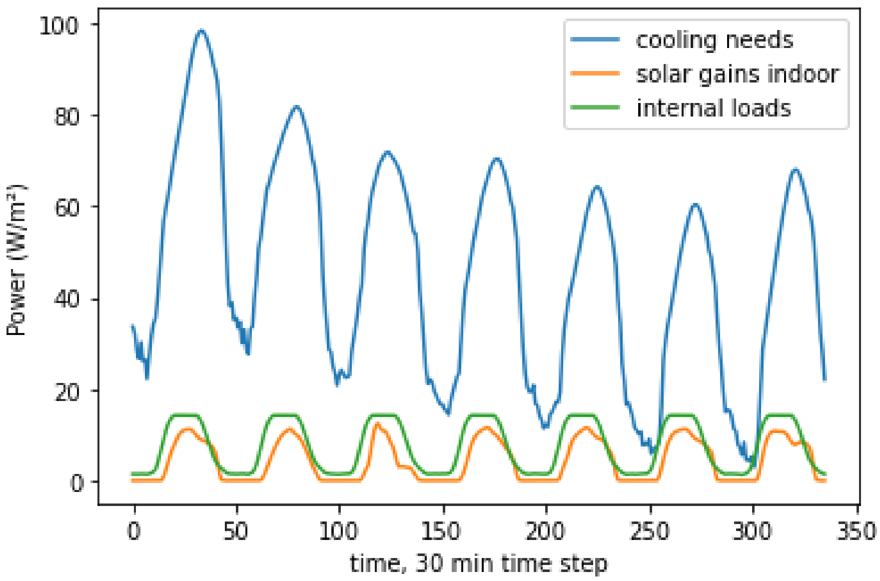

Figure 45 Space cooling demand compared to solar gain and the internal load of one hotel building in Greece in one week

- Restaurant buildings

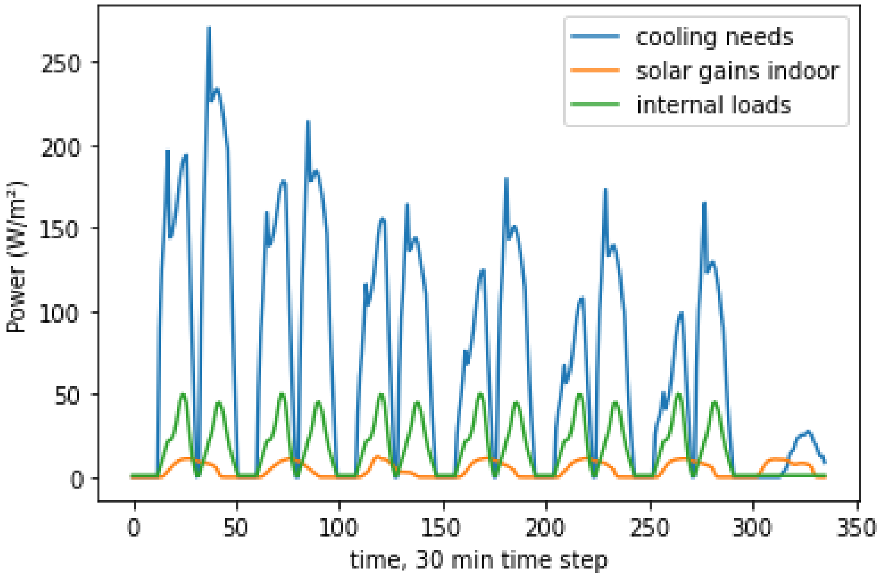

Figure 46 Space cooling demand compared to solar gain and the internal load of one restaurant building in Greece in one week

- Hospital buildings

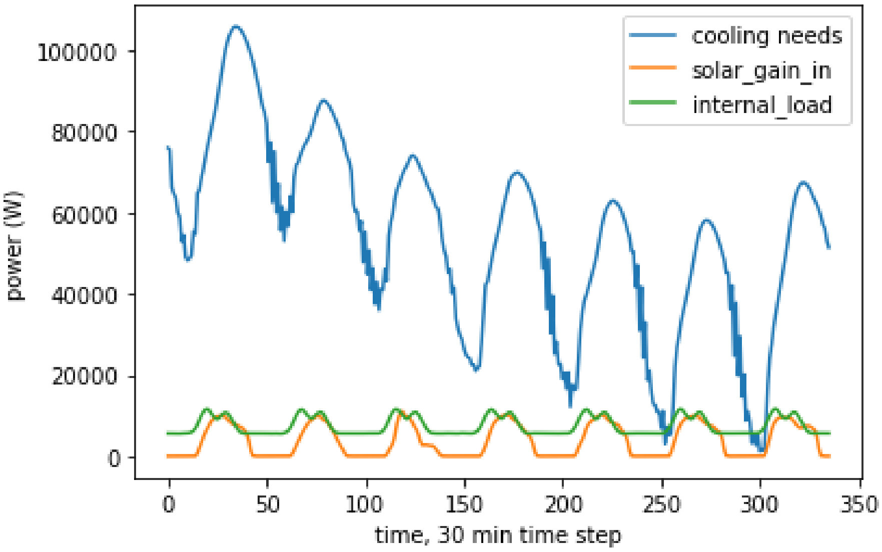

Figure 47 Example of space cooling needs compared to solar gain and the internal load of one hospital building in Greece in one week

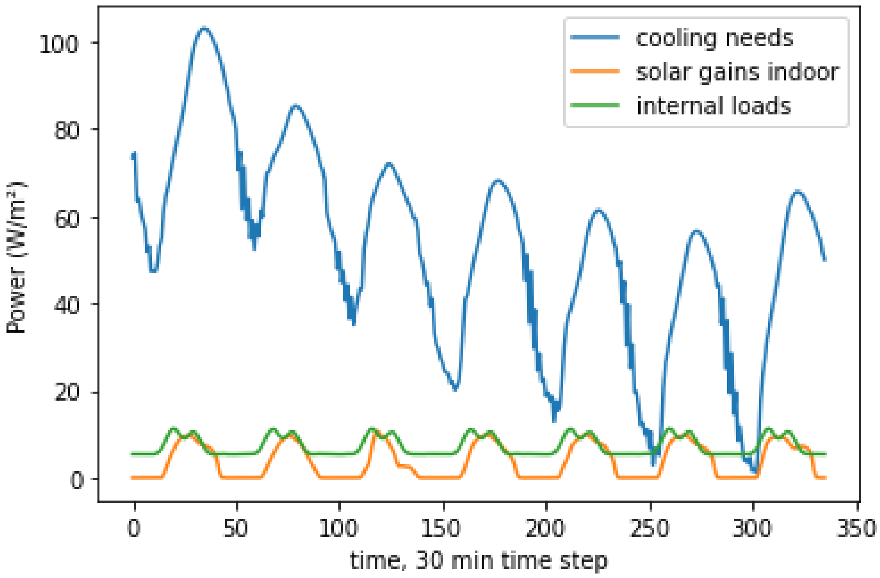

Figure 48 Space cooling demand compared to solar gain and the internal load of one hospital building in Greece in one week

Several observations can be made from the figure above, such as that turning on the air conditioning in the morning creates significant peaks in cold demand. Moreover, the internal and solar gains are of the same order of magnitude as the space cooling requirements. These two phenomena must be correctly parameterized (an average and in diversity) to represent the space cooling demand accurately. Besides, hospitals, hotels, and office buildings have the highest cooling demand due to a higher surface area of the building compared to trade and restaurant buildings.

Cooling estimation

Based on that repartition the estimation of the cooling demand of the EU27+UK countries is estimated by the CDD with a temperature reference of 18°C for office, trade, and residential buildings. The results are shown in Figure 49.

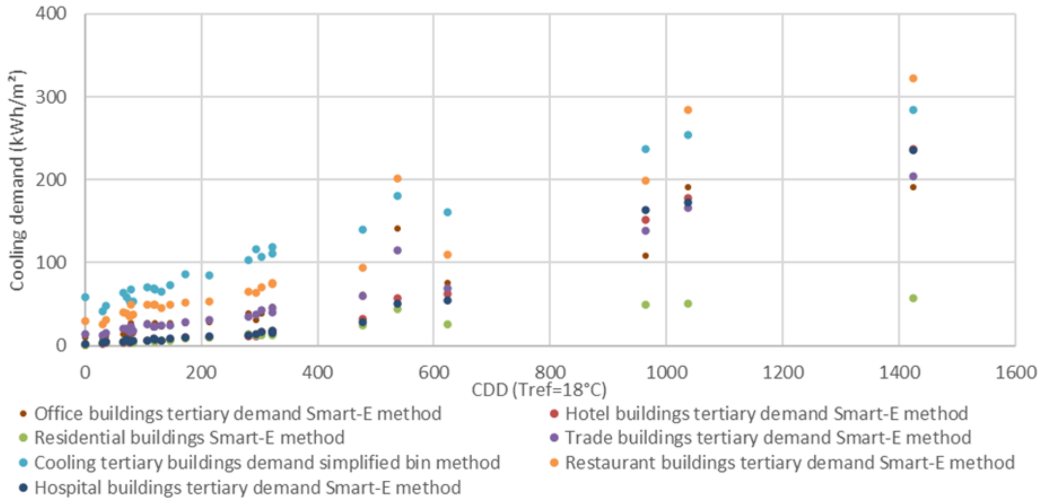

Figure 49 Estimation of the space cooling demand based on the Cooling Degrees Day of each country

The difference in the dependence for residential and tertiary buildings is mainly due to the definition of the space cooling season. For the country of Portugal (with a CDD of 538.4) and the country of Malta (with a CDD of 1037.6), the space cooling season is activated for all of the year.

The latter tends to give space cooling needs throughout the year due to the high solar gain of these countries. For that reason, Malta and Portugal have an important difference with the residential space cooling need and the tertiary space cooling need of the other countries in the EU27+UK and reduce the correlation between the tertiary space cooling need and the residential space cooling need.

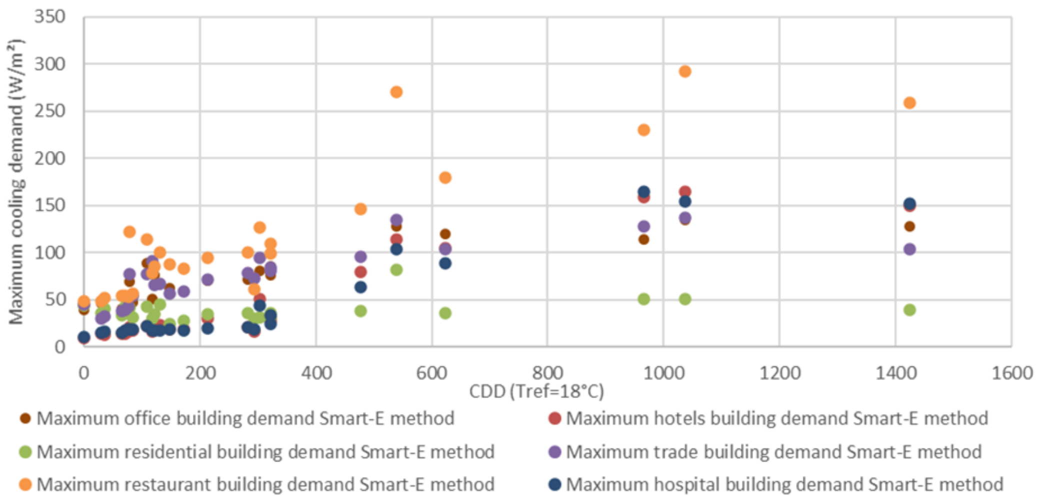

Figure 50 Maximum space cooling demand based on CDD of each country

The maximum space cooling demand is less dependent on the CDD due to the inclusion of the solar gain with the Smart-E method for the estimation of the hourly space cooling needs.

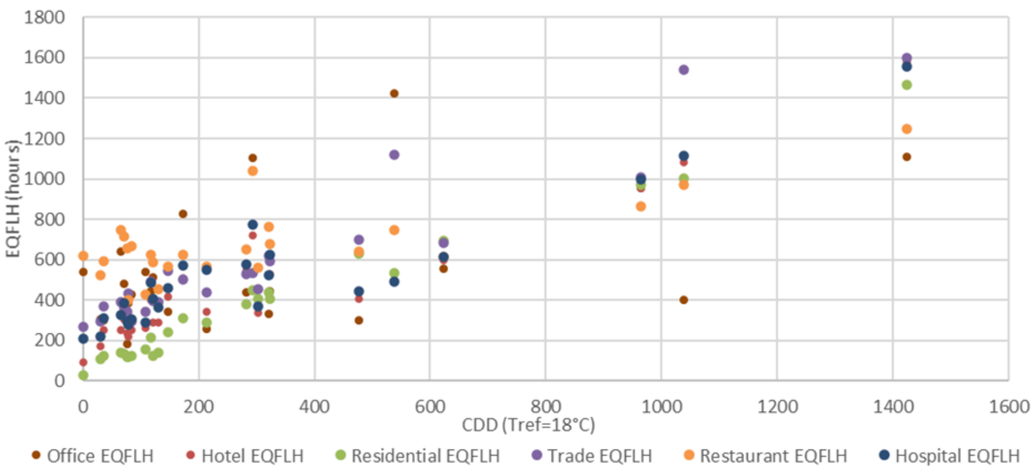

Figure 51 Equivalent full load hours based on CDD of each country

Equivalent full load hours weighting procedure

Finally, the current section highlights how the EFLHs, which were initially obtained for different sectors: offices, trade, hotels and restaurants, and hospitals and retirements, have been weighted and distributed for each EU27+UK country.

Some EU27+UK countries, such as Spain, France, Italy, and Germany presented more than one city to which the EFLHs have been addressed.

The weighting procedure started taking into consideration the necessity to obtain a single representative value of kWh/m^2 y per countries such as France, Spain, Italy, and Germany in which more than one kWh/m^2 y value has been associated. To do that, and to properly weight the different kWh/m^2 y values related to different cities, the constructed area data (Mm^2) of the service sector have been retrieved from the building stock of the H2020 HotMaps project (see HotMaps deliverable 2.3 [123]). Moreover, once the data (Mm^2) have been retrieved from each subsector (offices, trade, hotels, etc.), they have been also expressed in the percentage of the total constructed area (Mm^2) of the service sector.

Lastly, once the data was set up, the final kWh/m^2 y values have been obtained for Paris, Lyon, Marseille, Milan, Rome, Palermo, Berlin, Frankfurt, Madrid, Barcelona, and Seville.

Next, the values of kWh/m^2 y, W/m^{2,} and EFLHs were compared with cities CDD and resulted in graphs for each subsector. It has been observed that kWh/m^2 y and W/m^2 y are rather linear/monotonous as a function of CDD. Moreover, starting from the kWh/m^2 y values obtained above, the constructed area (Mm^2) of the building stock of the H2020 HotMaps project has been associated with each kWh/m^2 y value per subsector, resulting in the weighted constructed area (Mm^2) for the cities mentioned above.

Once again, the EFLHs values per subsectors mentioned above needed to be weighted with the constructed area (Mm^2) of the building stock of the H2020 HotMaps project, to obtain a single average EFLH value per country.

Please find the resulting EFLHs per country and sector (residential and service) in Figure 56 and Figure 61 respectively.

3.1.2. Process cooling – Calculation of equivalent full load hours

To calculate the EFLHs of PC, a different method has been used since the H2020 HotMaps project load curves have been considered not appropriate for the calculations. The method uses land surface temperature (LST) hourly profiles for a whole year (8760 hours) at a NUTS2 level. A constant-linear-constant law [33] is then applied to derive PC EFLHs. The approach and its various steps are explained in more detail below:

1. The Copernicus Global Land Service has been used to retrieve LST data [113]. The data are collected based on instantaneous observations, and the product is calculated globally every hour and made available to the user in near-real time with a timeliness of 4 hours. Further details can be found in the LST product user manual [114]. The selected dataset refers to the year 2018, the first year with a full hourly LST coverage. Land surface temperature data are affected by cloud cover and data consistency issues. However, they can be filtered according to the related quality flags encoded in each hourly acquisition. The process has allowed selecting only cloud-free areas. To fill incomplete data, all the CDD (cooling degree days) at the NUTS2 level retrieved from the public repositories of the H2020 HotMaps project [111], have been clustered into five different sets as has been done about SC (see the previous section). The clustering has been performed using the k-means algorithm [115]. If for a defined hour (h) and a specific NUTS2 (NUTS2i) no data were present, the missing LST value has been filled considering the median value of all available LST values (for h, i) and the according to the cluster.

2. Since some values of the elaborated temporal series were still missing, the following measures were applied:
   - The missing LST values were identified.
   - The identified missing values were substituted with the average value, for the same hour of the day, before and after.
   - A Savitzky-Golay filter [116] for a window of seven hours and polynomial order equal to 2 has been applied. This was necessary to produce an LST time series without discontinuities.

3. Following steps 1 to 2, a complete dataset of hourly LST was available at each ($_i$) NUTS2 level (LST_{Nuts2}). This data set has been used to calculate a normalized hourly time series for each ($_i$) NUTS2 ($LOAD_{Nuts2}$). According to the following (Eq.) 20, a constant-linear-constant hourly load law [33] has been applied, with LST referring to temperature and temperature levels expressed in degree Celsius (°C). The results are presented in Figure 52.

$$LOAD_{Nuts2i} = 0.8 \,\{if\ LST_{Nuts2i} < 5°C\}$$

$$LOAD_{Nuts2i} = 0.8 + \frac{0.2}{30} * (LST - 5) \,\{if\ 5°C \le LST_{Nuts2i} \le 35°C\} \quad \text{(Eq.) 20}$$

$$LOAD_{Nuts2i} = 1 \,\{if\ LST_{Nuts2i} > 35°C\}$$

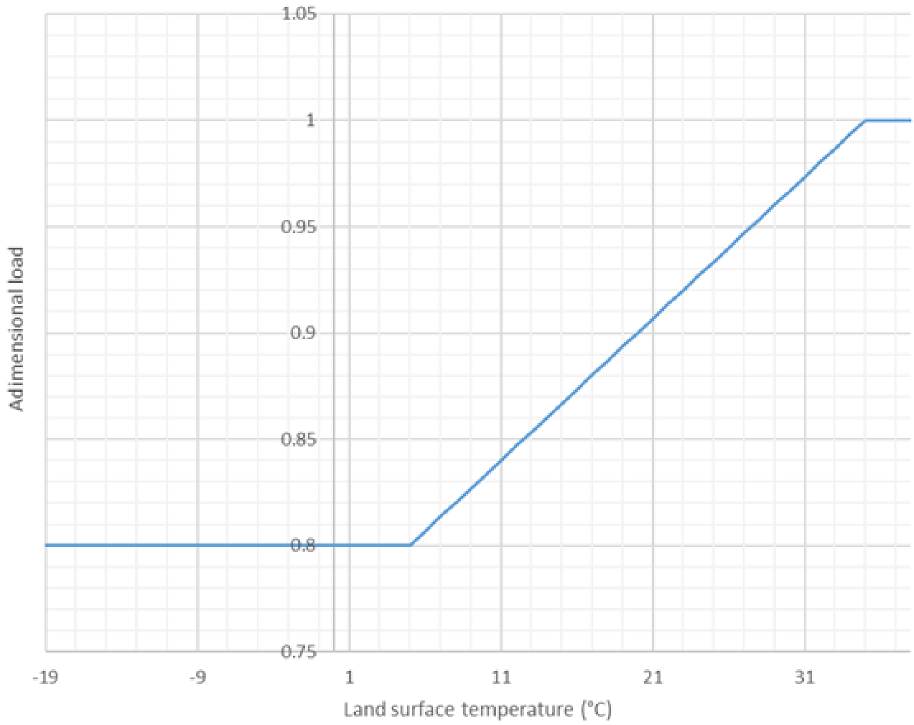

Figure 52 Load curve law for process cooling

4. The EFLHs at each (i) NUTS2 level (EFLHsNuts2) have been derived by applying the following (Eq.) 21, with 8760 referring to hours in a year:

$$EFLHs_{Nuts2i} = \sum_{i}^{8760} LOAD_{Nuts2i} \quad \text{(Eq.) 21}$$

Once the EFLHs for each ($_i$) NUTS2 region of the EU27+UK ($EFLHs_{Nuts2}$) were obtained, a national value for each country has been determined ($EFLHs_{National}$). Since cooling can be considered correlated with the gross domestic product (GDP) [117], it has been decided to weigh the NUTS2 level values of the EFLHs (EFLHsNuts2i) according to GDP at each (i) NUTS2 level (GDPNuts2i), according to (Eq.) 22.

$$EFLHs_{National} = \frac{\sum_i \quad (EFLHs_{Nuts2i} * GDP_{Nuts2i})}{GDP_{National}} \quad \text{(Eq.) 22}$$

Equivalent full load hours results of the PC sector at the national level for EU27+UK are shown in Figure 69. The included European mean value has been calculated by weighting all the national EFLHs values using the national GDP values.

Furthermore, SEPR values have been obtained by following the respective calculation methodology indicated in the European Standard EN 14825.

What’s more, regarding DC the methodology applied follows this of previous sections concerning SC as well as PC.

However, in this case, the capacity installed is provided by the country, since scientific data sources provide only such indications (e.g. [118]–[120]).

Moreover, in this case, we do not differentiate among final energy consumption between different sectors, since the sources utilized do not allow performing such calculations for the entire EU27+UK.

The energy efficiency parameter utilized as input for (Eq.) 23 is the SEER, provided by the Deliverable 3.2 of the Heat Roadmap Project (HRE) [53]. The data of the latter mentioned source have been actualized in 2020 utilizing the latest information available, provided by BSRIA Worldwide Market Intelligence (WMI) [121] and EUROVENT [52].

The equivalent full load hours (EFLHs) have been obtained by dividing the DC sales (MWh/y) through the respective capacity installed (MW) per country found mainly in the source [118].

Furthermore, to obtain the following useful energy demand (UED) for DC, the installed capacity ($C_{installed}$) has been multiplied by EFLHs ($T_{equivalent\ full\ load\ hours}$) per country – not taking into consideration the SEER. Please see (Eq.) 23:

$$UED_{District\ cooling} = T_{equivalent\ full\ load\ hours} * C_{installed} \quad \text{(Eq.) 23}$$

Finally, it has to be added that the map given in Figure 73 has been created by using geographic information systems (GIS) – in specific QGIS 3.6.

3.2. Main results

3.2.1. Residential (SC)

Due to a high number of values (for all single EU27+UK countries) the following figures display the main outcomes in aggregated form for the whole EU27+UK. Figure 58 shows the total final energy consumption for SC (TWh/y) for each country. The same structure has been followed for the following sections regarding the service and industry sectors as well as concerning DC.

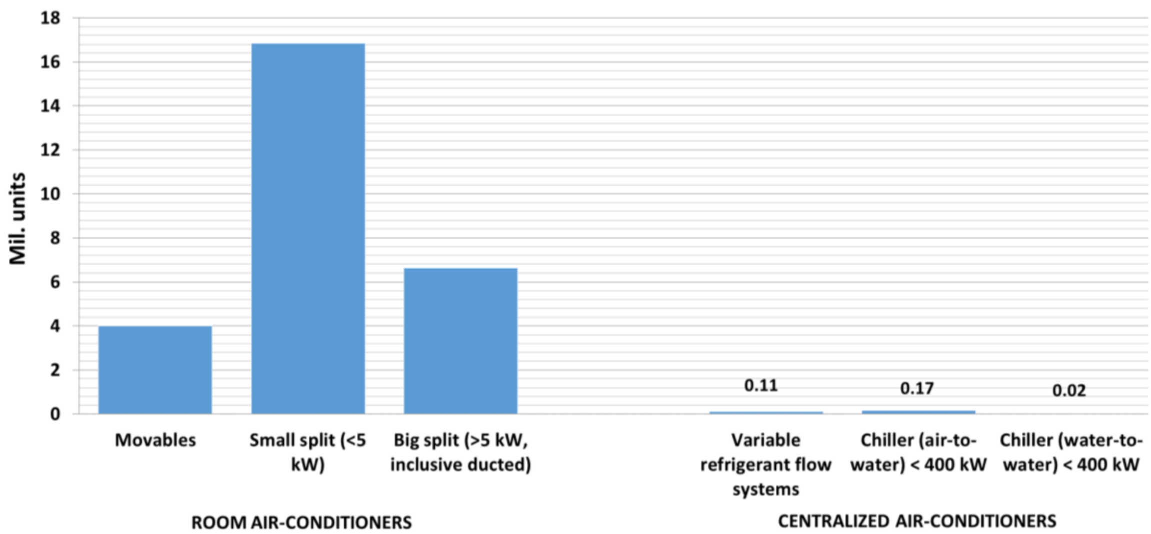

Figure 53 Amount of installed units per space cooling type in the residential sector, EU27+UK, the reference year 2016 [6], [37], [47], [48] – due to not being very visible, the amount of certain centralized air-conditioners are indicated by values over their bars

Small split (<5 kW) systems account for the majority of SC units per type with more than 16 million (mil.) installed devices. Big split (>5 kW, inclusive ducted systems) systems follow with almost 7 mil. systems. The least represented RAC system type is moveables, with about 4 mil. units. The amount of installed CAC systems is in order: around 0.17 mil. VRF systems, about 0.11 mil. chiller (air-to-water < 400 kW) and approximately 0.02 mil. chiller (water-to-water) < 400 kW.

Moreover, it has to be underlined that rooftop plus packaged units, chiller (air-to-water) > 400 kW, and chiller (water-to-water) > 400 kW come out to be with a limited presence in the residential sector [6], [49], [122]. Therefore, they have not been computed.

Next, Figure 54 indicates the average installed capacity per SC type in kW.

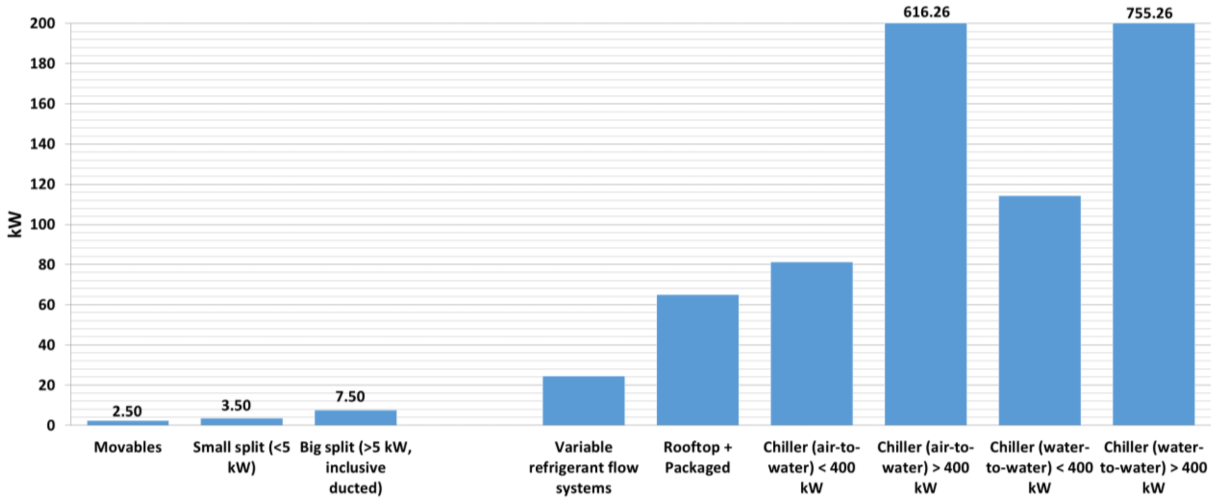

Figure 54 Average installed capacity per space cooling type in the residential sector, EU27+UK, the reference year 2016 [6], [37], [48] – due to not being very visible, some average installed capacities are indicated by numbers over their bars

Chiller (water-to-water) > 400 kW result in having the largest installed mean value: more than 750 kW. Chiller (air-to-water) > 400 kW follow with almost 620 kW. Chiller (water-to-water) < 400 kW come next with about 115 kW and chiller (air-to-water) < 400 kW result in having a mean capacity installed of about 80 kW. VRF systems are penultimate among CACs with about 65 kW and rooftops plus packaged units are last positioned with about 25 kW.

Furthermore, Figure 55 provides information concerning the SEER. Given, no installed units of rooftop plus packaged chiller (air-to-water) > 400 kW, and chiller (water-to-water) > 400 kW have been detected in the residential sector, the following figure lacks information concerning these SC types.

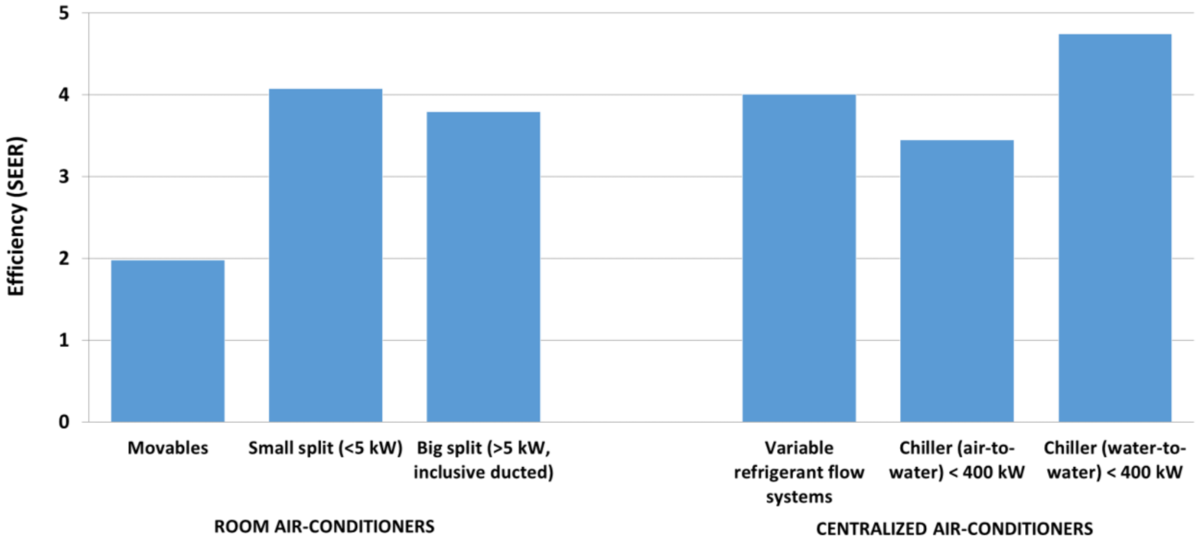

Figure 55 Seasonal energy efficiency ratio per space cooling type in the residential sector, EU27+UK, the reference year 2016 [6], [48], (indicated values refer to the weighted average per final cooling consumption)

The most efficient SC type emerges to be chiller (water-to-water) < 400 kW with a SEER of almost 5. Small split (>5 kW inclusive ducted) systems follow with a SEER value of more than 4. VRF systems and big splits (<5 kW) come next with a SEER of around 4. Chiller (air-to-water) < 400 kW follow with a SEER of around 3.5. Moveables are last, with a SEER of nearly 2.

Using the collected average capacity and SEER values per SC type, the corresponding electricity input in kW has been calculated.

Moreover, following Figure 56 displays information regarding the EFLHs of Europe's residential sector country-by-country.

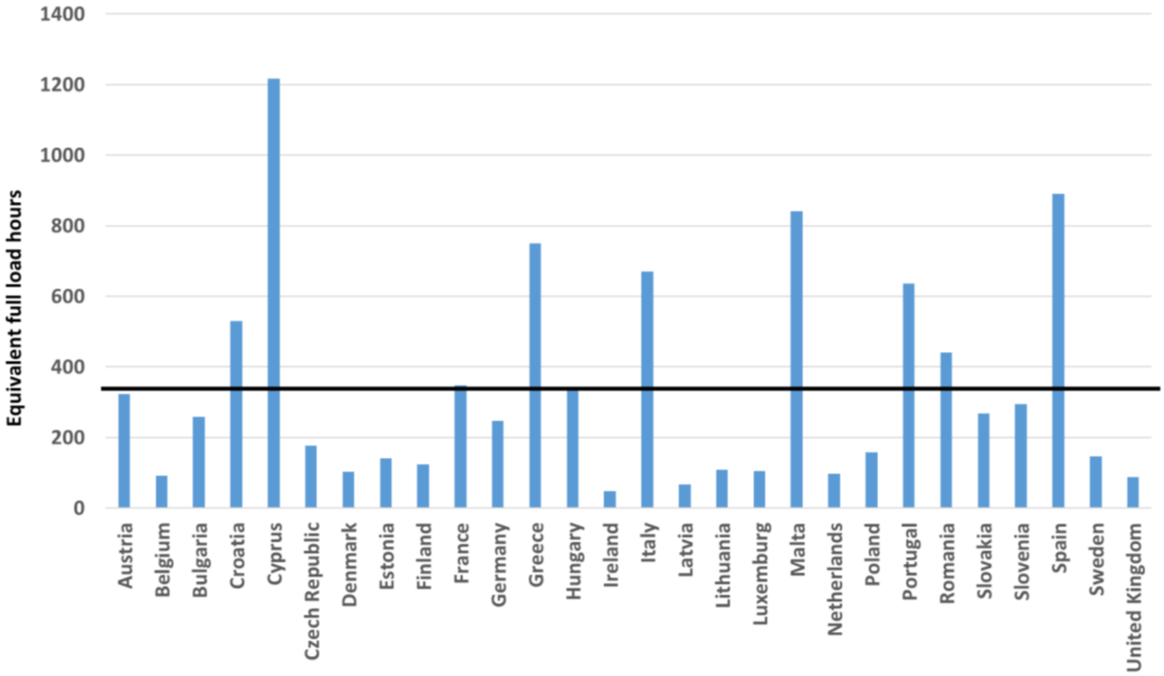

Figure 56 Equivalent full load hours in the residential sector, EU27+UK [6], [48], [123]

As visible in Figure 56, the EFLHs of Europe's residential sector result as highest in Cyprus with values reaching around 1200 EFLHs. Spain and Malta follow with more than 800 EFLHs each, while Portugal, Italy, and Greece follow with more than 600 EFLHs each. Romania and Croatia come next with values below 600 EFLHs. The remaining 19 countries show values below 400 EFLHs. Europe's residential sector's mean (please see the horizontal line in Figure 56 above) results in being about 340 EFLHs.

Please note that the ranking of EFLHs per country does not depend solely on the geographical location of the various nations but a series of other factors, such as consumer behaviour. This applies not only to the residential sector but also to the service (Figure 61).

Integrating the data of Figure 53 to Figure 56 in (Eq.) 18 results into Figure 57 and Table 36.

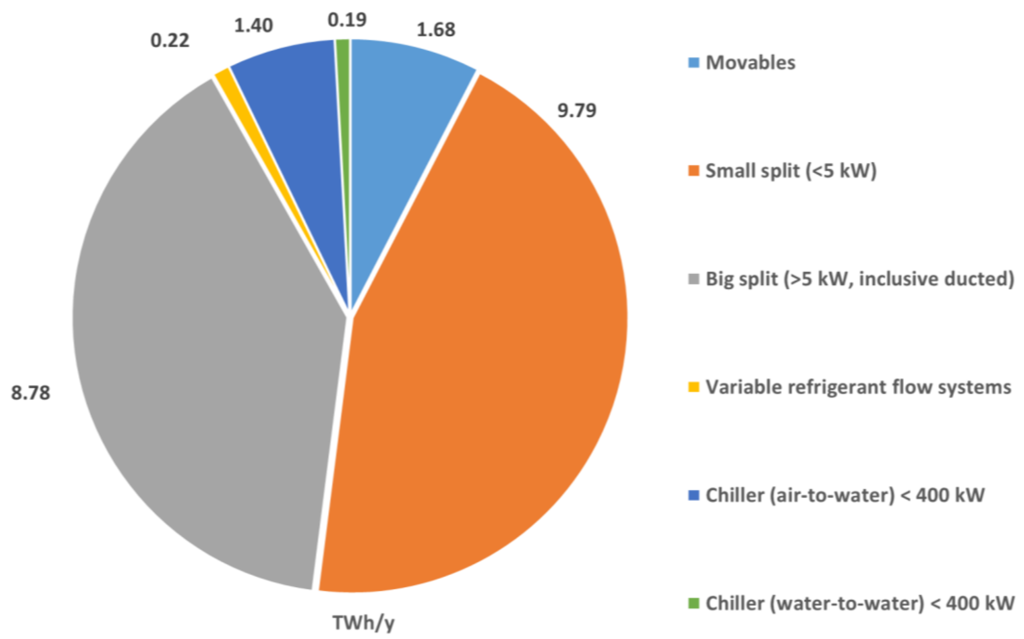

Figure 57 Final energy consumption for space cooling per type of technology in the residential sector, EU27+UK, the reference year 2016 [6], [37], [47], [48]

Table 36 Final energy consumption for space cooling per type of technology in the residential sector, EU27+UK, the reference year 2016 [6], [37], [47], [48]

TECHNOLOGY	FINAL ENERGY CONSUMPTION [TWh/y]
RACs	
Movables	1.68
Small split (<5 kW)	9.79
Big split (>5 kW, inclusive ducted)	8.78
CACs	
Variable refrigerant flow systems	0.22
Rooftop + Packaged	/
Chiller (air-to-water) < 400 kW	1.40
Chiller (air-to-water) > 400 kW	/
Chiller (water-to-water) < 400 kW	0.19
Chiller (water-to-water) > 400 kW	/

As visible in Figure 57 and Table 36, the most energy-consuming SC type are small split (<5 kW) systems with nearly 10 TWh/y of the total SC energy use registered. Big split (>5 kW, inclusive ducted) systems follow with almost 9 TWh/y. Moveables come next with almost 2 TWh/y. Chiller (air-to-water) < 400 follow with more than 1 TWh/y. VRF systems and chiller (water-to-water) < 400 kW are to find at penultimate and last position with 0.22 TWh/y and 0.19 TWh/y each.

Thus, RAC types account for the absolute majority of final SC consumption in the residential sector with more than 90%. The total amount of final SC consumption in Europe's residential sector comes out to be more than 22 TWh/y.

Finally, Figure 58 and Table 37 show the final cooling consumption shares per country.

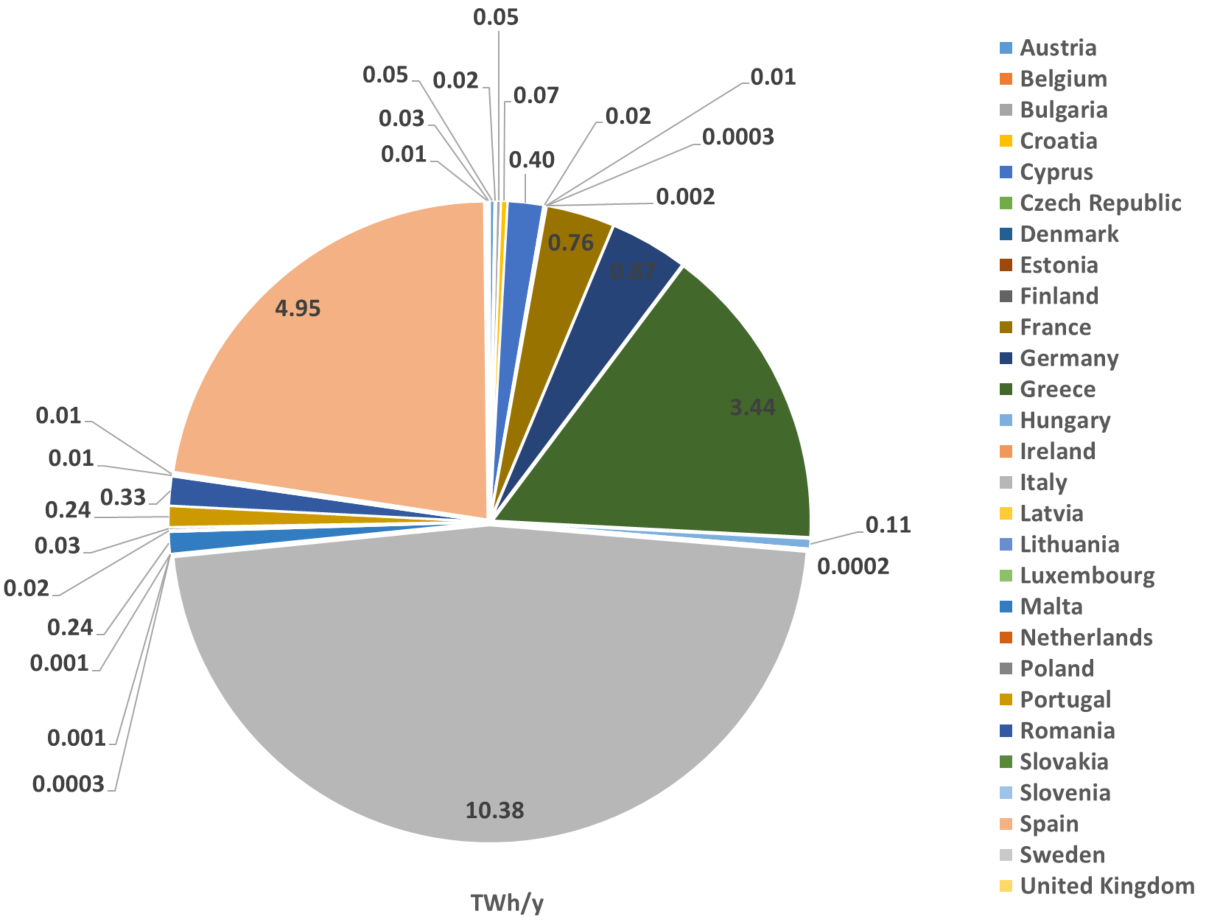

Figure 58 Final energy consumption for space cooling per country in the residential sector, EU27+UK, the reference year 2016 [6], [37], [47], [48]

Table 37 Final energy consumption for space cooling per country in the residential sector, EU27+UK, reference year 2016 [6], [37], [47], [48]

TWh/y PER COUNTRY – RESIDENTIAL SECTOR		PERCENTAGE
Austria	0.05	0.24%
Belgium	0.02	0.08%
Bulgaria	0.05	0.24%
Croatia	0.07	0.32%
Cyprus	0.40	1.80%
Czech Republic	0.02	0.11%
Denmark	0.01	0.03%
Estonia	0.0003	0.001%
Finland	0.002	0.011%
France	0.76	3.47%
Germany	0.87	3.95%
Greece	3.44	15.58%
Hungary	0.11	0.50%
Ireland	0.0002	0.001%
Italy	10.38	47.07%
Latvia	0.0003	0.00%
Lithuania	0.001	0.006%
Luxembourg	0.001	0.003%
Malta	0.24	1.10%
Netherlands	0.02	0.08%
Poland	0.03	0.14%
Portugal	0.24	1.07%
Romania	0.33	1.48%
Slovakia	0.01	0.06%
Slovenia	0.01	0.05%
Spain	4.95	22.42%
Sweden	0.01	0.06%
United Kingdom	0.03	0.12%
EU27+UK	22.06	100%

As shown in Table 37 and Figure 58, there are five countries (Italy, Spain, Greece, Germany, and France) accounting for more than 90% of Europe's final cooling consumption. Thus, the remaining 23 countries account for the left 10%.

3.2.2. Service (SC)

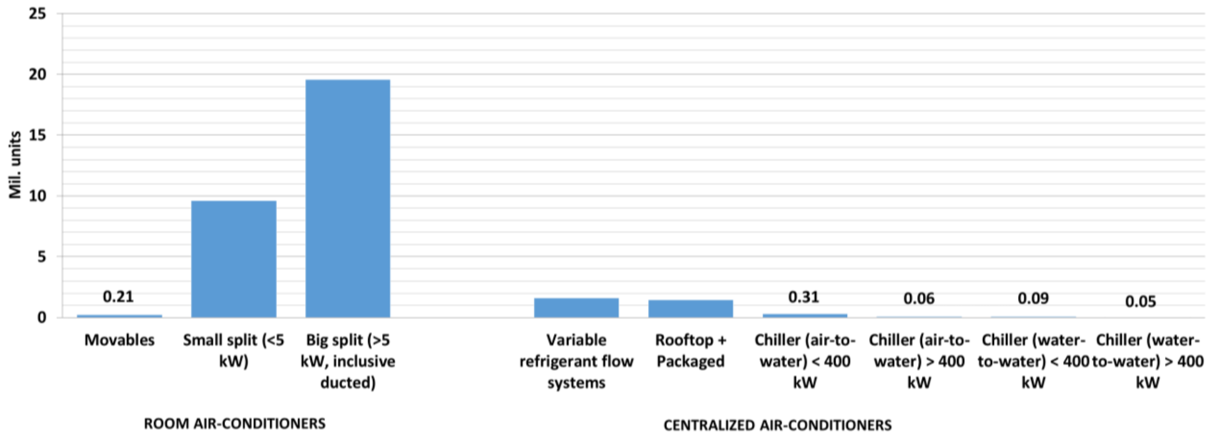

Figure 59 Amount of installed units per space cooling type in the service sector, EU27+UK, the reference year 2016 [6], [37], [47], [48] - due to not being very visible, the amount of certain air-conditioners are indicated by values over their bars

Different from the residential sector, in this case, the big split (>5 kW, inclusive ducted systems) systems are ranked first, with almost 20 mil. units. Small split (<5 kW) systems follow with almost 10 mil. units. In the third position, VRF units are allocated with almost 2 mil. units. Rooftop plus packaged units come next, with about 1.4 mil units, followed by chiller (air-to-water) < 400 kW with around 0.31 mil. units. Movables follow with more than 0.20 mil. units. The remaining chiller types show solely minor values: 0.09 mil. chiller (water-to-water) < 400 kW, 0.06 mil. chiller (air-to-water) > 400 kW, and finally 0.05 mil. chiller (water-to-water) > 400 kW.

The average installed capacity per SC type for the service sector correspond to these of households – please see Figure 54.

Furthermore, Figure 60 provides information concerning the SEER.

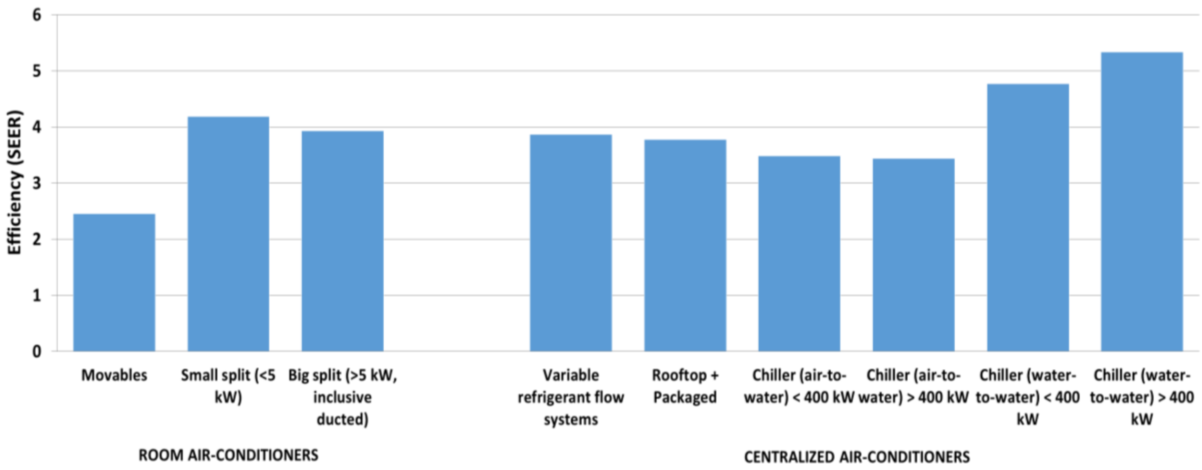

Figure 60 Seasonal energy efficiency ratio per space cooling type in the service sector, EU27+UK, the reference year 2016 [6], [37], [48] (indicated values refer to the weighted average per final cooling consumption)

The most efficient SC types emerge to be chiller (water-to-water) > 400 kW and chiller (water-to-water) < 400 kW with a SEER value of more and almost 5 respectively. Small split (<5 kW) follows with a SEER value of more than 4. VRF, rooftop plus packaged units, and big split (>5 kW, inclusive ducted) systems come next with a SEER of about 4. Chiller (air-to-water) < 400 kW and chiller (air-to-water) > 400 kW come next with SEER values of more than 3. Movables are last positioned with a SEER of more than 2.

Again, through the collected average capacity and SEER values per SC type, the corresponding electricity input in kW has been calculated.

Furthermore, the following Figure 61 displays information regarding the EFLHs of Europe's service sector country-by-country.

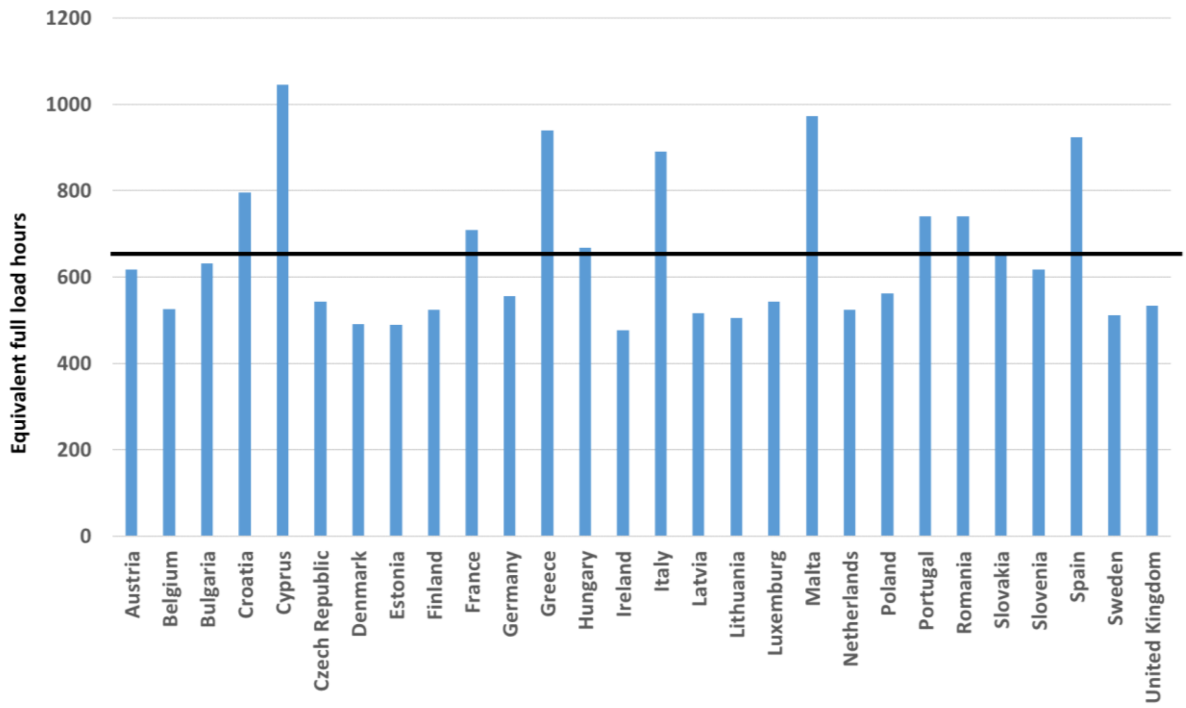

Figure 61 Equivalent full load hours in the service sector, EU27+UK [7], [11], [41]

As visible in Figure 61, the EFLHs of Europe's service sector are highest in Cyprus (as was the case for Europe's residential sector) with values reaching more than 1000 EFLHs. It follows Malta with almost 1000 ELFHs. Greece and Spain follow with values of more than 900 EFLHs. Italy and Croatia follow with almost 900 EFLHs and 800 EFLHs respectively. Romania, Portugal, and France follow with values over 700 EFLHs. Hungary, Slovakia, Bulgaria, Austria, and Slovenia follow with values of over 600 EFLHs. The remaining countries show values lower than 600 EFLHs. The service sector's mean (please see the horizontal line in Figure 61 above) results in being slightly more than 650 EFLHs.

Integrating the data of Figure 59 to Figure 61 in (Eq. 18) results into Figure 62 and Table 38.

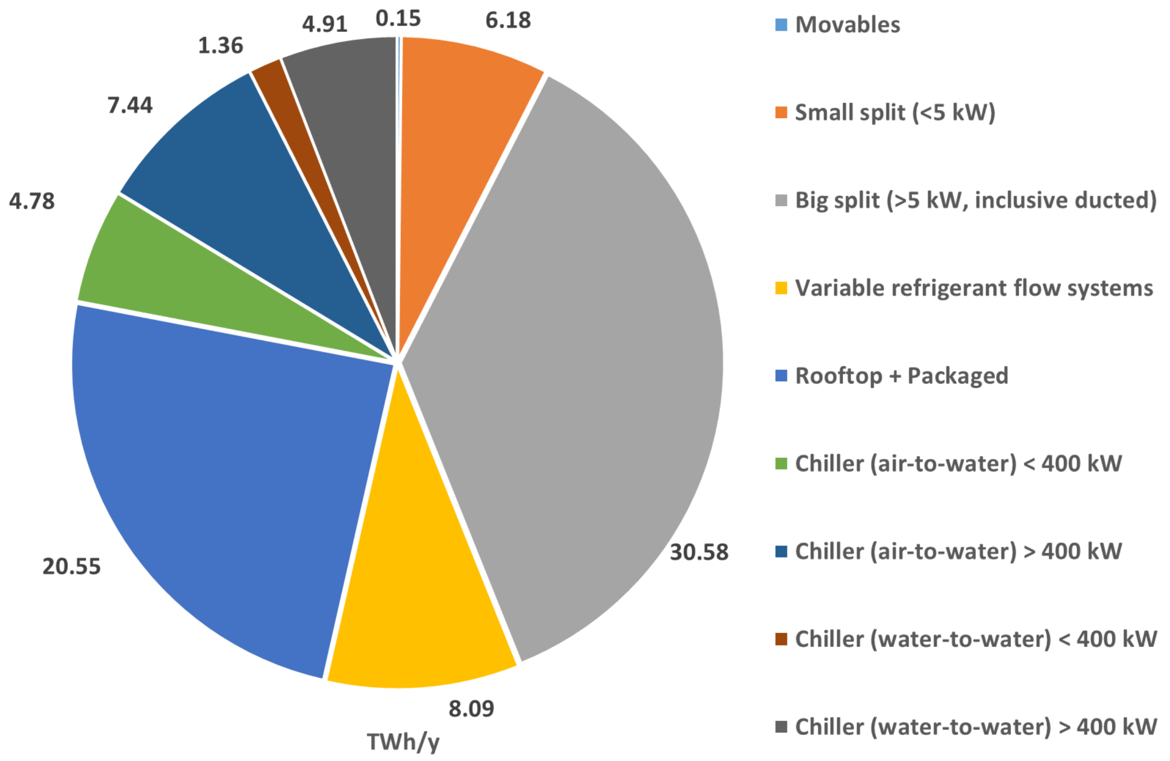

Figure 62 Final energy consumption for space cooling per type in the service sector, EU27+UK, the reference year 2016 [6], [37], [47], [48]

Table 38 Final energy consumption for space cooling per type in the service sector, EU27+UK, the reference year 2016 [6], [37], [47], [48]

TECHNOLOGY	FINAL ENERGY CONSUMPTION [TWh/y]
RACs	
Movables	0.15
Small split (<5 kW)	6.18
Big split (>5 kW, inclusive ducted)	30.58
CACs	
Variable refrigerant flow systems	8.09
Rooftop + Packaged	20.55
Chiller (air-to-water) < 400 kW	4.78
Chiller (air-to-water) > 400 kW	7.44
Chiller (water-to-water) < 400 kW	1.36
Chiller (water-to-water) > 400 kW	4.91

As shown in Figure 62 and Table 38, the most energy-consuming SC type are big split (>5 kW, inclusive ducted) systems with more than 30 TWh/y. Rooftop plus packaged units come next with more than 20 TWh/y. Variable refrigerant flow systems follow with more than 8 TWh/y. Chiller (air-to-water) > 400 kW and small split come next with more than 7 TWh/y and

6 TWh/y respectively. Chiller (water-to-water) > 400 kW and chiller (air-to-water) < 400 kW follow with almost 5 TWh/y respectively. Chiller (water-to-water) < 400 kW come with more than 1 TWh/y and movables are last positioned with 0.15 TWh/y.

Thus, in contrast to the residential sector, in this case, CACs prevail with around 60% of the final SC consumption. The total amount of final SC consumption in Europe's service sector comes out to be 84 TWh/y. Finally, Figure 63 and Table 39 show the final cooling consumption shares per country.

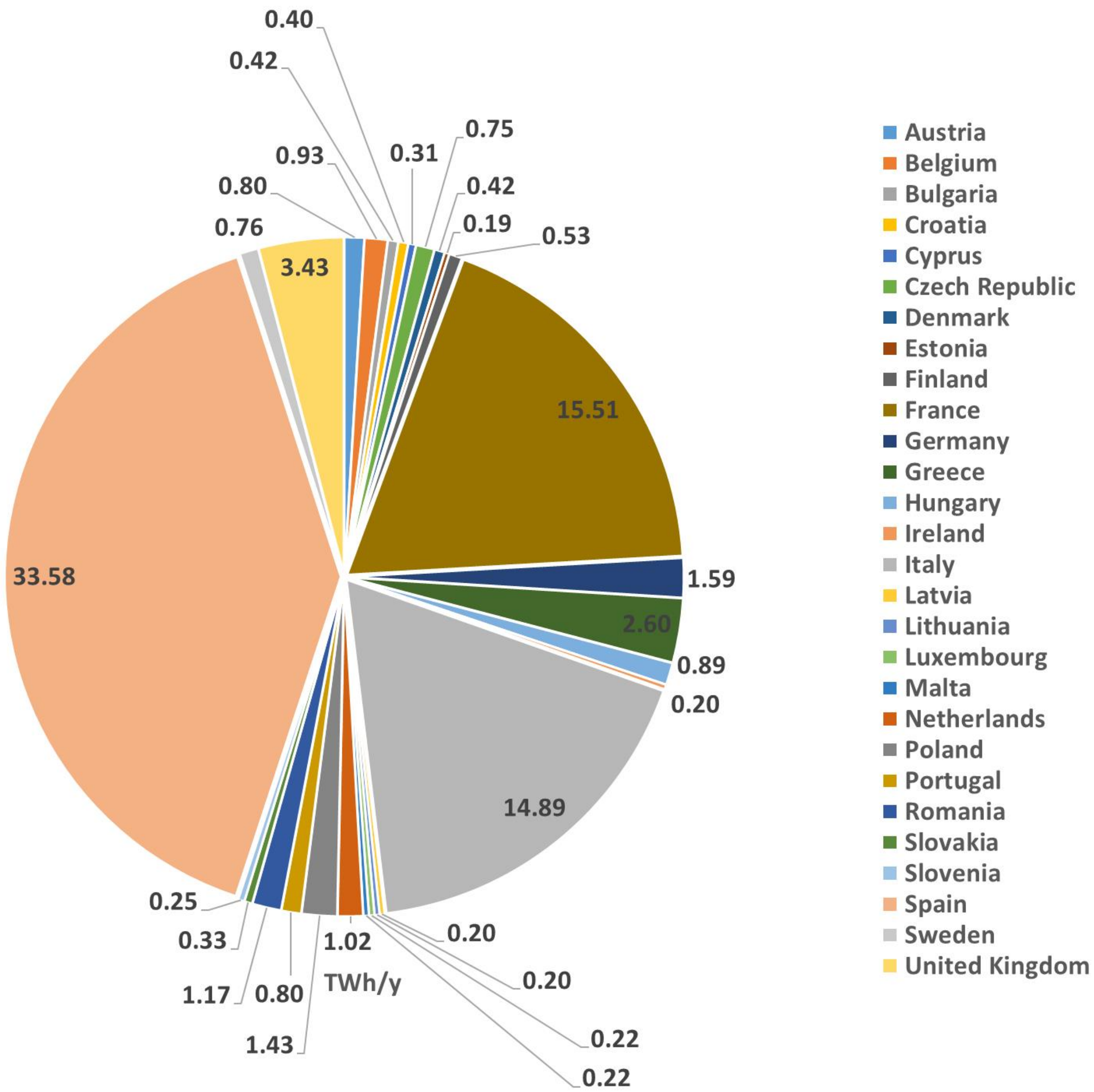

Figure 63 Final energy consumption for space cooling per country in the services sector, EU27+UK, the reference year 2016 [6], [37], [47], [48]

Table 39 Final energy consumption for space cooling per country in the services sector, EU27+UK, reference year 2016 [6], [37], [48], [47], [51]

TWh/y PER COUNTRY – SERVICE SECTOR		PERCENTAGE
Austria	0.80	0.95%
Belgium	0.93	1.10%
Bulgaria	0.42	0.50%
Croatia	0.40	0.48%
Cyprus	0.31	0.37%
Czech Republic	0.75	0.89%
Denmark	0.42	0.50%
Estonia	0.19	0.22%
Finland	0.53	0.63%
France	15.51	18.46%
Germany	1.59	1.90%
Greece	2.60	3.09%
Hungary	0.89	1.06%
Ireland	0.20	0.23%
Italy	14.89	17.72%
Latvia	0.20	0.24%
Lithuania	0.20	0.24%
Luxembourg	0.22	0.26%
Malta	0.22	0.27%
Netherlands	1.02	1.21%
Poland	1.43	1.70%
Portugal	0.80	0.95%
Romania	1.17	1.39%
Slovakia	0.33	0.39%
Slovenia	0.25	0.30%
Spain	33.58	39.95%
Sweden	0.76	0.90%
United Kingdom	3.43	4.09%
EU27+UK	84.04	100%

As it was the case for the residential sector, also in this case just a few countries account for the absolute majority of the final SC consumption amount of the entire EU27+UK. Spain, France, Italy, UK, Greece, and Germany, and together account for more than 80% of Europe's final SC consumption for the service sector. Thus, the remaining 22 countries account for the left 20%.

3.2.3. Residential and service (SC)

Summing up the results of previous Figure 57 and Figure 62, the according Figure 64 and Table 40 emerge.

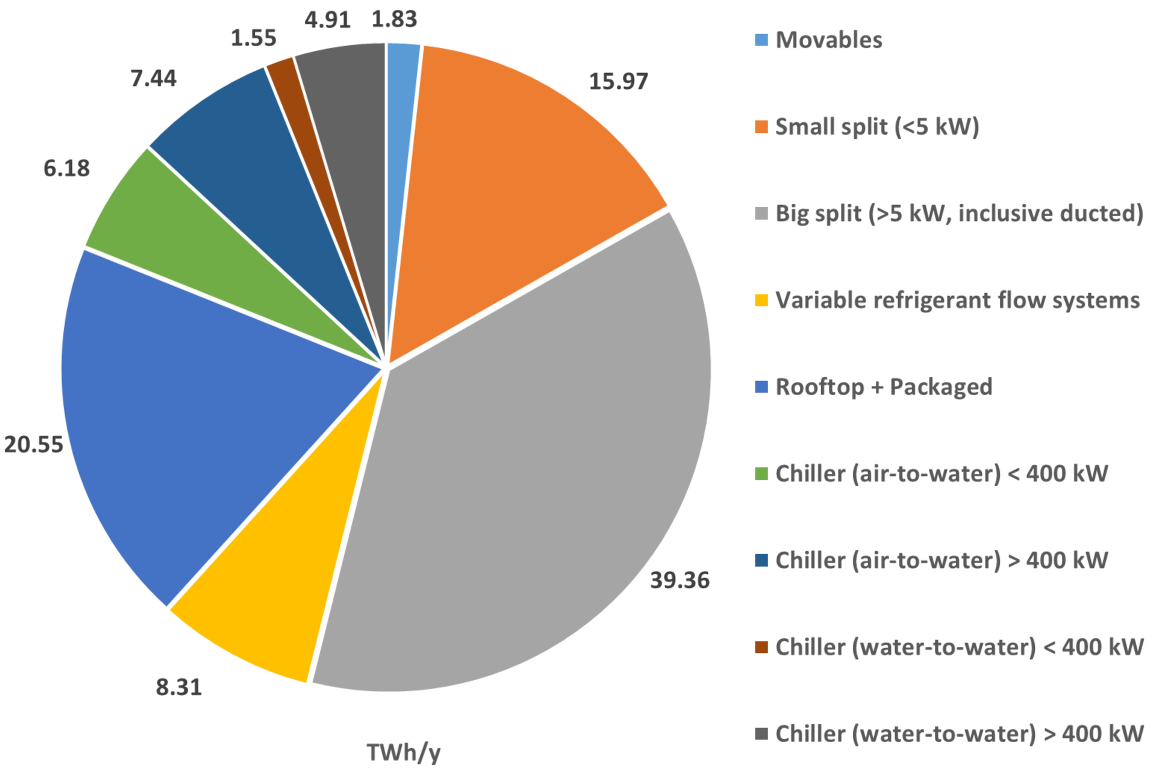

Figure 64 Final energy consumption for space cooling per type in the residential and service sectors, EU27+UK, reference year 2016 [6], [37], [48], [47], [49]

Table 40 Final energy consumption for space cooling per type in the residential and service sectors, EU27+UK, reference year 2016 [6], [37], [48], [47], [49]

TECHNOLOGY	FINAL ENERGY CONSUMPTION [TWh/y]
RACs	
Movables	1.83
Small split (<5 kW)	15.97
Big split (>5 kW, inclusive ducted)	39.36
CACs	
Variable refrigerant flow systems	8.31
Rooftop + Packaged	20.55
Chiller (air-to-water) < 400 kW	6.18
Chiller (air-to-water) > 400 kW	7.44
Chiller (water-to-water) < 400 kW	1.55
Chiller (water-to-water) > 400 kW	4.91

As shown in Figure 64, the most energy-consuming SC type are Big split (>5 kW, inclusive ducted) systems with almost 40 TWh/y. Rooftop plus packaged units follow with more than 20 TWh/y. Small split systems come next with almost 16 TWh/y. VRF systems and Chiller (air-to-water) > 400 kW and follow with more than 8 TWh/y and 7 respectively. Chiller (air-to-water) < 400 kW come next with more than 6 TWh/y. Chiller (water-to-water) > 400 kW follow with almost 5 TWh/y. Movables follow with almost 2 TWh/y. Chiller (water-to-water) < 400 kW are last positioned with more than 1 TWh/y.

The total amount of final SC consumption in Europe's residential and service sector comes out to be 106 TWh/y.

Concerning the entire final SC consumption (residential and service sectors) the RACs and CACs account for about the same percentage with approximately 50% of the final energy consumption each.

Concluding, summing up the results of previous Figure 57 and Figure 62, the according Figure 64 and Table 41 emerge.

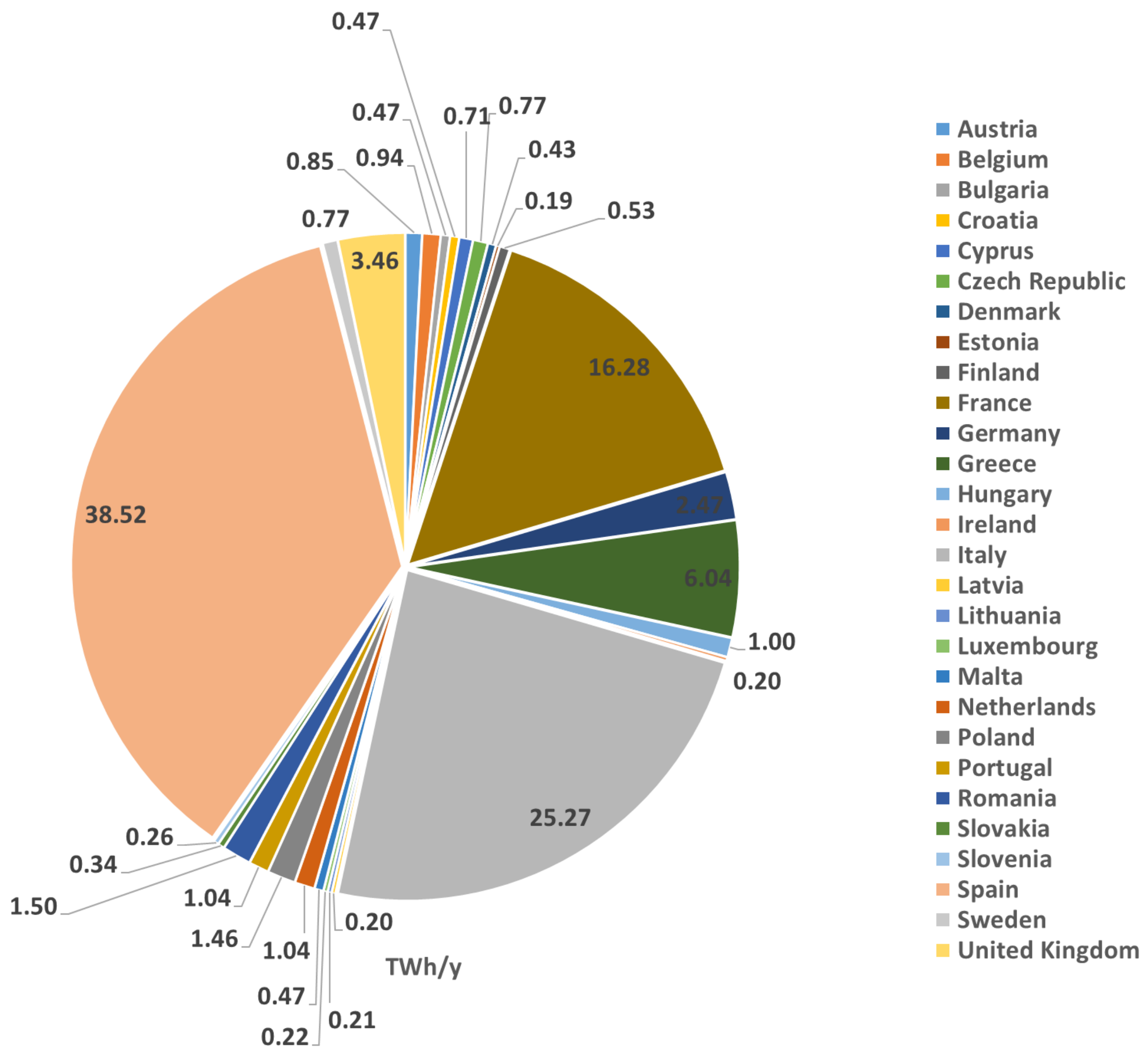

Figure 65 Final energy consumption for space cooling per country in the residential and service sectors, EU27+UK, reference year 2016 [6], [37], [48], [47], [49]

Table 41 Final energy consumption for space cooling per country in the residential and service sectors, EU27+UK reference year 2016 [6], [37], [48], [47], [49]

TWh/y PER COUNTRY – RESIDENTIAL + SERVICE SECTORS		PERCENTAGE
Austria	0.85	0.80%
Belgium	0.94	0.89%
Bulgaria	0.47	0.45%
Croatia	0.47	0.44%
Cyprus	0.71	0.66%
Czech Republic	0.77	0.73%
Denmark	0.43	0.40%
Estonia	0.19	0.18%
Finland	0.53	0.50%
France	16.28	15.34%
Germany	2.47	2.32%
Greece	6.04	5.69%
Hungary	1.00	0.94%
Ireland	0.20	0.18%
Italy	25.27	23.82%
Latvia	0.20	0.19%
Lithuania	0.21	0.19%
Luxembourg	0.22	0.21%
Malta	0.47	0.44%
Netherlands	1.04	0.98%
Poland	1.46	1.38%
Portugal	1.04	0.98%
Romania	1.50	1.41%
Slovakia	0.34	0.32%
Slovenia	0.26	0.25%
Spain	38.52	36.31%
Sweden	0.77	0.73%
United Kingdom	3.46	3.26%
EU27+UK	106.10	100%

Once again, just a few countries account for the absolute majority of the final SC consumption amount of the entire EU27+UK. Spain, Italy, France, Greece, UK, and Germany come out to account for more than 85% of Europe’s final SC consumption for the residential and service sectors. Thus, the remaining 22 countries account for the remaining 15%.

3.2.4. Industry (PC)

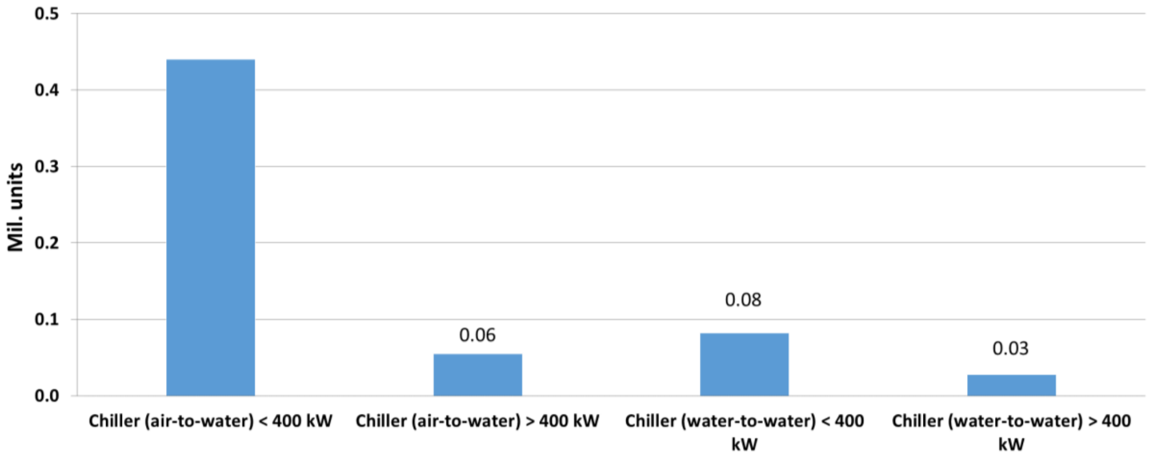

Figure 66 Amount of installed units per process cooling type (industrial sector), EU27+UK, the reference year 2016 [53], [48], [124]

Chiller (air-to-water) < 400 kW account for the majority of PC units per type with more than 0.4 mil. installed devices. Chiller (water-to-water) < 400 kW follow with 0.08 mil. units. Chiller (air-to-water) > 400 kW and chiller (water-to-water) > 400 kW come next with about 0.06 and 0.03 mil. units each.

Subsequently, Figure 67 indicates the average installed capacity per PC type in kW.

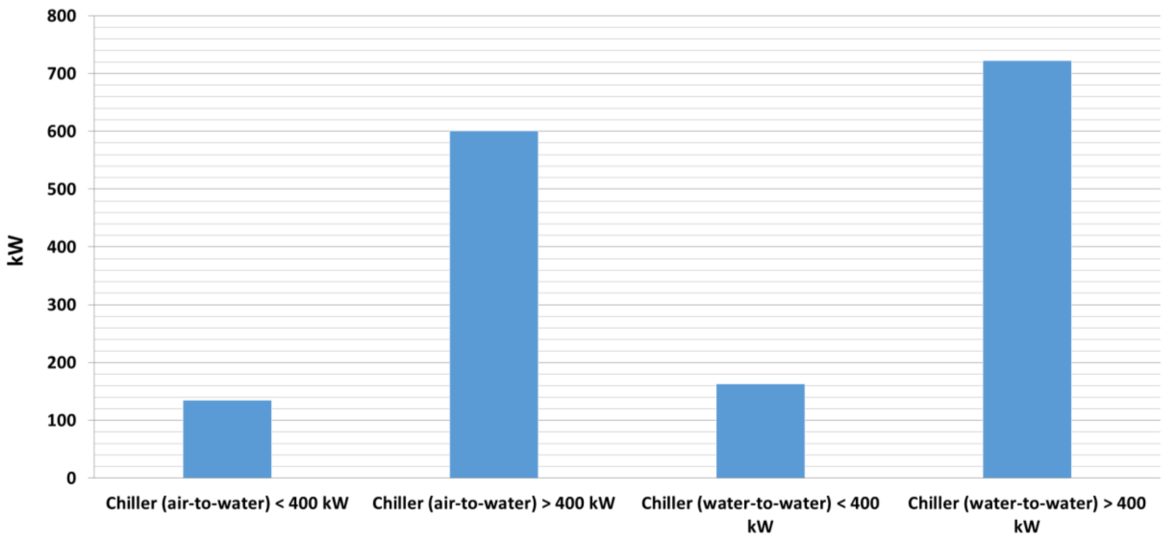

Figure 67 Average installed capacity per process cooling type (industrial sector), EU27+UK, the reference year 2016 [53], [48], [124]

Chiller (water-to-water) > 400 kW result in having the largest installed mean value: more than 700 kW. Chiller (air-to-water) > 400 kW follow with about 600 kW. Chiller (water-to-water) < 400 kW come next with more than 160 kW and chillers (air-to-water) < 400 kW result in having a mean capacity installed of more than 130 kW.

Furthermore, Figure 68 provides information concerning the SEPR.

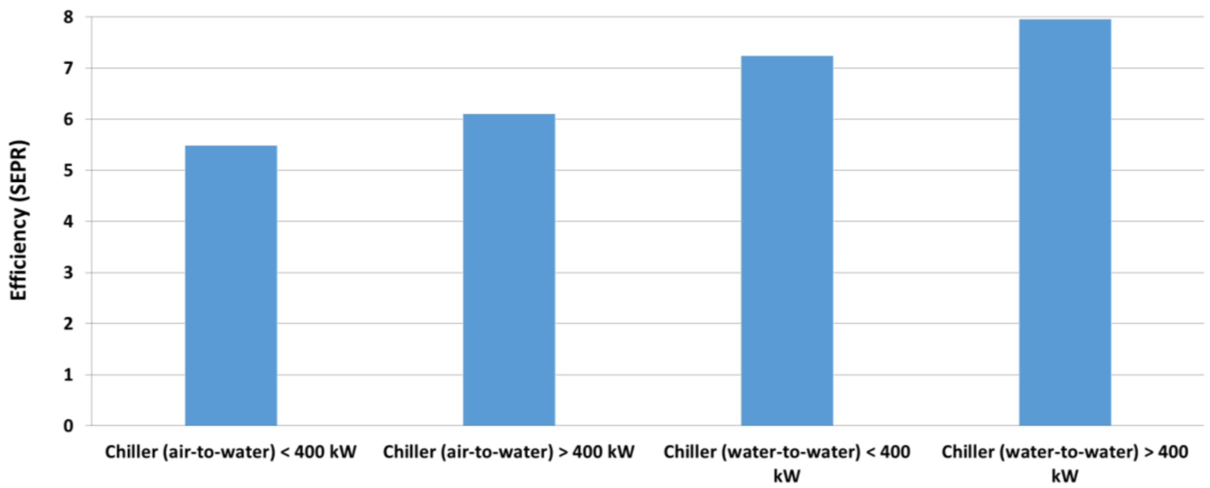

Figure 68 Seasonal energy performance ratio per process cooling type (industrial sector), EU27+UK [49] (indicated values refer to the weighted average per final cooling consumption)

The most efficient PC type emerges to be chiller (water-to-water) > 400 kW with a value of almost 8. Chiller (water-to-water) < 400 kW follow with a number equal to 7.2. Chiller (air-to-water) > 400 kW come next with a value of 6.1. Chiller (air-to-water) < 400 kW are last positioned with a number equal to 5.5.

Again, through the collected average capacities and SEPR values per PC type, the corresponding electricity input in kW has been calculated.

Furthermore, following Figure 69 displays information regarding the EFLHs of Europe's industrial sector country-by-country.

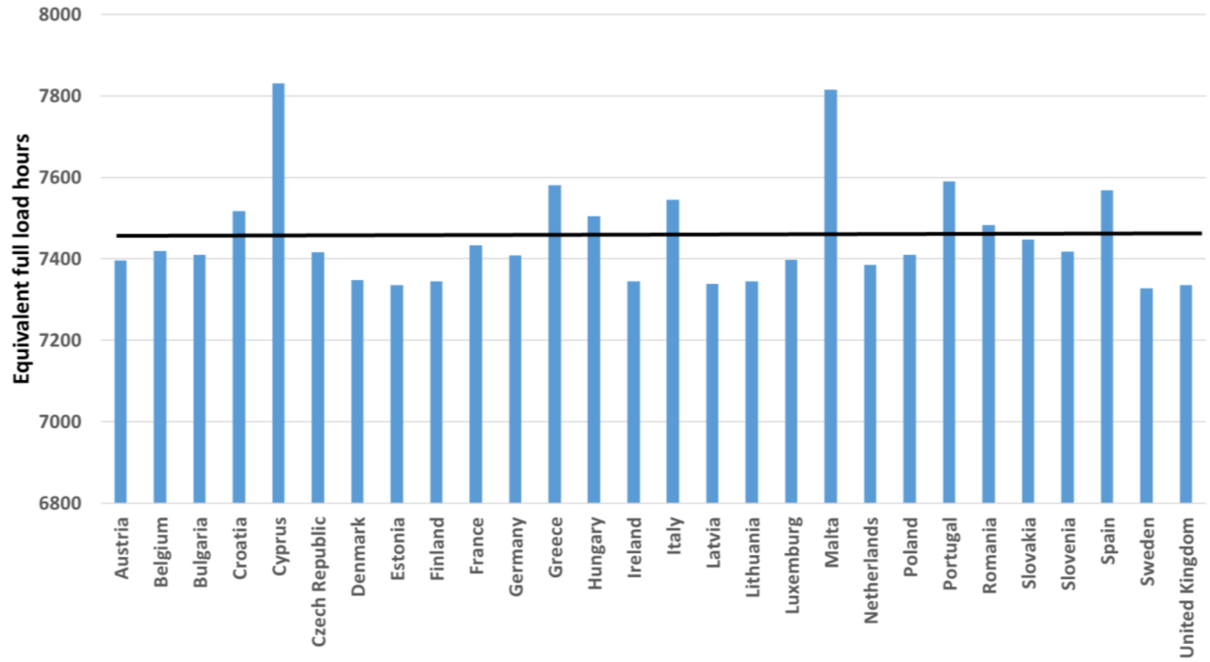

Figure 69 Equivalent full load hours in the industrial sector, EU27+UK, the reference year 2016 [7], [10], [44]

As visible in Figure 69, the EFLHs of Europe's industrial sector are all over 7200. Peaks are provided by Cyprus and Malta. Portugal, Greece, Spain, Italy, Croatia, and Hungary follow before all other remaining countries. However, as shown in the chart above, there are no major differences among EFLHs of European states. Only Malta and Cyprus result in having a difference to the industrial sector's mean (about 7450 EFLHs - please see the horizontal line in Figure 69 above) higher than 4%. Integrating the data of Figure 66 to Figure 69 in (Eq.) 18, results in Figure 70 and Table 42.

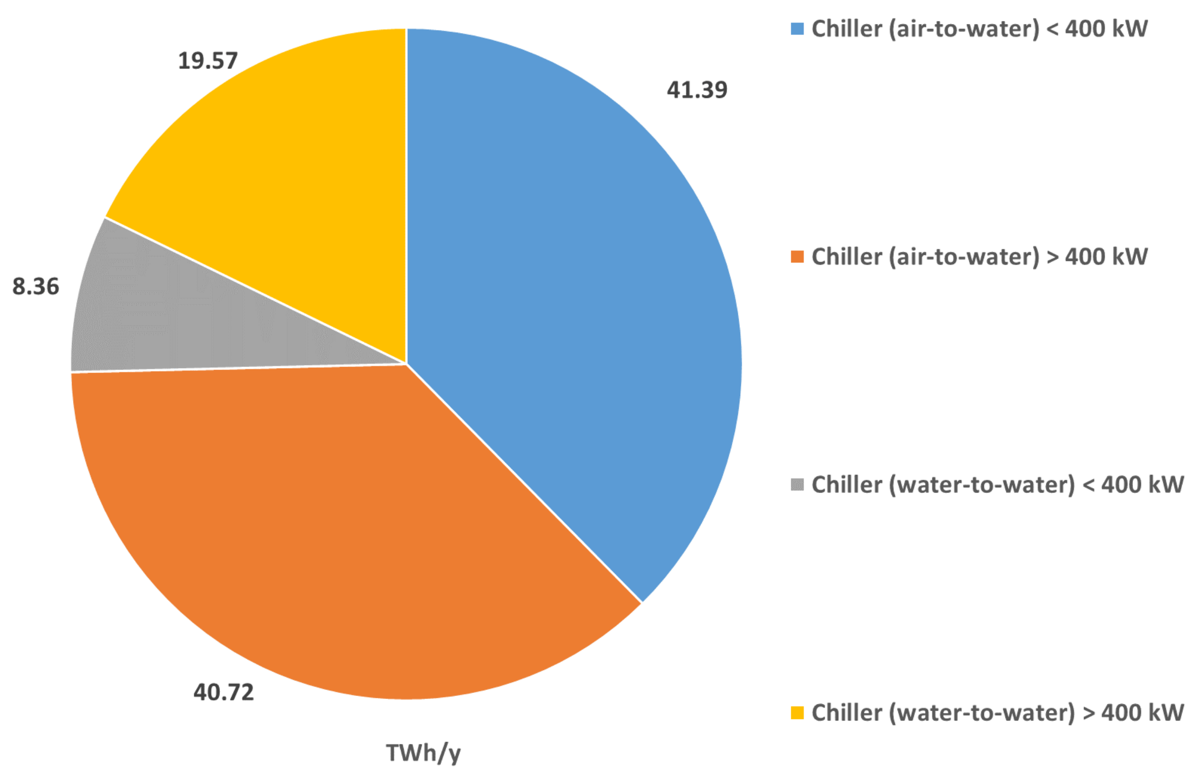

Figure 70 Final energy consumption for process cooling per type (industrial sector), EU27+UK, reference year 2016 [37], [47], [125]

Table 42 Final energy consumption for process cooling per type (industrial sector), EU27+UK, reference year 2016 [37], [47], [125]

TECHNOLOGY	FINAL ENERGY CONSUMPTION [TWh/y]
Chiller (air-to-water) < 400 kW	41.39
Chiller (air-to-water) > 400 kW	40.72
Chiller (water-to-water) < 400 kW	8.36
Chiller (water-to-water) > 400 kW	19.57

As shown in Figure 70 and Table 42, the most energy-consuming PC type are chiller (air-to-water) < 400 kW with more than 41 TWh/y. Chiller (air-to-water) > 400 kW follow with more than 40 TWh/y. Chiller (water-to-water) > 400 kW come next with about 20 TWh/y and chiller (water-to-water) < 400 kW are last positioned, with more than 8 TWh/y. The total amount of final PC consumption in Europe's industrial sector comes out to be 110 TWh/y.

Finally, Figure 70 and Table 43 visualize the final PC consumption shares per country.

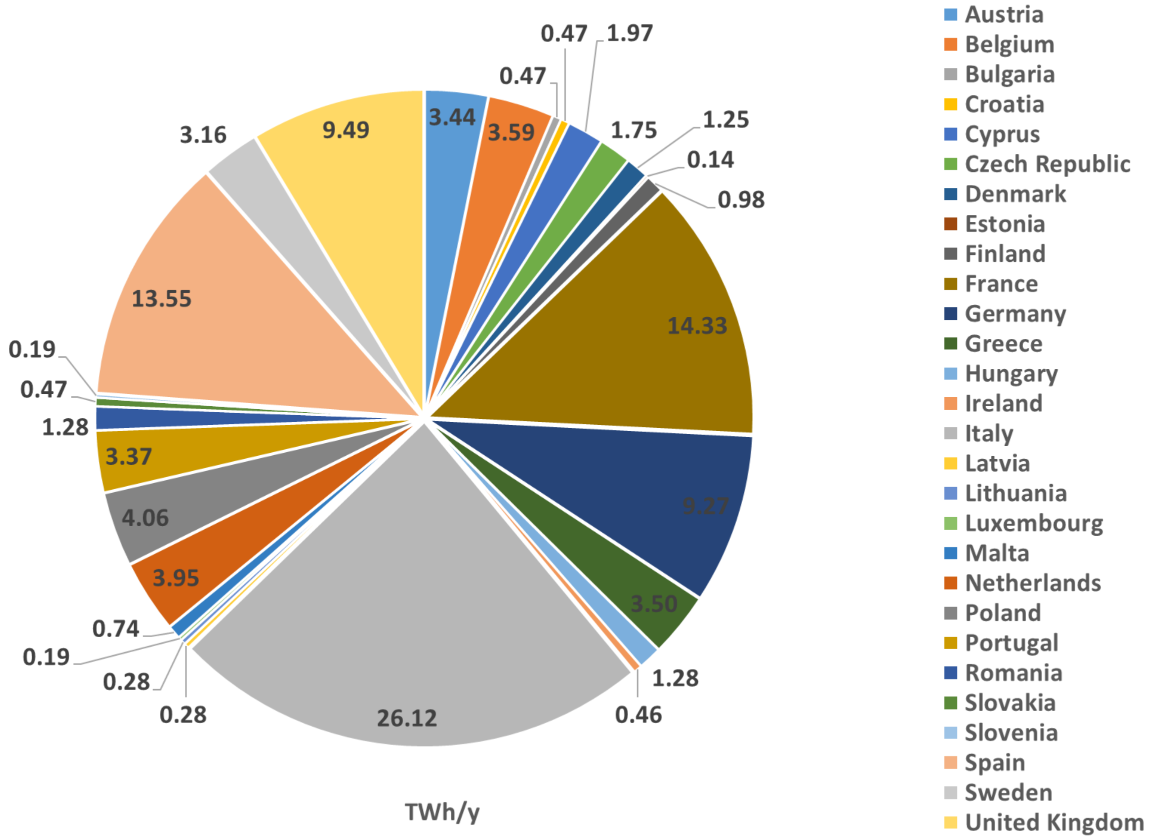

Figure 71 Final energy consumption for process cooling per country (industrial sector), EU27+UK, reference year 2016 [37], [47], [125], [55]

Table 43 Final energy consumption for process cooling per country (industrial sector), EU27+UK, reference year 2016 [37], [47], [125], [55]

TWh/y PER COUNTRY – PC – INDUSTRIAL SECTOR		PERCENTAGE
Austria	3.44	3.13%
Belgium	3.59	3.26%
Bulgaria	0.47	0.42%
Croatia	0.47	0.43%
Cyprus	1.97	1.79%
Czech Republic	1.75	1.59%
Denmark	1.25	1.14%
Estonia	0.14	0.13%
Finland	0.98	0.89%
France	14.33	13.03%
Germany	9.27	8.42%
Greece	3.50	3.18%
Hungary	1.28	1.16%
Ireland	0.46	0.42%
Italy	26.12	23.74%
Latvia	0.28	0.25%
Lithuania	0.28	0.25%
Luxembourg	0.19	0.17%
Malta	0.74	0.67%
Netherlands	3.95	3.59%
Poland	4.06	3.69%
Portugal	3.37	3.06%
Romania	1.28	1.17%
Slovakia	0.47	0.43%
Slovenia	0.19	0.17%
Spain	13.55	12.31%
Sweden	3.16	2.87%
United Kingdom	9.49	8.63%
EU27+UK	110.03	100%

As visible in Figure 71 and Table 43, just a few countries account for the absolute majority of the final PC consumption amount of the entire EU27+UK. Italy, France, Spain, United Kingdom, Germany, Poland, Netherlands, Belgium, Greece, Austria, Portugal, Sweden, Cyprus come out to account for 90% of Europe's final PC consumption. Thus, the remaining 15 countries account for the left 10%.

As visible above, the calculation performed to quantify the PC portion in Europe entails chiller (air-to-water or water-to-water with more or less than 400 kW capacity installed) applied in the industrial sector. The main applications for these chillers are pharmaceutical, automotive, plastic, bakeries, and process industries related to construction such as cement, plastic, and glass industries; fish and meat industries need this equipment as well. Process chiller has started to be used in close control technologies like computer and network rooms in banks, companies HQ's, government departments, to create a better environment for the IT equipment [127].

However, there are further technologies utilized for process cooling (PC) purposes in various sectors and subsectors [5], [128], [129]. Please see the following Table 44 concerning the application of further VC technologies.

Table 44 Sectors, subsectors, processes, and technologies (vapour compression technologies, besides chiller air-to-water or water-to-water) utilized for process cooling purposes

SECTOR	SUBSECTOR	PROCESS	TECHNOLOGY
INDUSTRY	Wineries	Ambient air cooling	Small split (<5 kW) and Big split (>5 kW) [130]
	Tobacco	Ambient air control	Packaged [131]
	Paper, pulp, and printing	Cooling of printing machinery	Packaged [132]
TERTIARY	Telecommunications	Shelter cooling	Small split (<5 kW) and Big split (>5 kW) [133]
	Warehouses	Ambient air cooling	Variable refrigerant flow systems [134]
			Rooftop [135]
	Supermarket freezers and cells	Refrigeration and freezing	Small split (<5 kW) and Big split [136]
	Data centres	Electronic equipment cooling	Packaged computer room air conditioners (CRAC) [137], [138]

For a more complete list entailing also non-VC technologies as well as further sectors, subsectors, and processes, please see the Annex: Process cooling - sectors, subsectors, processes, and technologies.

The amount of final PC consumption occurring in the indicated sectors and subsectors is highly relevant. For example [139], indicates the final energy consumption for cooling in Europe's data centres to be more than 40 TWh/y in 2020. However, due to a lack of data and information, it was not possible to quantify Europe's final PC consumption in the sectors specified in Table 44. See Table 63 in Annex: Process cooling - sectors, subsectors, processes, and technologies for further details.

Also, in the agriculture sector , PC applications (as well as SC applications – e.g. for workers in greenhouses) are getting more and more important. However, due to a lack of data/information on cooling applications in this field, it was not possible to provide a respective quantification [140], [141], [142], [143].

3.2.5. Distribution of final energy consumption for process cooling per subsectors

General methodology

To determine the total final energy consumption for process cooling (PC)[11] in the EU, distributed per subsectors, a bottom-up estimation has been carried out, based on a Danish mapping study of the energy use in the industry and commercial sectors [144]. The study has been carried out in 2014 and is mainly based on the final energy consumption data of 2012. The data has been extrapolated to 2016 and upscaled to EU27+UK as follows.

Within this study, PC solely has been taken into consideration – and not space (comfort) cooling. The latter two mentioned cooling types are segregated because the Danish tax laws have different tax rates for process energy use (lower rates) vs for space (comfort) cooling and heating. If the same equipment is producing cooling for both processes and human comfort, the energy use of the equipment is split between the two purposes.

Data for PC for each sector has been extrapolated from 2012 to 2016 based on the development of the production value of the sector [145] and the change in final energy consumption from 2012-2016 [146].

The projected data for the Danish final electricity consumption in 2016 for PC has been upscaled to the EU level by using the production value for each sector in Denmark and the equivalent for the EU. For a few sectors, the EU production value was not available, and the upscaling was made with the GDP for Denmark vs. GDP for EU27+UK.

The final energy consumption for PC has been divided into three temperature intervals <5 °C, 5-30 °C, and >30 °C. This segregation is based on previously performed mappings of industries in Denmark, and general knowledge from industry experts at Viegand Maagøe from the consortium of the current project.

Methodology for data centres

Due to the recent large development in the number and capacities of data centres in Denmark and the entire EU, especially of hyper-scale data centres - while the Danish data centre sector was limited at the time of the mapping study – another source for final energy consumption for PC in data centres has been used [147] and incorporated in the calculations carried out for the subsector 'Information and communication'.

The analysis of the final energy consumption for data centres uses data submitted by enterprises participating in the European Code of Conduct for Data Centre Energy Efficiency program, a voluntary initiative created in 2008 by the European Commission, Joint Research Centre in response to the increasing energy use in data centres and the need to reduce the related environmental, economic and energy supply security impacts. The study analyses the PUE (Power Usage Efficiency, which is the total final energy consumption divided by final energy consumption for servers, storage, and network equipment) of the mapped data centres. It estimates an average cooling need of about 40% out of the total energy request for data centres. The analysis predicts a final energy consumption of 104 TWh in 2020, thus approximately 40 TWh is assumed to be used for PC.

[11] Please note that within given subsection, process cooling entails refrigeration (temperature level: <5 °C).

Results

The results are shown in Table 45 and Figure 72 below.

Table 45 Share of final energy consumption for process cooling per subsectors

Subsector	Upscaling		Process cooling	
	Prod. value	GDP	Other sources	Share
Crop and animal production, hunting, and related service activities	X			3.1%
Forestry and logging	X			0.3%
Processing and preserving of meat and production of meat products	X			9.6%
Processing and preserving of fish, crustaceans, and molluscs	X			0.8%
Manufacture of dairy products	X			4.7%
Manufacture of bakery and farinaceous products	X			1.4%
Other food industry	X			4.7%
Manufacture of beverages	X			1.8%
Printing and reproduction of recorded media	X			0.2%
Manufacture of industrial gases	X			0.3%
Manufacture of other organic basic chemicals	X			1.7%
Manufacture of other basic chemicals	X			1.7%
Manufacture of paints and soap, etc.	X			1.4%
Manufacture of basic pharmaceutical products and pharmaceutical preparations	X			1.0%
Manufacture of rubber and plastic products	X			2.9%
Manufacture of fabricated metal products, except machinery and equipment	X			0.3%
Manufacture of other electronic equipment, electric motors, etc., as well as wires and cables	X			0.1%
Manufacture of engines, wind turbines, and pumps	X			0.2%
Manufacture of other machinery	X			0.2%
Toys and other manufacturing	X			0.1%
Wholesale and retail trade and repair of motor vehicles and motorcycles		X		0.1%
Wholesale on a fee or contract basis		X		8.1%
Retail trade, except motor vehicles and motorcycles		X		18.4%
Hotels and similar accommodation		X		2.0%
Food and beverage service activities		X		5.0%
Information and communication		X	X	29.3%
Knowledge service		X		0.2%
Travel agency, cleaning, and other operational services		X		0.1%
Culture and leisure		X		0.3%
Total				100%

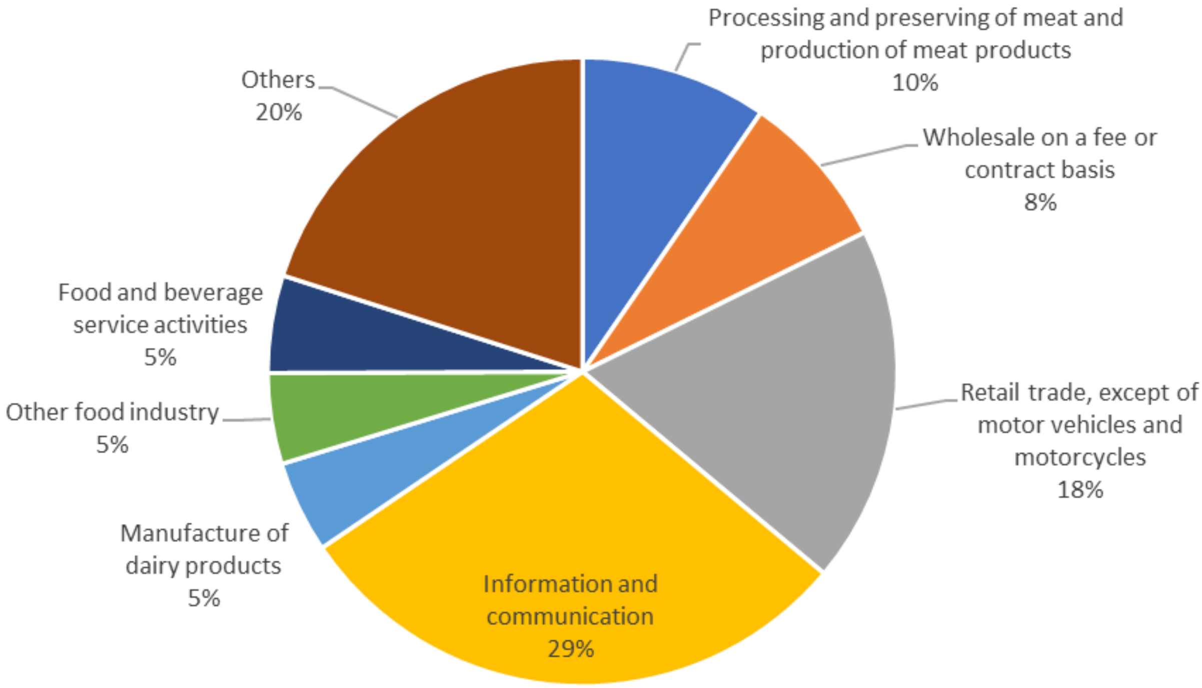

Figure 72 Distribution of process cooling use per subsector

The split of PC use per temperature level comes out to be as follows:

- <5°C: 54%
- 5-30°C:16%
- >30°C: 30%

For further details, please see the Annex: Case study of process cooling use per subsector in Denmark and the EU27+UK – Table 70.

Uncertainties and assumptions

The bottom-up method has a range of uncertainties:

- There is no exact definition of PC, which makes it difficult to compare different research results as the definition might vary.
- As data is extrapolated from a Danish mapping study, the definition of PC found in the study is used in this analysis.
- The share of final electricity consumption in each sector is assumed to be the same in Denmark and the EU27+UK.
- The share of final electricity consumption for PC is assumed to be the same in Denmark and the EU27+UK.
- The energy intensity in Denmark and EU27+UK is being considered to have the same energy intensity across all sectors.
- It was only possible to find valid data within the timeframe for the production values at the EU level for the sectors: Manufacturing, agriculture, forestry, and fisheries. The remaining sectors are upscaled based on GDP.
- As the data is based on a small part of the total final electricity consumption in Europe the results are subject to uncertainty when upscaled to the EU level. Lack of data also

contributes to uncertainty. However, the data give an approximation of the amount of PC in the subsectors.

- Furthermore, the following subsectors are rarely found in Denmark or do not have a corresponding share in DK:
  - 05 Mining and coal lignite;
  - 07 Mining of metal ores;
  - 08 Other mining and quarrying (08.00.09 included in Danish assessment);
  - 09 Mining support service activities;
  - 19 Manufacture of coke and refined petroleum products;
  - 20 Manufacture of chemicals and chemical products (exists in DK, but other countries may have a much larger chemical industry than DK);
  - 26 Manufacture of computer, electronic and optical products;
  - 29 Manufacture of motor vehicles, trailers, and semi-trailers.

3.2.6. District cooling (SC & PC)

District Cooling provides SC and PC primarily for commercial and public buildings, but also for the industrial and residential sectors [125]. The amount of DC is currently marginal in Europe but is increasing constantly for decades [118]–[120].

The following text goes towards the DC final energy consumption/useful energy demand in the EU27+UK, country-by-country, and provides an overview concerning the diffusion of respective technology. The reference year of the following results is 2016.

Please note that within the following text, when referring to final DC consumption we intend final energy consumption of DC plants to deliver cooling to customers, while useful DC demand refers to DC sales. Both, final DC consumption and useful DC demand are indicated with a unit of TWh/y.

Following Figure 73 provides indications about the diffusion of district cooling systems (DCSs) in the EU27+UK – in total, an amount of more than 200 applications has been identified:

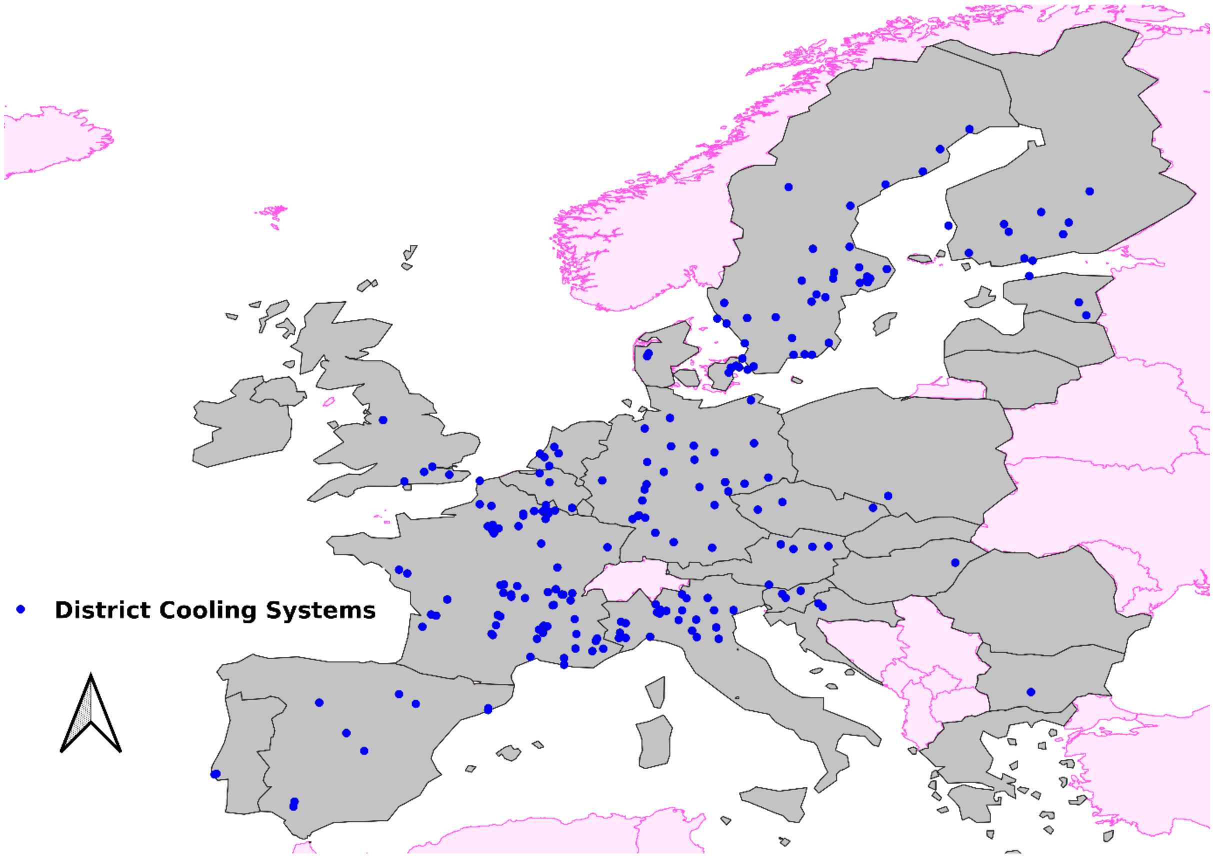

Figure 73 Diffusion of district cooling systems per country. Please note that this figure has been created with the geographic information systems software QGIS 3.6 using as input the data provided by the following sources [148], [149], [150], [151], [152], [153], [154], [155], [83] (blue dots in the map indicate the location of district cooling systems)

As visible in Figure 73 above, the majority of DC applications can be found in France, Sweden, Germany, and Italy. In the fifth position, we find Finland and Spain with the same amount of installations. The remaining countries are characterized by a minor amount of installations. It has to be underlined that Nordic countries of the EU (Denmark, Finland, and Sweden) are characterized by a relatively high number of installations, despite cold weather conditions.

Next, Table 46 provides indications regarding the amount of capacity installed per country. Please note that countries marked with a slash ("/") refer to countries for which indicated sources mention that there is no DCSs present so far.

Table 46 District cooling capacity installed per country (MW), EU27+UK, reference year 2016 [148], [152], [153], [154], [157]

COUNTRIES	CAPACITY INSTALLED (MW)
Austria	130
Belgium	1
Bulgaria	0.5
Croatia	7
Cyprus	/
Czech Republic	35
Denmark	22
Estonia	13
Finland	283
France	761
Germany	241
Greece	/
Hungary	1
Ireland	/
Italy	202
Latvia	/
Lithuania	/
Luxembourg	19
Malta	/
Netherlands	23
Poland	43
Portugal	40
Romania	/
Slovakia	/
Slovenia	5
Spain	122
Sweden	5787
United Kingdom	76

The total amount of DC capacity installed in the base year 2016 amounts to almost more than 7800 MW. As visible in the table above, Sweden is first ranked with nearly 6000 MW. France follows with nearly 800 MW. Finland, Germany, and Italy follow with capacities ranging from about 200 and 300 MW. Austria, Spain, and the UK come next with installed capacities of around 100 MW. The remaining European countries are characterized by just minor values.

Furthermore, following Table 47 displays indications concerning the SEER of DC plants per country, grouped per Temperate, Warm, and Cold Europe.

Table 47 District cooling seasonal energy efficiency ratio per country/country group, EU7+UK, the reference year 2016 EU27+UK [148], [152], [153] (due to France has been divided into two parts - France North and South, for respective calculations, a mean value among Temperate and Warm Europe has been applied for the latter mentioned country)

Temperate Europe: Germany, Austria, Netherlands, Belgium, Luxemburg, France (North), Poland, Czech Republic, Slovakia, Slovenia, Hungary	SEER: 5.1
Warm Europe: Spain, Italy, Greece, Portugal, France (South), Croatia, Bulgaria, Cyprus, Malta, Romania	SEER: 4.0
Cold Europe: Sweden, Denmark, Finland, UK, Ireland, Estonia, Latvia, Lithuania	SEER: 9.4

Moreover, next coming Figure 74 displays the distribution of DC EFLHs among EU27+UK countries.

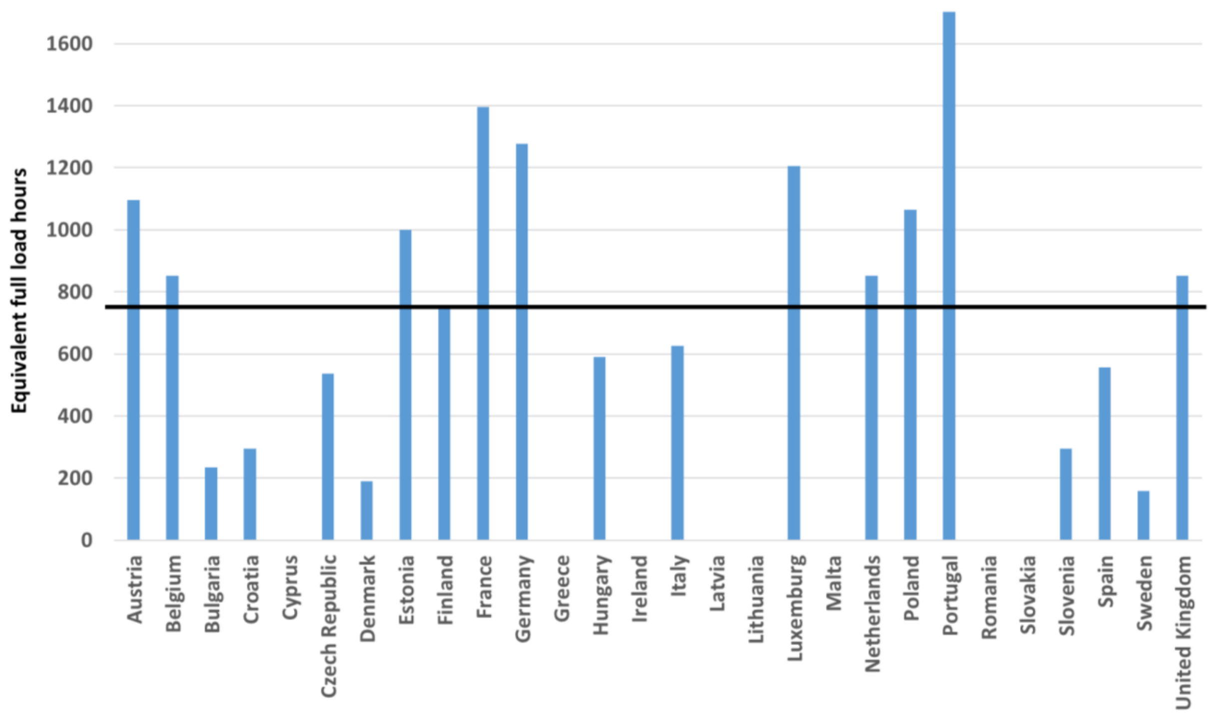

Figure 74 District cooling equivalent full load hours per country, EU27+UK, the reference year 2016, EU27+UK [43], [148], [152], [153], [154], [157] (due to no district cooling systems could be identified in Cyprus, Greece, Ireland, Latvia, Lithuania, Malta, Romania, and Slovakia respective equivalent full load hours are not available)

As visible in Figure 83 above the DC EFLHs in the EU27+UK reach a maximum value of 1600 in Portugal. The minimum value is about ten times less with nearly 160 EFLHs in Sweden. The mean EFLHs for DC in Europe come out to be approximately 780.

The full load hours calculated based on the available data and presented in Figure 74, show considerable deviations between countries and also deviations to the values presented in e.g. Figure 56 for residential SC supply. Also, countries with similar climates like Sweden and Finland or Portugal and Spain show highly deviating values of EFLHs. There are several reasons which may help to substantiate this result: first, the type of consumer connected makes a large difference (e.g. in cold climate from about 7455 EFLHs for process cooling to only a hundred EFLHs for residential customers). Second, the construction of DC capacity may be ahead of customer connection, or the other way round, large customers may disconnect if they find a cheaper supply, or the industry closes, etc. Third, the moderate number of DC grids for most countries leads to a substantial potential impact of the first two arguments on the overall result.

Overall, this shows that the values of EFLHs should not be considered as representative information of DC or a delivering a starting point for future DC grids to be constructed. Rather, they should be understood as a snapshot of the state of the DC in the year 2016.

Integrating the data of Table 46, Table 47, and Figure 74 in equation (Eq.) 18 results into Figure 75 and Table 48.

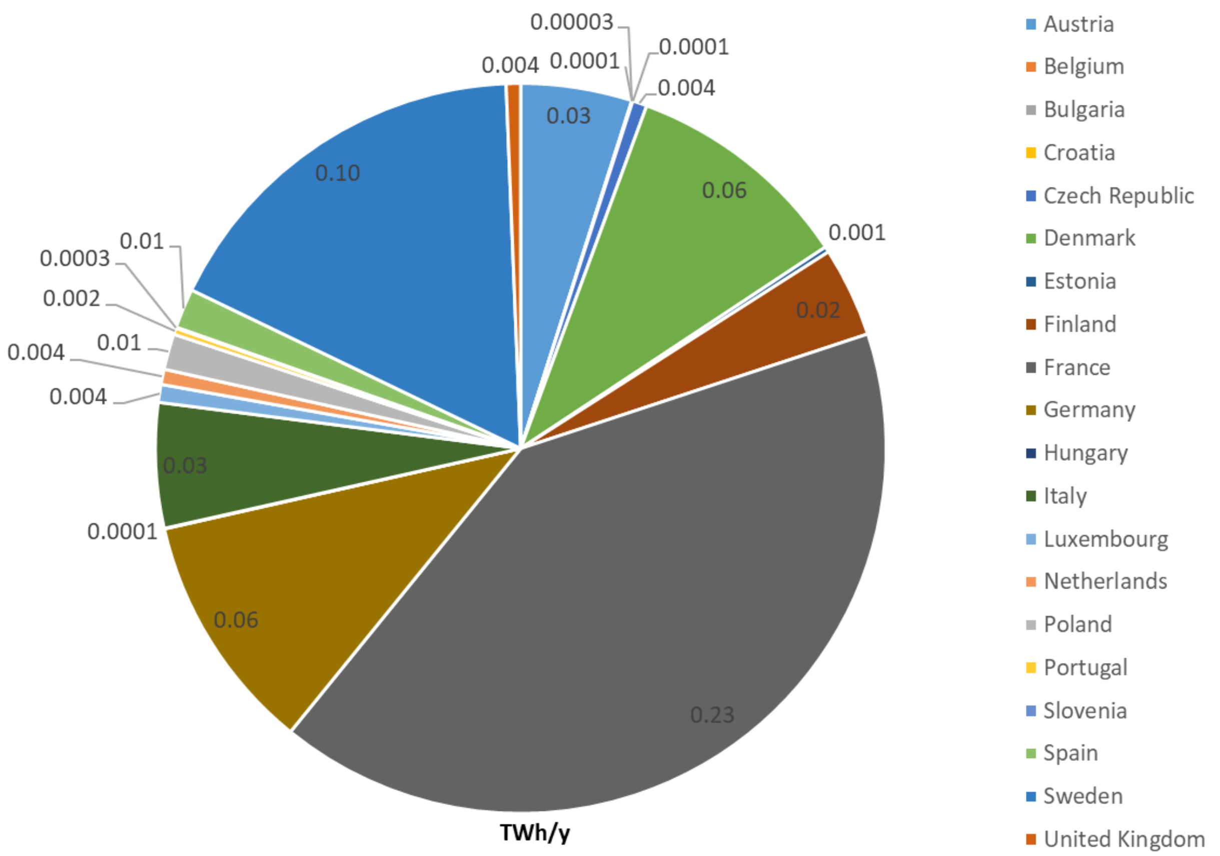

Figure 75 District cooling final energy consumption per country, EU27+UK, reference year 2016 [148], [149], [150], [151], [152], [153], [154], [155], [157]

Table 48 District cooling final energy consumption per country, EU27+UK, reference year 2016 [148], [149], [150], [151], [152], [153], [154], [155], [157]

TWh/y PER COUNTRY – RESIDENTIAL, SERVICE, AND INDUSTRIAL SECTORS		PERCENTAGE
Austria	0.03	4.91%
Belgium	0.0001	0.02%
Bulgaria	0.00003	0.005%
Croatia	0.0001	0.03%
Czech Republic	0.004	0.64%
Denmark	0.06	10.10%
Estonia	0.001	0.24%
Finland	0.02	3.98%
France	0.23	40.93%
Germany	0.06	10.61%
Hungary	0.0001	0.02%
Italy	0.03	5.54%
Luxembourg	0.004	0.79%
Netherlands	0.004	0.68%
Poland	0.01	1.58%
Portugal	0.002	0.28%
Slovenia	0.0003	0.05%
Spain	0.01	1.75%
Sweden	0.10	17.21%
United Kingdom	0.004	0.64%
Sum	0.57	100%

As visible in Figure 75 and Table 48 above, France is first ranked with more than 0.20 TWh/y. Sweden follows with around 0.10 TWh/y. Germany comes next with about 0.06 TWh/y. Italy and Austria follow with about 0.03 TWh/y each. Finland and Spain come next with approximately 0.02 TWh/y. Poland follows with approximately 0.01 TWh/y. The remaining countries show just minor values. The total amount of final DC consumption in Europe reaches more than 0.5 TWh/y.

Finally, integrating the data of Table 46 and Figure 74 in (Eq.) 23 results into Figure 76 and Table 49, which visualize the useful DC cooling demand (DC sales) shares per country.

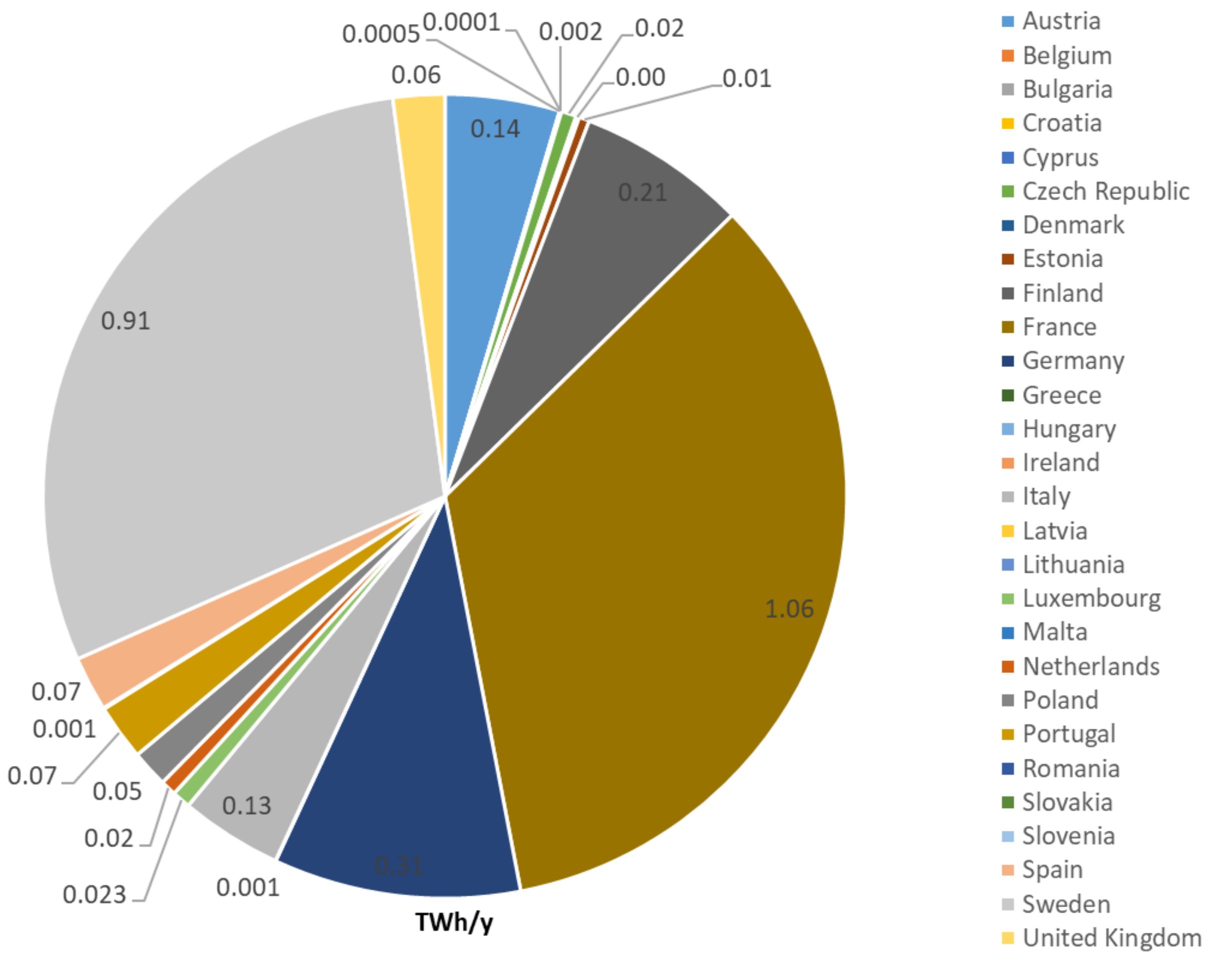

Figure 76 Useful district cooling demand (district cooling sales) per country, EU27+UK, reference year 2016 [48], [148], [152], [153], [154], [157]

Table 49 Useful district cooling demand (district cooling sales) per country, EU27+UK, reference year 2016 [48], [148], [152], [153], [154], [157]

TWh/y PER COUNTRY – USEFUL ENERGY DEMAND		PERCENTAGE
Austria	0.14	4.60%
Belgium	0.0005	0.02%
Bulgaria	0.0001	0.00%
Croatia	0.002	0.07%
Cyprus	/	/
Czech Republic	0.02	0.60%
Denmark	0.00	0.13%
Estonia	0.01	0.42%
Finland	0.21	6.83%
France	1.06	34.31%
Germany	0.31	9.94%
Greece	/	/
Hungary	0.001	0.02%
Ireland	/	/
Italy	0.13	4.09%
Latvia	/	/
Lithuania	/	/
Luxembourg	0.023	0.74%
Malta	/	/
Netherlands	0.02	0.63%
Poland	0.05	1.48%
Portugal	0.07	2.24%
Romania	/	/
Slovakia	/	/
Slovenia	0.001	0.05%
Spain	0.07	2.20%
Sweden	0.91	29.55%
United Kingdom	0.06	2.08%
Sum	3.09	100.00%

As visible in the figure and table above, France is first ranked with more than 1 TWh/y. Sweden follows with almost 1 TWh/y. Germany follows with slightly more than 0.30 TWh/y. Finland comes next with more than 0.20 TWh/y. Austria and Italy follow with more than 0.10 TWh/y. Portugal, Spain, and the UK come next with less than 0.1 TWh/y each. The remaining European countries show just minor values. The total amount of useful DC demand (DC sales) in the EU27+UK reaches more than 3 TWh/y.

Finally, please find in the Table 50 below indications regarding the portion of free cooling (in percentage) of the energy supplied by DCS in various countries subdivided in Temperate, Warm, as well as Cold Europe.

Table 50 Free cooling portion of district cooling systems per country, Temperate, Warm, and Cold Europe, EU27+UK, the reference year 2016 [48]

Temperate Europe: Germany, Austria, Netherlands, Belgium, Luxemburg, France (North), Poland, Czech Republic, Slovakia, Slovenia, Hungary	Free cooling part: 40%
Warm Europe: Spain, Italy, Greece, Portugal, France (South), Croatia, Bulgaria, Cyprus, Malta, Romania	Free cooling part: 20%
Cold Europe: Sweden, Denmark, Finland, UK, Ireland, Estonia, Latvia, Lithuania	Free cooling part: 80%

3.2.7. Comparison and a brief recapitulation

As visible from Figure 57 and Figure 62, Europe's service sector is responsible for almost four times the final SC consumption of Europe's residential sector (with 84 and 22 TWh/y each).

While in the residential sector, the RAC types prevail with about 90% of the final SC consumption, in the service sector approximately 60% is provided by CACs. In total (residential and service sectors), the RACs and CACs are responsible for around 50% of the final SC consumption each.

In both sectors (residential and service) just a few countries are responsible for the absolute majority of the final SC consumption. Spain, Italy, France, UK, and Greece come out to account for more than 80% of the final SC consumption in both sectors.

Europe's final SC and PC consumption result in accounting for approximately 106 and 110 TWh/y each.

As already mentioned above, TDHPs account for about 1% of Europe's cooling market [52]. However, TDHPs are mainly powered by waste heat (according to EUROVENT statistics [52]) and thus final energy consumption indications are negligible in this case.

District cooling so far comes out to be responsible for just a minor part of Europe's useful cooling demand (about 3 TWh/y). Moreover, the penetration of DC varies considerably from country to country. Especially the European Northern countries show a high capacity installed compared to other MSs. Around 80% of Europe's DC capacity can be found in Sweden, Finland, and Denmark - Sweden alone accounts for almost 75%. In contrast, there are several countries located in Warm Europe (Cyprus, Greece, Malta, and Romania) that appear to not make use of DCS. However, DC is constantly growing in Europe for decades, characterized by a high growth potential, especially in commercial areas for offices and retail, as well as campus areas, hospitals, airports, and universities.

Please see below a synthesis of the values reported above. Table 51 and Table 52 report the final cooling consumption as well as the useful cooling demand (supply) in Europe.

Table 51 Final cooling consumption, EU27+UK, reference year 2016 [37], [15], [48], [157], [114]

FINAL COOLING CONSUMPTION (TWh/y)					
Cooling devices	SC residential	SC Service	PC	Total	Percentage of the total supply
Movables	1.7	0.1		1.8	0.8%
Small split (<5 kW)	9.8	6.2		16.0	7.3%
Big split (>5 kW, inclusive ducted)	8.8	30.6		39.4	18.1%
Variable refrigerant flow systems	0.2	8.1		8.3	3.8%
Rooftop + Packaged		20.6		20.6	9.4%
Chiller (air-to-water) < 400 kW	1.4	4.8	41.4	47.6	21.8%
Chiller (air-to-water) > 400 kW		7.4	40.7	48.2	22.1%
Chiller (water-to-water) < 400 kW	0.2	1.4	8.4	9.9	4.5%
Chiller (water-to-water) > 400 kW		4.9	19.6	24.5	11.2%
Waste heat absorption				1.3	0.6%
District cooling total				0.5	0.2%
District cooling Electric chillers				0.2	0.1%
District cooling Pumps				0.3	0.1%
Final cooling (electricity) consumption (TWh/y)	22.1	84.0	110.0	217.9	100.0%
Percentage of total supply	10%	39%	50%	100%	

Table 52 Useful cooling demand, EU27+UK, reference year 2016 [37], [15], [48], [157], [114]

USEFUL COOLING DEMAND/SUPPLY (TWh/y)					
Cooling devices	SC residential	SC Service	PC	Total	Percentage of the total supply
Movables	4.1	0.4		4.5	0.4%
Small split (<5 kW)	39.8	25.4		65.3	5.9%
Big split (>5 kW, inclusive ducted)	33.7	117.5		151.2	13.6%
Variable refrigerant flow systems	0.8	31.1		32.0	2.9%
Rooftop + Packaged		77.5		77.5	7.0%
Chiller (air-to-water) < 400 kW	4.8	16.6	227.2	248.6	22.3%
Chiller (air-to-water) > 400 kW		25.6	248.8	274.3	24.6%
Chiller (water-to-water) < 400 kW	0.9	6.5	60.5	67.9	6.1%
Chiller (water-to-water) > 400 kW		26.2	155.8	181.9	16.3%
Waste heat absorption				7.7	0.7%
District cooling total				3.1	0.3%
District cooling Electric chillers				1.4	0.1%
District cooling/ Natural liquid cold source				1.7	0.2%
Total cooling supply (TWh/y)	84.2	326.8	692.3	1114.1	100%
Percentage of total supply	8%	29%	62%	100%	

Finally, following Figure 77 compares the main results of this study with further scientific literature.

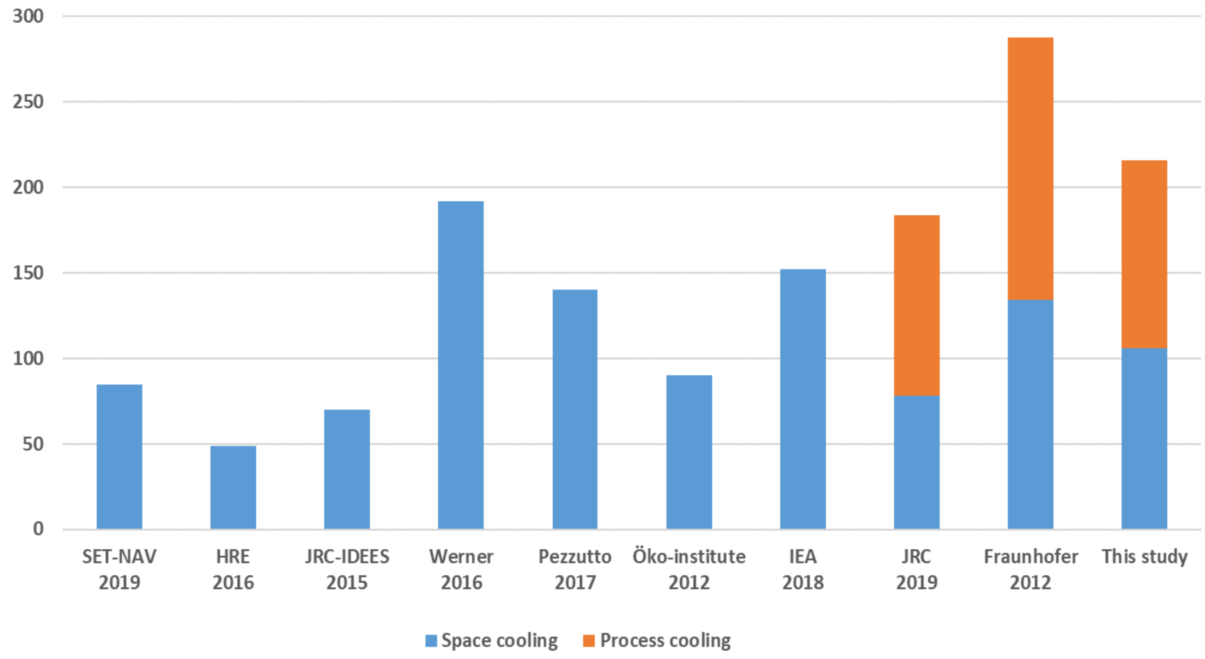

Figure 77 Comparison of these study findings with further scientific literature concerning final cooling consumption in Europe [12,13] [40], [41], [85], [159]–[165]

As visible in Figure 86 above, the values indicated concerning final SC consumption range from about 50 to 200 TWh/y. Given study states final SC consumption in Europe (2016) to be 106 TWh/y. Moreover, regarding process cooling (PC) scientific literature indications range from approximately 100 to 160 TWh/y. This study indicates final PC consumption (2016) in the EU27+UK to be 110 TWh/y. In total (SC & PC) reaches a value of more than 210 TWh/y (about 216 TWh/y) in the given investigation.

Finally, please find in following Figure 78 the share of final energy consumption for cooling (space cooling plus process cooling) on total final energy consumption, country-by-country for the entire EU27+UK (2016).

[12] Please note that the value calculated for final DC consumption within this study (approximately 0.6 TWh/y) has not been included in the values indicated for “This study” (~200 TWh/y) due to missing information of the final DC consumption portion for SC and/or PC purposes.

[13] Please note that time indications next to authors refer to the publication year. These range from 2012 to 2019. Certainly, this might be one possible reason for SC and PC indications diverging from source to source.

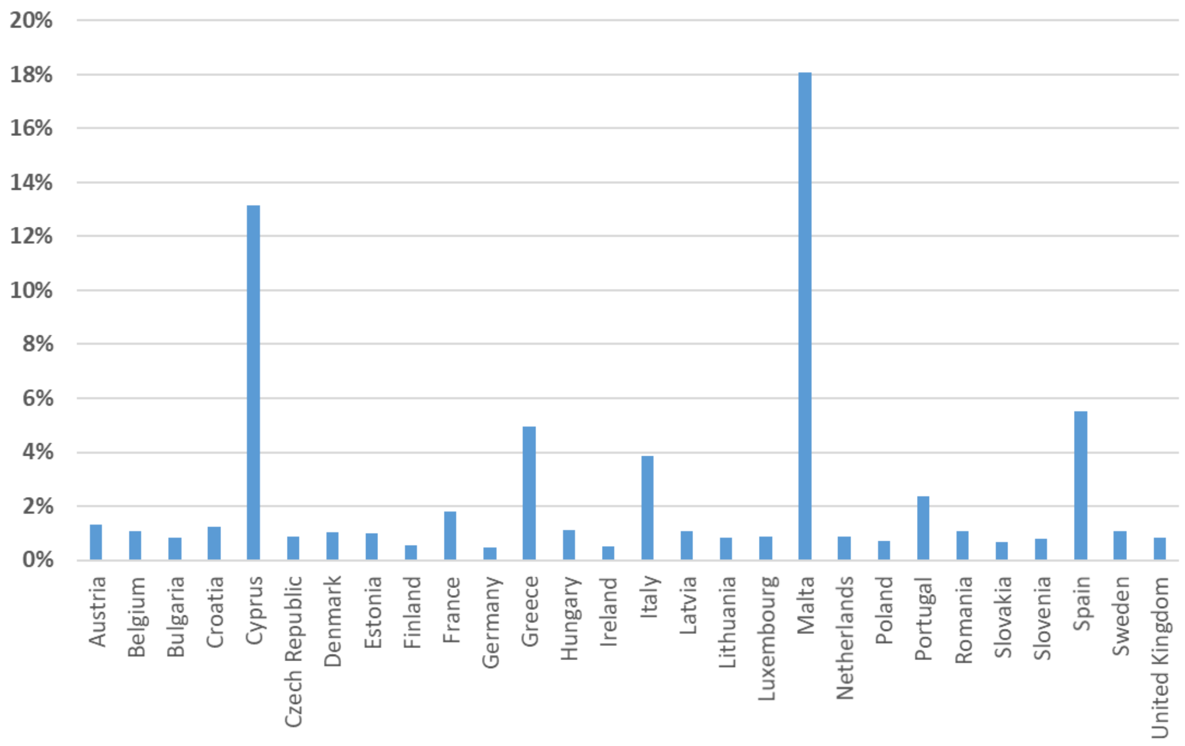

Figure 78 Share of final energy consumption for cooling (space cooling plus process cooling plus district cooling) on total final energy consumption, EU27+UK, the reference year 2016

As visible in Figure 78, the share of final energy consumption for cooling (space cooling plus process cooling) on total final energy consumption is particularly striking for Malta and Cyprus, with values around 18% and more than 13% respectively. Spain and Greece follow with values around 5%, and Italy follows with about 4%. France accounts for a value of nearly 2%. The remaining countries are characterized by minor values.

3.3. Limits of the study

While the European space heating market is already well researched, there is a lack of data/information concerning cooling. Concerning PC and DC, the study team experienced notable difficulties in finding data/information – even more than for SC. Moreover, it has to be underlined that at present time, a huge amount of data concerning the cooling market in Europe is based on estimations [6], [49], [126].

Not all collected information appears to be trustworthy. Notably, the latter concerns market size and efficiency values for cooling equipment. Such data have been excluded from carried-out calculations.

One of the principal complications faced during this study is the fact that the terms useful energy demand and final energy consumption are erroneously used interchangeably and only laboriously obtainable data are available for the European cooling market.

Moreover, it has to be underlined that the final energy consumption values indicated above do not entail the refrigeration sector, due to the potential of RES for freezing is very limited and thus not being in the scope of the present study.

4. Past, present, and future cooling market in Europe

This section presents insights regarding the past, present, and future cooling market (SC and PC - including DC) of the EU27+UK.

There has been an increment in the European final energy consumption for cooling during the past three decades. Both the sales volume of cooling equipment and the cooled floor area have significantly increased since 1990 [6], [52], [158], [166]. Concerning space cooling (SC), an increase in the European specific and total final energy consumption has been registered during the latter mentioned period [6].

The next coming text sheds light on a possible development of Europe’s cooling market for the upcoming decade (until 2030).

4.1. Methodology

Following the methodology proposed in [166], the study team carried out expert interviews to collect input data and information feeding a model (Porter’s five forces analysis – PFFA) and a tool (Multiple criteria decision analysis – MCDA) to generate an outlook. A total amount of 56 experts (one for each country and model as well as a tool) has been contacted.

Interviewees were asked to provide indications concerning both, SC, and PC. Moreover, experts interviewed were asked to answer regarding entire Europe (EU27+UK).

The following text explains briefly the above-mentioned model (PFFA) and tool (MCDA) utilized to generate a forecast as well as the respective validation method (consistency analysis). It has to be stressed, that the PFFA is a quantitative model, while the MCDA is a qualitative tool. The results of both methods have then been compared to obtain a common understanding of the future cooling market in Europe until 2030.

4.1.1. Porter’s five forces analysis (PFFA)

The PFFA model provides indications concerning the status quo of a market and, based on the starting point, predicts its future development. This tool takes into consideration the de facto framework of a market [167]. Starting from a traditional PFFA, a more elaborate tool has been developed. To create a more transparent evaluation of the single forces, a grading scheme and a weighting scale were implemented. A calculation system to evaluate the model’s results were provided as well. The developed model analyses a market by taking into consideration five competitive forces:

- Force 1 - Threat of new entrants
- Force 2 - Threat of substitute products or services
- Force 3 - Bargaining power of suppliers
- Force 4 - Bargaining power of buyers
- Force 5 - Rivalry among existing competitors

These forces in turn were characterized by their respective factors. The single factors´ influence on the market (positive: + or negative: −) and their importance (ranging from 10+ to 10−, with 0 indicating no influence) had to be specified. The results for forces 1-4 were identified by summing the individual factors characterizing the single forces. Force 5 was identified by setting the outcomes of forces 1, 2, 3, and 4 against each other. The result of Force 5 gets marked by an evaluation scale, which emerged from summing up the number of factors used to quantify forces 1, 2, 3, and 4, multiplied by the values of 10+ and 10− (upper and lower boundary). Finally, the result of force 5 was transformed into a percentage by dividing its outcome by the boundary value of the corresponding evaluation scale. This scale, in turn, was also transformed into percentages: 100%+ and 100%−. Figure 79 visualizes the PFFA calculation scheme.

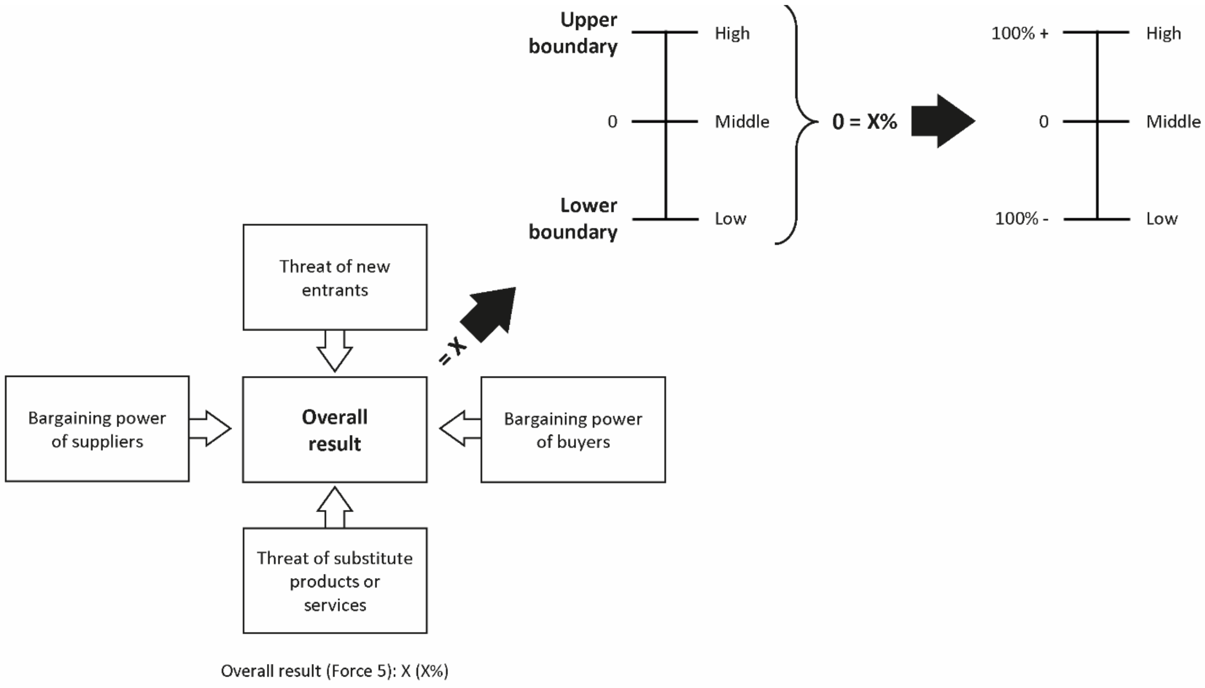

Figure 79 Porter's five forces analysis diagram [168]

The enhanced PFFA was applied to the actual cooling market of all EU27+UK countries. The term "cooling market" refers to VC cooling as dominant technology within Europe's cooling market, while ventilators, thermally driven heat pumps (TDHPs), natural ventilation, etc. were considered substitute products because they are competing for products to VC technologies.

A consistency analysis was implemented as well, which determines how much experts agreed on the importance of the factors. The interquartile range (IQR) of the distribution of the weights was used to quantify the agreement level. This metric indicates the difference between the 75th percentile and the 25th percentile of the data. The 75th percentile is the weight under which 75% of all the weights per sub-goal or sub-factor lie. A high IQR indicates a low agreement level among the experts [6], [166], [168], [169].

4.1.2. Multiple criteria decision analysis (MCDA)

To generate reliable future development predictions for the cooling market, a form of MCDA was applied. This tool considers both the market's participants' goals and the external factors characterizing the market development until 2030. The goals and factors are structured into sub-goals and sub-factors, respectively. The goals, factors, and respective sub-items importance were weighted by experts. Once more, 28 experts were chosen, and again, each EU27+UK country is represented by one expert. All experts are different from the previous PFFA. The single sub-goals and sub-factors weights range, in turn, from 10− to 10+, depending on their importance and influence (positive: + or negative: −) on the market development. As was the case in the PFFA, one indicates the minimum importance, 10 the maximum importance, and zero no importance at all. Once again, the sign "+" stands for a positive and the mark "−" for a negative influence. Essentially, the mentioned tool followed the indicated procedure: the weighted goals, factors, and respective sub-items were respectively ordered vertically and horizontally to form the borders of a matrix. Next, the influence of each sub-factor is specified on each sub-goal. Hence, the influence of the external sub-factors on the respective market participant sub-goals is measured through the multiplication of the sub-factors weights with the related sub-goals weights. If a negative value is multiplied by a positive one, the result is negative, and if two negative values are multiplied, the negative sign remains. Then, by summing up the resulting terms, a value per sub-factor is obtained, indicating the measured influence and importance of the sub-factor on the market participants' sub-goals. Later, the sub-factors results were marked by an evaluation scale (ranging from low, middle to high). The upper limit of the evaluation scale was identified by multiplying the highest weight possible (value: 10) with the number of sub-goals given (upper boundary marked by + and lower boundary by −). Finally, the measured influence and importance of the external sub-factors on the market participant sub-goals were compared to discuss outcome indications. Thus, the core of the calculation was evaluating the influence of the single external factors on the goals of the market participants to subjectively deliver predictions for possible future market development. Figure 80 shows the MCDA calculation scheme.

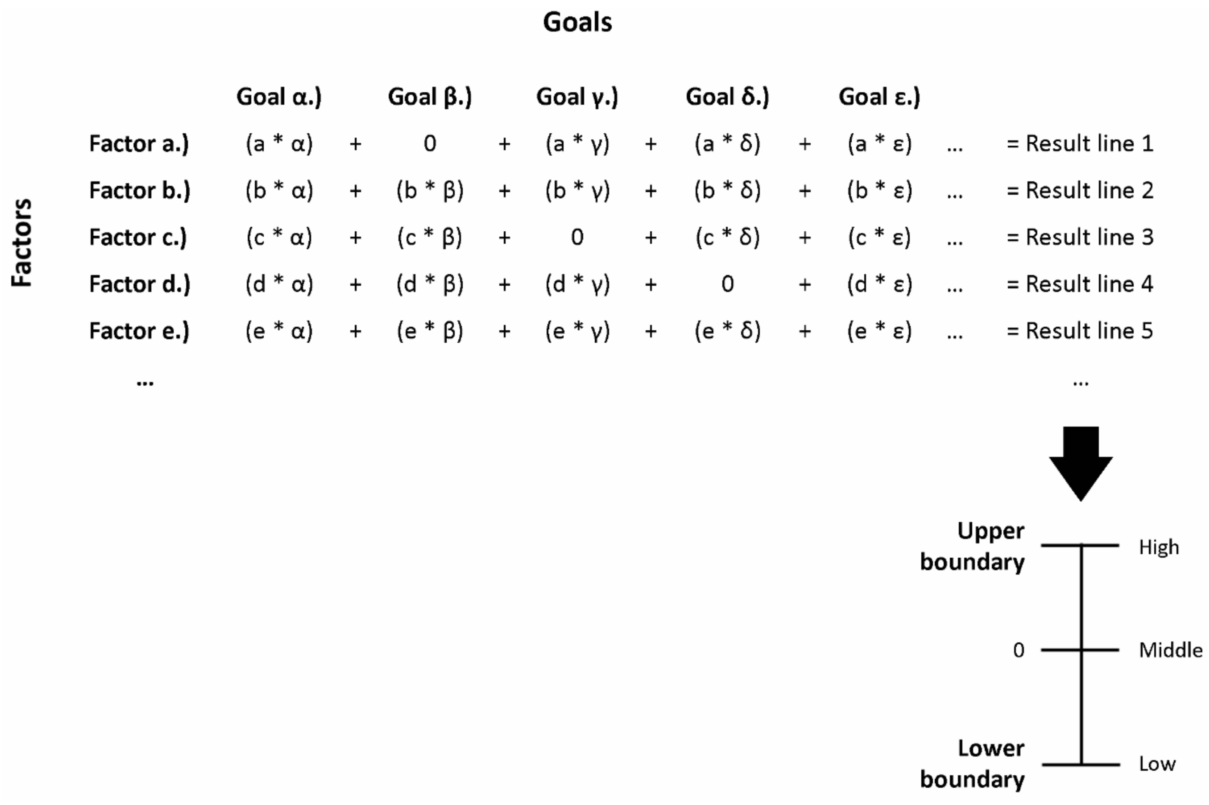

Figure 80 Multiple-criteria decision analysis scheme [168]

The results per sub-factor were compared to give indications concerning the investigation's outcome. Once the consistency analysis was implemented, it determined how much the experts agreed on the importance of the sub-goals and sub-factors. Similar to the PFFA, the IQR of the distribution of the weights was again used to quantify the agreement level among experts. About the selection of market participants, goals, factors and their respective sub-items, relevant for the possible future development of the analysed market, the experts' declarations were considered. As in the PFFA for factors, the following goals, factors, and related sub-items evaluations here were adopted (mean calculation) from the weights given by the experts interviewed. The different experts' weights per goal, factors, and respective sub-items have been averaged and rounded to full numbers. All following goals, factors, and related sub-issues descriptions were obtained from the declarations given by interviewees and counterchecked by scientific sources. Interviewees’ answers have been summed up, and unproven information has been eliminated. For both applied methodologies, per factor, sub-goal, and sub-factor, all experts attributed either + or − signs solely [6], [166], [168].

4.2. Results

4.2.1. Porter’s five forces analysis

Figure 81 provides an overview of the factors with the respective importance and influence of the PFFA indicated by experts. As shown in Figure 81 the majority of the named factors relate to the threat of new entrants (Force 1) and bargaining power of suppliers (Force 3). The latter mentioned categories also include the majority of positive points.

In contrast, most of the negatively marked issues are to find in the threat of new entrants and bargaining power of buyers (Force 4), followed by the threat of substitute products or services (Force 2). The bargaining power of suppliers results in having solely one negative point (competitiveness), which is characterized by very low importance: 1-.

The threat of substitute products or services and bargaining power of buyers have only a limited number of factors compared to the other two present forces. Both latter mentioned factors are characterized by the majority of negative points.

Experts named one-third more issues concerning the threat of new entrants than for its counterpart. Furthermore, there is more than double the amount of points in the bargaining power of suppliers than in the section bargaining power of buyers. Thus, the bargaining power of suppliers proves to be the force with the most positive influence on the treated market, while the bargaining power of buyers registers the absolute majority of negative impacts. The bargaining power of the buyers’ category is characterized by solely one positive point (Risk of failure: 5+).

FORCE 1 - THREAT OF NEW ENTRANTS	Economics of scale	Costs of market entrance	Legislations	Technology protection	Market saturation	Market Image	Market importance	Substitution of services	Transportation costs	Export duties	RESULT FORCE 1
	7+	8+	7+	6+	6-	5-	4-	7+	3+	5+	28+
FORCE 2 - THREAT OF SUBSTITUTE PRODUCTS OR SERVICES	Ventilators	Thermally driven heat pumps	Natural ventilation	Renouncement	District cooling	Other technologies*	Energy efficiency of buildings				RESULT FORCE 2
	1-	2-	1-	4+	2+	3+	1-				4+
FORCE 3 - BARGAINING POWER OF SUPPLIERS	Competitiveness	Size and concentration of suppliers relative to the industry participants	Possibility to forward integration of suppliers	Fragmentation of customers	Market support	Investors' interest	Climate change	Multifunctionalities	Customer loyalty measures	Comfort	RESULT FORCE 3
	1-	8+	6+	1+	4+	5+	9+	3+	3+	9+	48+
FORCE 4 - BARGAINING POWER OF BUYERS	Sale price reduction	Concentration of customers	Differentiation of technologies	Risk of failure							RESULT FORCE 4
	6-	3-	3-	5+							7-

*Figure 81 Factors with respective importance and influence of Porter's five forces analysis regarding cooling in Europe until 2030 (*Other technologies relates to membrane heat pumps, magnetocaloric cooling, acoustic cooling, and building integrate building-integrated heat and moisture exchange panels)*

Figure 82 summarizes the performed factors' evaluations obtained from the expert interviews. The calculations for force 5 result in a value of 73+ over a maximum of 310 units (31 factors). This outcome corresponds to approximately 24%+ (maximum: 100%+). Hence, the rivalry among existing competitors is moderate positive. Several experts stated that global warming and increasing comfort requests are the main drivers of the investigated market. A further factor mentioned in this context is the energy efficiency of buildings, which is characterized by solely a low value (1-), due to minor refurbishment rates of the existing building stock in Europe as well as low new construction activities [170], [171].

As already mentioned above, we used a consistency analysis to determine how much the experts agreed on the importance of the factors. Each IQR per factor is less than three, which is relatively low. Therefore, a certain consistency of the expert weights is assumed. Details about interviewees' responses for each factor are given in Table 61 (Appendix: Experts indications per factors – Porter's five forces analysis).

											Results	Evaluation's scale range (+/-)
FORCE 1 - THREAT OF NEW ENTRANTS	7+	8+	7+	6+	6-	5-	4-	7+	3+	5+	28+	
FORCE 2 - THREAT OF SUBSTITUTE PRODUCTS OR SERVICES	1-	2-	1-	4+	2+	3+	1-				4+	
FORCE 3 - BARGAINING POWER OF SUPPLIERS	1-	8+	7+	1+	4+	5+	9+	3+	3+	9+	48+	
FORCE 4 - BARGAINING POWER OF BUYERS	6-	3-	3-	5+							7-	
FORCE 5 - RIVALRY AMONG EXISTING COMPETITORS											73+	310
FORCE 5 - RIVALRY AMONG EXISTING COMPETITORS (%)											24%+	100% +/-

Figure 82 Porter's five forces analysis of the cooling market: evaluation of the treated factors and related calculations, EU27+UK

4.2.2. Multiple criteria decision analysis

Within the present market analysis, the EU, cooling equipment producers, and customers have been identified as key market participants, and thus, their goals and sub-goals have been taken into consideration.

- EU: the cooling market is characterized by EU legislation, which includes energy efficiency requirements, environmental impact reductions, and the use of energy coming from RES. Hence, the cooling market is characterized by some respective EU directives, regulations, and standards.
- Cooling equipment producers: the future cooling market is marked by the equipment producers' ambition to maximize their income. Profitability is defined as the business's ability to generate earnings above their expenses and other costs incurred during a specific time [6], [172].
- Cooling equipment customers: the future cooling market is influenced by the cooling equipment customers' interest to acquire equipment with the best possible cost-benefit ratio. The cost-benefit ratio represents the ratio between the present gain of an investment and its initial cost. It indicates the quality and life span of a commodity [6], [172].

Figure 83 and Figure 84 visualize the goals, factors, and respective sub-items, with respective importance and influence indicated by experts.

			Weights
Goals	EU Directives	2010/31 EU: EPBD	6+
		2018/2001EU: REDII	5+
		2009/125 Ecodesign Dir.	3+
		EU - EED 2018/2002	4+
	EU Regulations	66/2010: EU Ecolabel	6+
		EU Reg. N° 517/2014	4+
	EU Standards	Test requirements	6+
	Income Max.	Earnings generation	8+
		Expenses reduction	8+
	Benefit to Cost Max.	Gain Max.	8+
		Cost Min.	8+

Figure 83 Goals and sub-goals of the future cooling market participants, EU27+UK

			Weights
Factors	Market potential	Number of installed units	6+
		Energy Efficiency	7+
	R&D	R&D funding	7+
	Habits	Energy consumption for cooling purposes	6+
	Weather	Climate change	9+
	Costs	Costumer´s investemt costs	5-
		Running costs	4-
		Disposal costs	3-
		Transportation costs	2-
	Replacement	Life span of cooling equipment	3+
	Comfort	Comfort requests	8+
	Competition	Size and concentration of the cooling market	4+
		Costumer loyality measures	1+
	Building	Buildings efficiency increase	2-

Figure 84 External factors and sub-factors influencing the future cooling market development, EU27+UK

Next, Figure 85 provides information concerning which sub-factors influence which sub-goals (cells filled with colour indicate a relation between respective sub-goals and sub-factors, and cells not filled indicate a nonrelation).

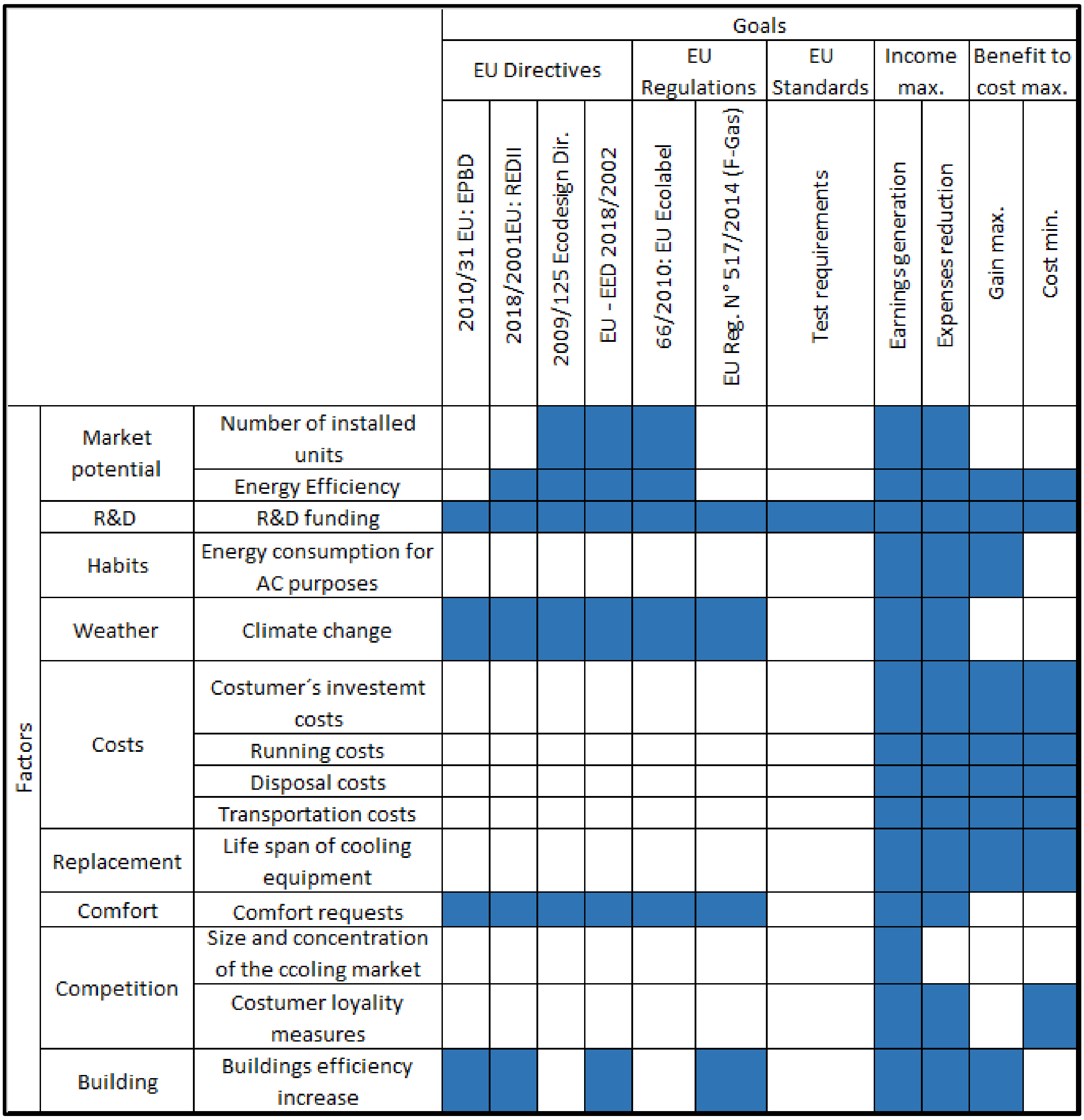

Figure 85 Related external sub-factors and market participants' sub-goals of the future cooling market, EU27+UK

Finally, Figure 86 shows the results of the calculations performed to measure the influence of the single external sub-factors on the sub-goals of the market participants.

Several external factors indicate a positive influence on the future cooling market development.

First of all, it has to be stated that once more climate change comes out to have a strong positive influence on the future cooling market development. Among others, climate change affects in particular income increases of cooling equipment producers. Due to cooling equipment producers sell more devices because of climate change, they experience also an expenses reduction due to economics of scale.

Furthermore, also habits of the European population come out to increase significantly the cooling market in the future. Once more, the habits of Europe's population affect especially the income increase of cooling equipment producers and consequently fewer expenses for these in producing their commodities. Interviewees underlined that European habits will increase especially the final cooling consumption in the household sector, while a certain amount of the service sector is already covered by cooling devices [55], [100]. Concerning the households, experts mentioned that in particular moveables (portable units) will be purchased during warm summers, to be used especially for bedrooms. This factor is strictly correlated to higher comfort requests by the European population.

Moreover, the energy efficiency of cooling equipment appears to have a quite strong influence on the future European cooling market. Due to the increase of cooling equipment's energy efficiency, customers are encouraged to purchase such devices in particular due to lower running costs.

Further external factors display a lower influence on the investigated market.

In contrast, a number of external factors indicate a negative influence on the future cooling market development. All major external factors influencing negatively the future cooling market are related to costs.

As many experts stated, the increase in demand for cooling units will lead to higher costs for customers. Thus, the customer´s investment costs are the major external factor influencing negatively the analysed market.

Running costs are second positioned among the negative influencing factors. Concerning the running costs, it has to be stressed that electricity prices increased significantly in the past decades within Europe and are expected to do so also in the future [166], [174]–[176].

Disposal costs are third among the negatively influencing factors. As an indicative disposal cost, a typical price of approximately 33€ is mentioned (for equipment up to 100 kg weight) [6], [14].

Further external factors display a minor influence on the investigated market.

As in the PFFA, climate change proves to be the driving force of the treated market. Higher comfort requests by the European population are ranked second also in this case. Moreover, within the PFFA the costs of the market entrance are third-ranked, while in the MCDA the energy efficiency of cooling equipment is to find in the latter mentioned position.

Figure 86 restates the performed goals, factors, and respective sub items' evaluations and calculations, leading to the overall result concerning the analysed market outlook.

			Goals											Results	
			EU Directives				EU Regulations		EU Standards	Income max.		Benefit to cost max.			
			2010/31 EU: EPBD	2018/2001EU: REDII	2009/125 Ecodesign Dir.	EU - EED 2018/2002	66/2010: EU Ecolabel (F-Gas)	EU Reg. N° 517/2014	Test requirements	Earnings generation	Expenses reduction	Gain max.	Cost min.		
		Weights	6+	5+	3+	4+	6+	4+	6+	8+	8+	8+	8+	Sum	%
Factors	Market potential	Number of installed units	6+			18+	24+	36+			48+	48+			174+	35+
		Energy Efficiency	7+		35+	21+	28+	42+			56+	56+	56+	56+	350+	44+
	R&D	R&D funding	7+	42+	35+	21+	28+	42+	28+	42+	56+	56+	56+	56+	462+	42+
	Habits	Energy consumption for cooling purposes	6+								48+	48+	48+		144+	48+
	Weather	Climate change	9+	54+	45+	28+	36+	54+	36+		72+	72+			396+	50+
	Costs	Costumer´s investemt costs	5-								40-	40-	40-	40-	160-	40-
		Running costs	4-								32-	32-	32-	32-	128-	32-
		Disposal costs	3-								24-	24-	24-	24-	96-	24-
		Transportation costs	2-								16-	16-	16-	16-	64-	16-
	Replacement	Life span of AC equipment	3+								24+	24+	24+	24+	96+	24+
	Comfort	Comfort requests	8+	48+	40+	24+	32+	48+	32+		64+	64+			352+	44+
	Competition	Size and concentration of the cooling market	4+								32+				32+	32+
		Costumer loyality measures	1+								8+	8+		8+	24+	8+
	Building	Buildings efficiency increase	2-	12-	10-		8-		8-		16-	16-	16-		86-	12-

Figure 86 Influence of the single external sub-factors on the sub-goals of the market participants and respective results, EU27+UK

The solutions of the MCDA contained in Figure 86 can be also shown graphically as it is reported in Figure 87 below.

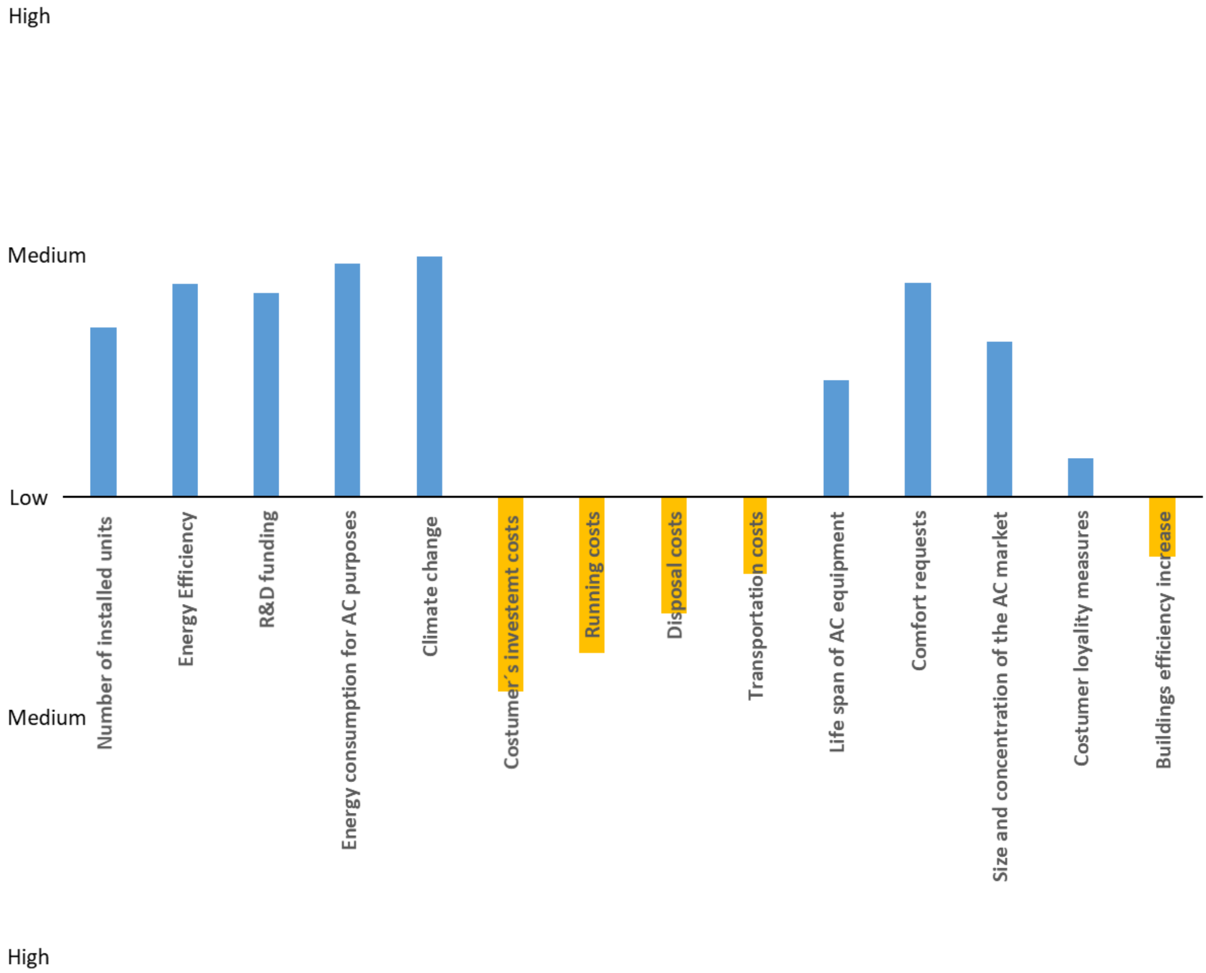

Figure 87 Results of the MCDA Analysis - influence of the external factors on the goals of the most relevant market players (external sub-factors with a negative influence are under the low line; external sub-factors with a positive influence are over the low line)

As visible in Figure 87, nine factors are influencing positively the future market development. In contrast, five factors are influencing negatively the investigated market. Hence, the positive factors are almost double. Moreover, the positive factors are characterized by higher importance. The five highest factors (more than one-third) are positive factors.

Taking into consideration the aforementioned indications concerning Figure 87, once more the European cooling market appears to be characterized by moderate future growth.

A consistency analysis is implemented again, which determines how much the experts agreed on the importance of the sub-goals and sub-factors. The resulting IQR per sub-goal and sub-factor is given in Table 62 (Annex: Experts' indications per factors – Porter five forces analysis and Multiple criteria decision analysis). No IQR per sub-goal or sub-factor exceeds a value of four, which is rather low. Therefore, once more, a certain consistency of the experts' weights is considered to have been given.

Finally, if the increase (in percentage) of the European cooling market indicated by the PFFA (and confirmed by the MCDA), is applied from to values obtained for the year 2016 (calculated in section 3) a value of nearly 270 (268) TWh/y emerges for 2030.

Thus, it is assumed the European cooling market increases by 1 to 2% a year. This means that the obtained value for 2016 (about 220 TWh/y) does not diverge significantly from the calculated value regarding 2017 and as such it might be valid for European Green Deal considerations [177].

If the value obtained for the year 2030 (268 TWh/y) is compared to the respective result provided by the IEA [178] (about 300 TWh/y), this study's outcome appears to be smaller. Concerning that, please note that the survey to generate input data/information to perform the outlook of Europe's cooling market until 2030 has been carried out during the Coronavirus (COVID) pandemic. Thus, interviewees' answers might have been influenced concerning a potentially upcoming economic crisis in Europe.

5. Analysis of space cooling consumption based on a building stock analysis

The space cooling consumption in the residential and service sectors has been assessed using a second approach, so to compare the results with the values resulting from previous section 4.

In this case, the cooled floor area per type of building or service subsector together with the respective specific final energy consumption (kWh/m^2 y) is required. The methodology used for the new assessment of the SC consumption is described below and refers also to the reference year 2016.

5.1. Methodology

The assessment of the European SC consumption starts with the data collection (input). First Invert/EE-Lab, a tool providing data about the disaggregated building stock for all countries of the EU27+UK [179], has been used to collect data concerning the total surface for the residential and service sectors (building stock in million square meters – Mm^2). For every country of the EU27+UK, the data regarding the building stock has been reorganized and clustered according to the H2020 HotMaps project (see HotMaps deliverable 2.3 [123]). Please see here the clustering of the building stock utilized:

Residential buildings have been divided in:

- **Single-family houses** (SFHs)
- **Multi-family houses** (MFHs)
- **Apartment blocks** (ABs – high-rise buildings that contain several dwellings and have more than four storeys)

The service sector has been divided according to the following categories:

- **Offices**: private and public offices; office blocks
- **Trade**: individual shops, department stores, shopping centres, grocery shops, car sales and garages, bakeries, hairdresser, service stations, laundries, congress, and fair buildings, and other wholesale and retail infrastructures
- **Education**: primary, secondary and high schools, universities, infrastructure for professional training activities, school dormitories, and research centres/laboratories
- **Health**: private and public hospitals, nursing, and medical care centres
- **Hotels and restaurants**: hotels, hostels, cafés, pubs, restaurants, canteens, and catering in business
- **Other non-residential buildings**: warehouses, transportation, and garage buildings, military barracks, agricultural buildings (farms, greenhouses), and sports facilities (e.g. sports halls, swimming pools, and gyms).

Buildings have been subdivided also according to their construction year as it follows:

- **Before 1945**: generally classified as historic buildings.
- **1945-1969**: buildings erected between World War II and 1969 are generally characterized by nearly missing insulation and inefficient energy systems.
- **1970-1979**: present the first insulation applications

- **1980-1989** and **1990-1999**: buildings constructed during these two periods reflect the introduction of the first national thermal efficiency ordinances.
- **2000-2010**: buildings considered to be influenced by the impact of the EU Energy Performance of Buildings Directive (2002/91/EC and following recasts).
- **After 2010**: recently constructed. The present analysis contains data updated until the year 2016.

The clustered surfaces described above (expressed in Mm^2), need to be reduced to a fraction representing the cooled floor area for each building type and construction year. For this reduction, the cooled floor area percentage values proposed by [123] have been used. Specific final energy consumption values (expressed in kWh/m^2 y) are required per building type, state and construction. These values have been taken from [180]. The final cooling energy consumption for each sector/building type (i) per EU27+UK MS (k) has been calculated using the following equation (Eq.) 24 using the previously mentioned input data.

$$SC_{consumption\ i,k}\left[\frac{TWh}{y}\right] = \frac{CFA_{i,k}\ [Mm^2] * SCC_{i,k}\ \left[\frac{KWh}{y * m^2}\right]}{1000} \qquad \text{(Eq.) 24}$$

Where:

- SC $_{consumption\ i,\ k}$ = Space cooling energy consumption for the sector “i” in the European state “k”. Expressed in TWh/y
- CFA $_{i,\ k}$ = Cooled floor area for the sector “i” in the European state “k”. Expressed in million square meters Mm^2
- SCC $_{i,\ k}$ = Specific space cooling consumption for the sector “i” in the European state “k”. Expressed in TWh/y

After calculating the single SC consumption, the aggregated data per state both in the residential sector and in the services sector have been produced. The following equations have been used:

$$SC_{consumption,\ NATION} = \sum_i SC_{consumption\ i,k}\left[\frac{TWh}{y}\right] \qquad \text{(Eq.) 25}$$

5.2. Main results

Figure 88 shows both the residential and the service sectors' final SC consumption, specifically for every single MS of the EU27+UK. Furthermore, the whole final SC consumption per state is provided. The majority of final SC consumption is related to the needs of just a few states (mainly Spain, Italy, France, Greece, and the UK), as was already pointed out by section 3.2. More details concerning specifically the residential and the service sectors are provided in the next two chapters. For more detailed values concerning the final SC consumptions per EU27+UK countries, please see Annex: Building stock analysis - complete results for final space cooling consumption in the residential and service sectors.

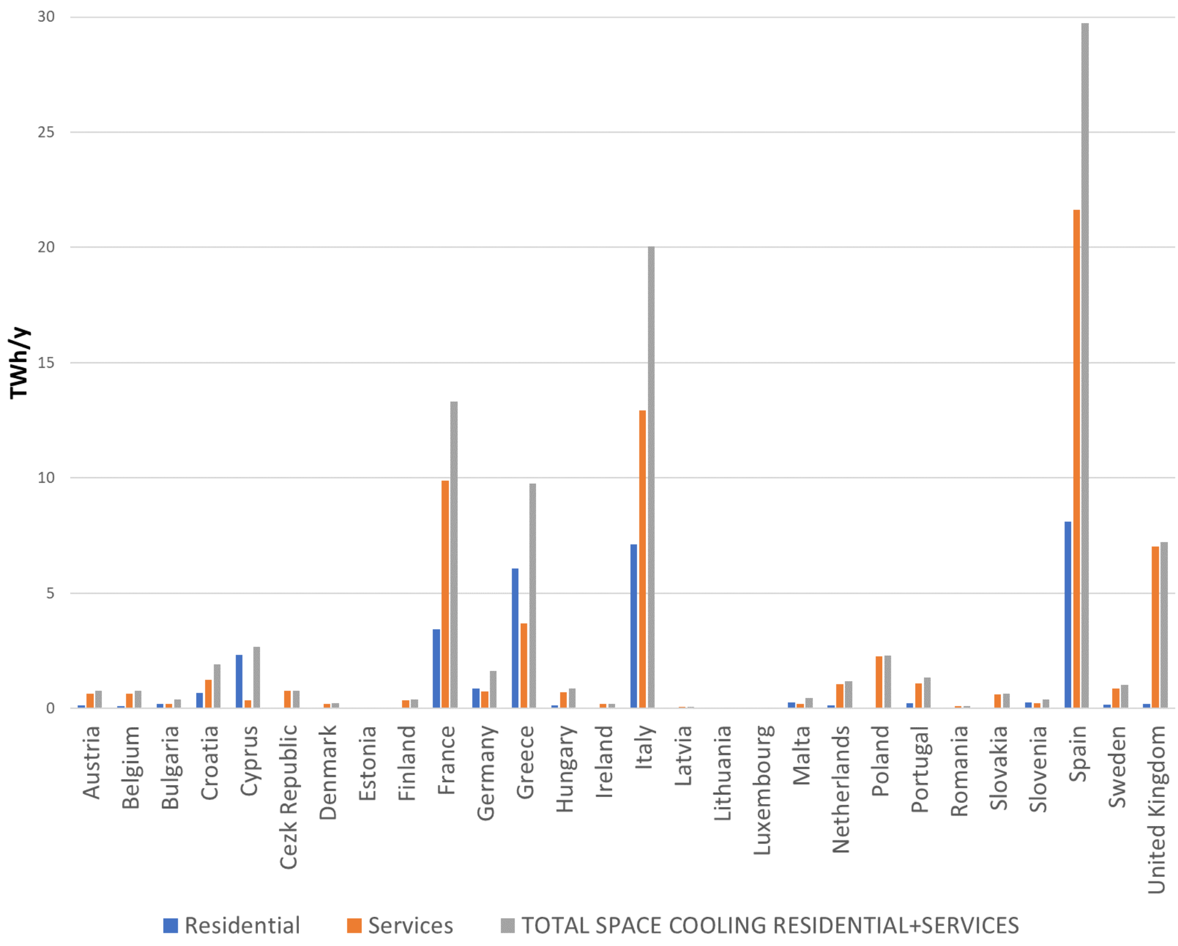

Figure 88 Final space cooling consumption in residential and service sector for the single EU27+UK MSs (TWh/y) - building stock analysis [179], [123], [180]

5.3. Residential sector – Space cooling

As explained in the previous sub-chapter (Methodology), the residential sector has been divided in:

- Single-family houses (SFHs)
- Multifamily houses (MFHs)
- Apartment blocks (ABs – high-rise buildings that contain several dwellings and have more than four storeys)

The final SC consumption per each state and building type has been evaluated. Since the amount of data that has been calculated is huge, only the aggregated results per EU27+UK are shown. Figure 89 and Table 53 display the final SC consumption per sub-sector, which is at a European level quite uniformly distributed. The total final consumption for residential SC at a EU27+UK level results in being about 30 TWh/y.

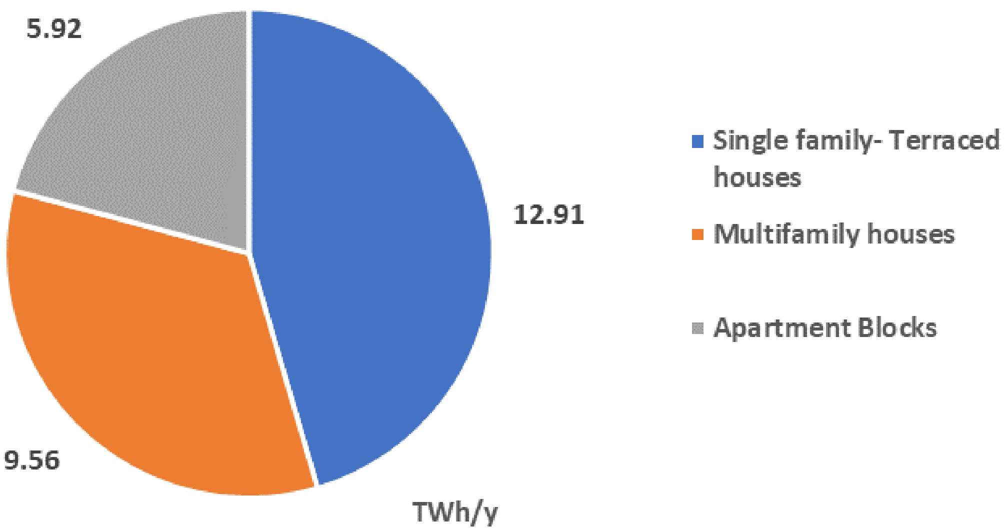

Figure 89 Final space cooling consumption per building type, residential sector, EU27+UK, reference year 2016 (TWh/y) [179], [123], [180]

Table 53 Final space cooling consumption per building type, residential sector, EU27+UK, reference year 2016 (TWh/y) [179], [123], [180]

Space Cooling – Residential Sector – EU27+UK – 2016 – TWh/y			
Total	Single-family- Terraced houses	Multifamily houses	Apartment Blocks
30.6	12.91	9.56	5.92

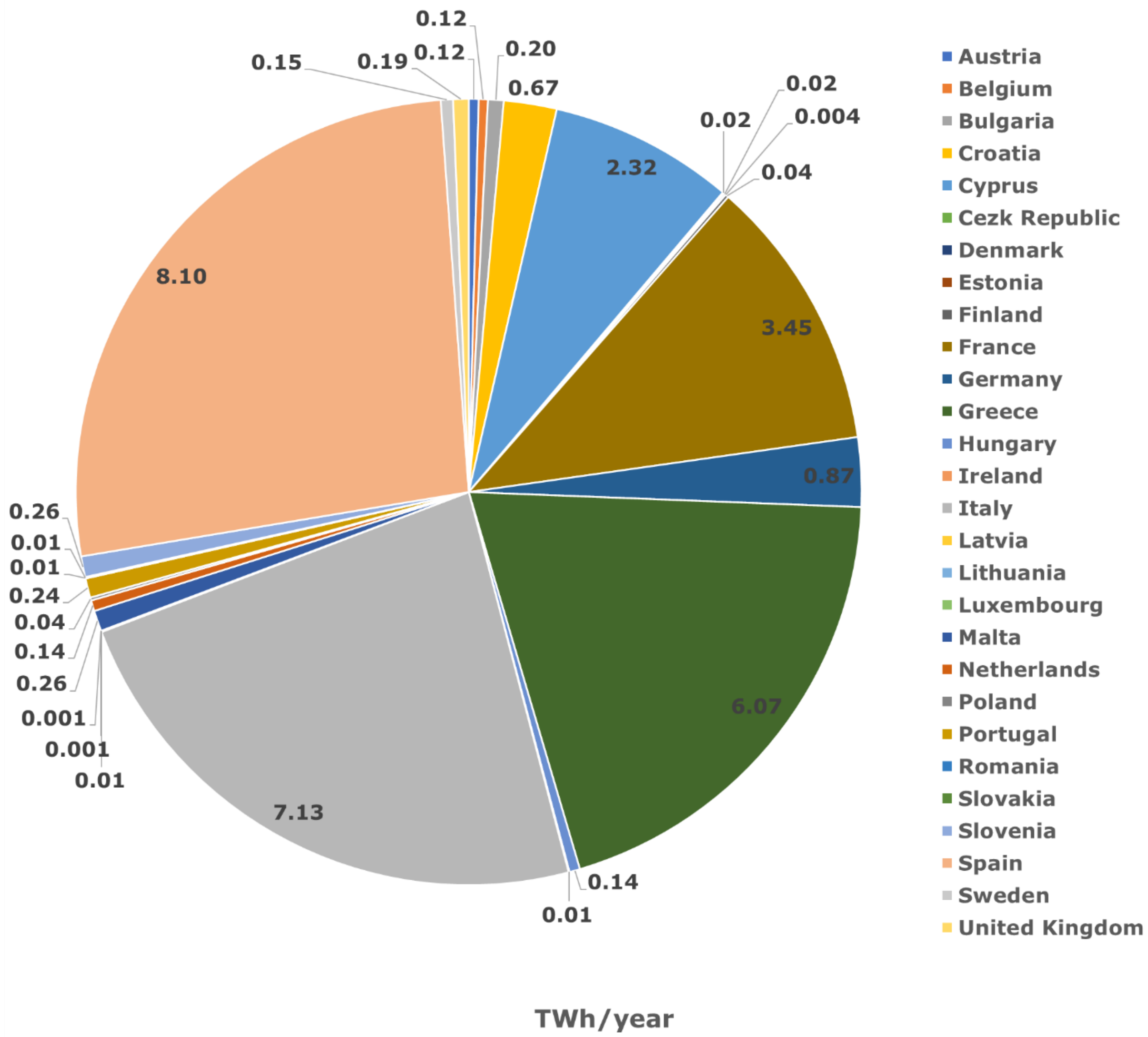

Figure 90 Space cooling final energy consumption per country, residential sector, EU27+UK, reference year 2016 (TWh/y) [179], [123], [180]

Figure 90 shows a disaggregated representation of the national shares within the EU27+UK for the final SC consumption in the residential sector. Spain is the state responsible for the highest share of consumption (26.5%) consuming about 8.10 TWh/year and is followed by Italy and Greece, respectively responsible for the consumption of 7.13 and 6.07 TWh/y. France follows at fourth place consuming every year 3.45 TWh for SC in the residential sector. Please see Table 64 in Annex: Building stock analysis - complete results for final space cooling consumption in the residential and service sectors for more detailed values concerning final cooling consumption in the residential sector for all the EU27+UK countries.

5.4. Service sector – Space cooling

As already described in subchapter Methodology above, the service sector has been divided in:

- Offices
- Trade

- Education
- Health
- Hotels and restaurants
- Other non-residential buildings

The final SC consumption for each service subsector and MS has been calculated. Given a large amount of data, just the aggregated values for the whole EU27+UK are shown. Figure 91 and Table 54 show the final SC consumption per subsector. Trade is the most energy-consuming subsector, followed by other non-residential buildings, offices, and education buildings. The total final SC consumption for the EU27+UK tertiary sector results to be almost 70 TWh/y.

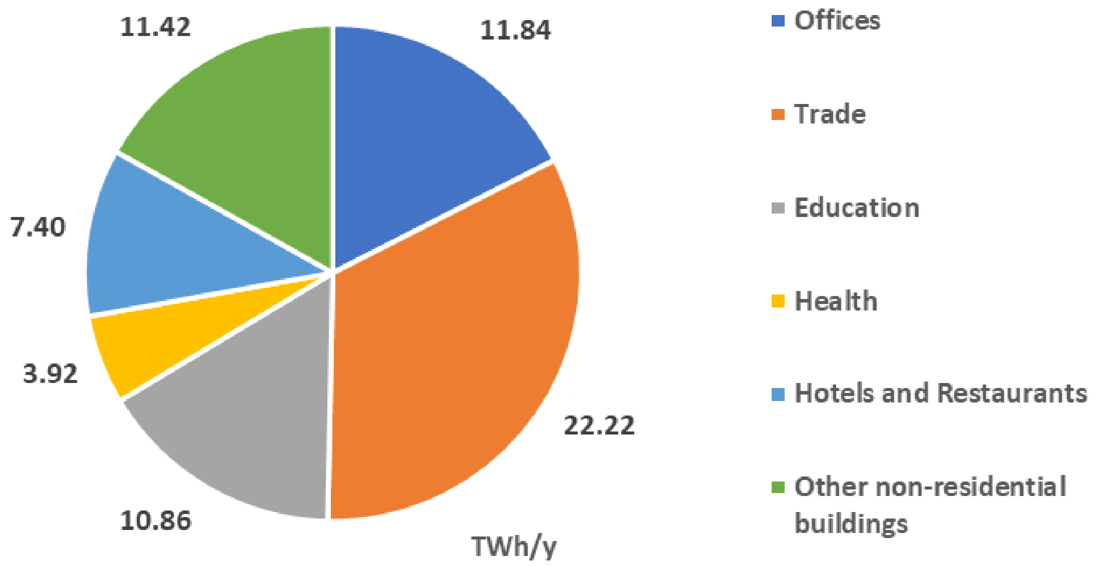

Figure 91 Final space cooling consumption, service subsectors, EU27+UK, reference year 2016 (TWh/y) [179], [123], [180]

Table 54 Final space cooling consumption, service subsectors, EU27+UK, reference year 2016 (TWh/y) [179], [123], [180]

Space Cooling – Service subsectors – EU27+UK – 2016 – TWh/y						
Total	Offices	Trade	Education	Health	Hotels and Restaurants	Other non-residential buildings
67.79	11.84	22.22	10.86	3.92	7.40	11.42

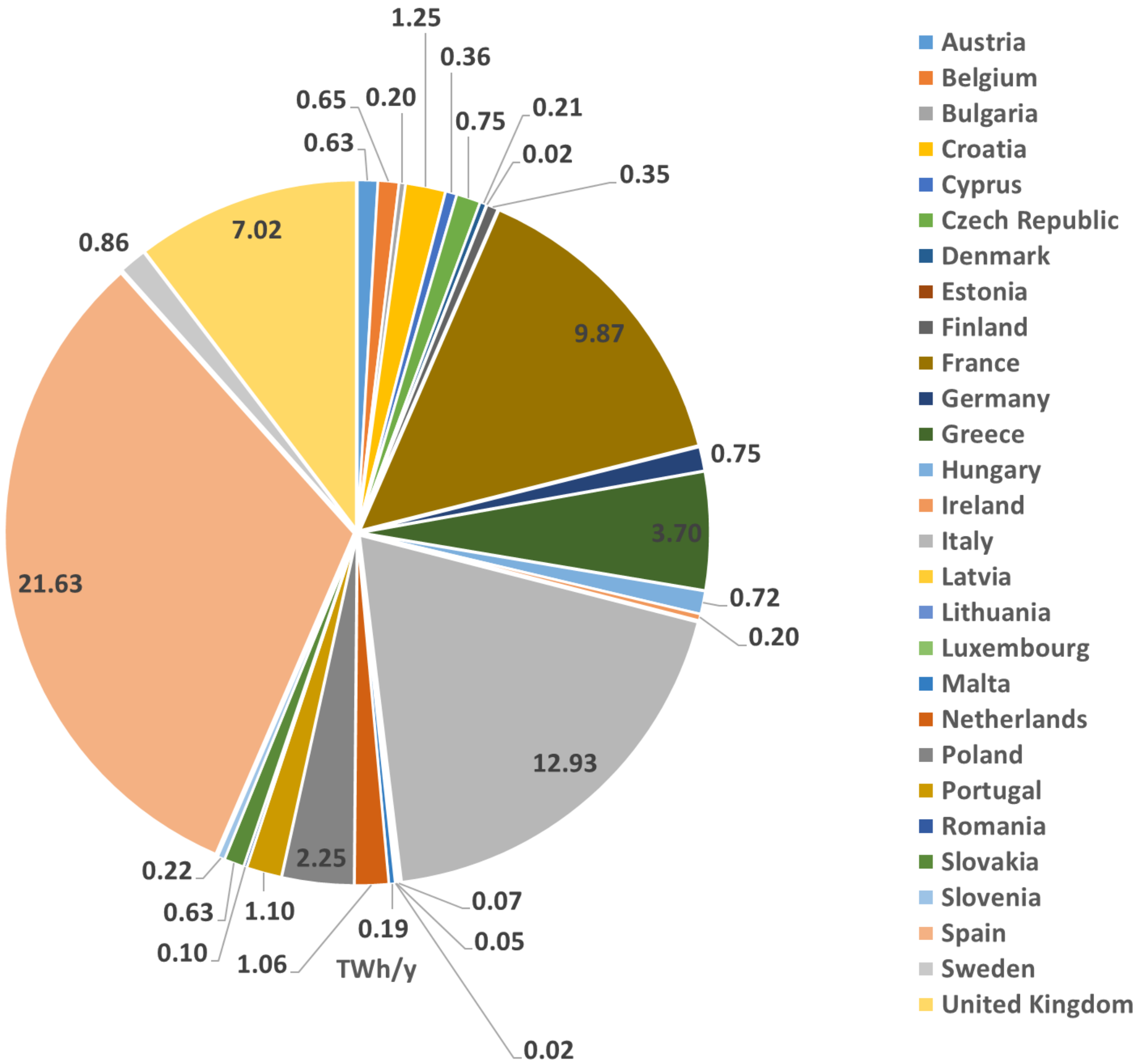

Figure 92 Final space cooling consumption per country in the services sector, EU27+UK, the reference year 2016 [179], [123], [180]

Figure 92 shows that the most consuming state for SC in services sector is Spain (about 22 TWh/year - ~30%). Spain is followed by Italy, France, and the UK, respectively consuming around 13, 10, and 7 TWh. For the full dataset concerning final SC consumption in the services sectors, please see Annex: Building stock analysis - complete results for final space cooling consumption in the residential and service sectors.

5.5. Results comparison

The dataset gained by the procedure described in section 5.1 above has been finally compared with the results indicated in section 3.2.

The datasets are compared in Figure 93, where values for SC in the residential sector, in the services sector, and the total SC (residential + services sectors) are reported.

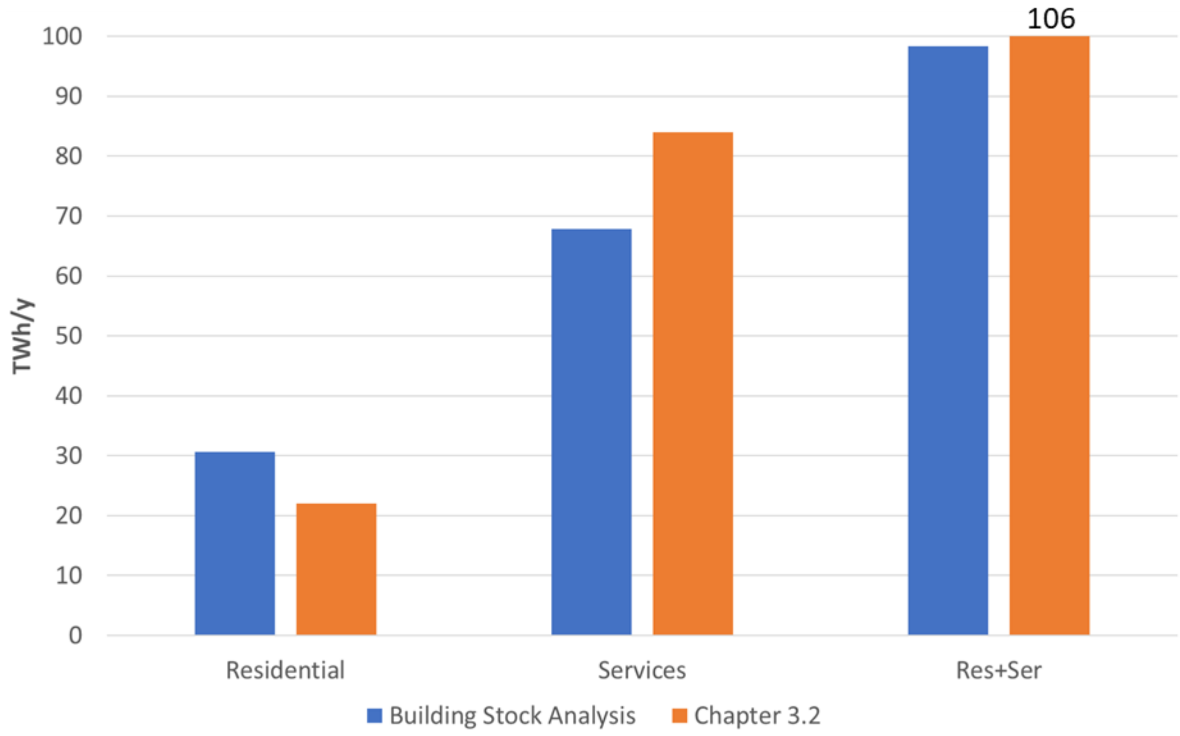

Figure 93 Final space cooling consumption, residential and service sectors, EU27+UK, the reference year 2016 (TWh/y) – comparison of the final results [179], [123], [180]

The data displayed in Figure 93 are also reported in Table 55.

Table 55 Residential, Services and Residential + Services sectors final space cooling consumption for the EU27+UK – comparison of the final results

METHODOLOGY	Final space cooling consumption, residential and service sectors, the reference year 2016, EU27+UK (TWh/y)		
	Residential	Services	Residential + Services
Building Stock Analysis	30.6	67.79	98.99
Section 3.2	22.06	84.04	106.10

The differences between the two datasets concern the services sector with around 16 TWh/year for the whole EU27+UK and about 8 TWh/y concerning the residential sector. Also, the total final SC consumption obtained in the present section results to be slightly lower than the one provided by section 3.

Figure 94 shows the aggregated values shown in Figure 93 concerning the total final SC consumption but splitting it for the singles countries of the EU27+UK.

Figure 94 Final space cooling consumption, residential and service sectors, EU27+UK countries, the reference year 2016 (TWh/y) – comparison of the final results [179], [123], [180]

6. The contribution of free cooling

6.1. Introduction

A free cooling system is a cooling system using a natural cold source to extract heat from the space or process to be cooled via fluid(s) transportation with pump(s) and/or fan(s) and which does not require the use of a cooling generator. Free cooling can be defined as an approach for lowering the air temperature in a building or data centre by using naturally cool air or water instead of mechanical cooling. Practically free cooling is not entirely free since pumps - fans and other air/water-handling equipment are needed [181]. The use of this cooling approach could result in a considerable lowering of the annual final cooling energy consumption in different sectors.

First, a literature analysis has been performed to identify at a European level which are the main sectors/services employing free cooling for lowering their final energy consumption.

6.2. Free cooling applicability

As already mentioned, there are two main sources for free cooling: free ambient air and free water sources (e.g. lakes, rivers, seawater, aquifers, etc.). Concerning the first one, some limitations have to be highlighted: using ambient air can be a limiting factor since the performance of the cooling system is strictly related to the climate conditions. A deep focus needs to be set on the external air temperature, quality (i.e. pollutants, particles, etc.), and relative humidity before using it as a cooling medium [182]. The second cooling medium usable for free cooling is water. Water is usually subjected to lower temperature fluctuations, resulting in a more reliable cooling medium. Attention needs to be set also on water quality. The main concern in using water for free cooling is the ecological and ecosystem-related consequences of increasing the water temperature: water is extracted from the natural source and heat is extracted from the “cooled environment” and transferred to the water itself which gets warmer. The extraction and rejection points need to be at an adequate distance so as not to interfere with each other and a temperature difference not higher than 5-7 °C is preferable [183]. After underlining the restrictions for the application of free cooling techniques, literature research has been performed and the main applications at a European level (EU27+UK) have been resumed in Table 56 below. Some examples of possible study cases have been added to the table itself.

Table 56 Free cooling applications in Europe

SECTOR/APPLICATION	FREE COOLING	STUDY CASES
Data centers cooling	Air/water source free cooling	Lefdal mine data center (Maloy - Norway) [184]
Food storage cooling	Air/water source free cooling	Melinda – Cave apple storage (Segno – Non-Valley) [185] [186]
Space cooling in the services sector	Air/water source free cooling	Hotel Victoria cooling system (Freiburg – Germany) [187]
	ATES (Aquifer Thermal Energy Storage)	Stockholm Arlanda airport (Stockholm – Sweden) [188] German Federal State Parliament Building (Berlin – Germany) [189] Netherlands national ATES system (Netherlands) [190]
Health Sector	SSIS (Seasonal Snow or Ice Storage)	Hospital in the city of Sundsvall (Sundsvall - Sweden) [191]

A deeper analysis of the study cases reported in the previous table has been performed in the next sections.

6.3. Data centres free cooling

Data centres represent an important factor for the worldwide electricity consumption [192]: the increase in the world's Internet Protocol (IP) traffic going through data centres is causing exponential growth in the theoretical energy consumption for data centres, which is damped by the increase in the efficiency of the technologies used. Greater connectivity is therefore propelling demand for data centre services and energy use (mostly electricity). Global data centre electricity use in 2019 was around 200 TWh/y, or around 0.8% of global final electricity usage according to the estimations provided by the IEA [137]. Further data provided by different studies and proposing different projections are reported in Table 57. The data we are mainly interested in is the total electric final energy consumption for data centres in the EU27+UK, which can be assessed for the base year 2016 linearly interpolating the data provided for 2010 by Whitehead and 2020 by Bertoldi [194]. The final electricity consumption in 2016 for data centres in the EU27+UK can be assessed to be around 90 TWh. This result seems to be in line with the JRC research published in 2017 "Trends in data centre energy consumption under the European Code of Conduct for Data Centre Energy Efficiency" [195] assessing the total electric consumption of data centres in Europe to be between 70 and 100 TWh/year.

Table 57 Final energy consumption for data centres assessment from a European, American, and Global perspective [TWh/year]

CONSUMPTION (TWh)	REPORTING YEAR	REFERENCE
EU Consumption		
18.3	2000	Koomey
41.3	2005	Koomey and Whitehead
56	2007	Bertoldi
72.5	2010	Whitehead
104	2020	Bertoldi
US Consumption		
91	2013	Ni
140	2020	Ni
Global Consumption		
216	2007	Van Heddeghem
269	2012	Van Heddeghem

According to the above-mentioned research of JRC [195] around 40% of the total final electricity consumption in a data center is traditionally consumed by the cooling systems ensuring proper cooling to the IT equipment. This data is confirmed by a study by Koronen et al. [194] estimating the traditional VC cooling system to be responsible for about 30 to 50% of the total final electricity consumed in a data center. Assuming the final cooling energy consumption to be 40% of the total final electricity consumption calculated in the previous paragraph, final cooling consumption of 36.5 TWh/y for data centres in the EU27+UK. Evaluating the study case of the data center located in the Lefdal Mine (Maloy - Norway) [184], which is one of the biggest in Europe exploiting the best free cooling technologies, it is possible to evaluate the improvements concerning final cooling consumption by using free cooling. It is then possible to extend these results to the whole data centres stock of Europe assessing so the potential overall energy savings employing ideal exploitation of free cooling. According to the Lefdal Mine database, less than 3% of the energy spent on IT equipment is used for cooling [184]. Applying this lower percentage to the 91.4 TWh of final energy consumption, as all data centres would employ the free cooling technologies employed in the Lefdal data center, only 2.75 TWh would be consumed for cooling. Comparing this result with the one gained by cooling with traditional vapour compression technologies (36.5 TWh) it is possible to assess a reduction of 33.75 TWh (-92%). This is an ideal scenario but clearly shows the high potential of free cooling in reducing the final electricity consumption for cooling in data centres.

6.4. Food storage cooling

The temperature level at which food is stored or refrigerated is perfectly suitable for the exploitation of free cooling natural sources such as water and air (always considering temperature fluctuations). A really interesting project related to free cooling and final cooling consumption minimization is the one developed by Melinda for string the apple they produce: instead of building new traditional storage for their apples, they decided to use some partly natural and partly artificial caves in the Non-Valley, Italy (275 m depth). Inside these caves, a constant temperature of about 10°C is registered all year long. This allows lowering the cooling energy need since the inner temperature of the caves needs to be lowered only by about 8°C. Furthermore, the caves are gas-tight and good insulators, allowing so to preserve the cold produced inside and keep a low oxygen content (preferable for reducing the degradation of apples) [185]. After the rock is chilled, it can maintain a consistent temperature for a long time. This ensures the machines pumping out cold air work less and the amount of water for cooling is reduced. The final energy consumption for cooling is about half of the one required by a traditional cooling system [186].

6.5. Space cooling in the services sector

Free cooling is particularly useful for reducing the cooling load of medium-high cooling use applications such as residential districts or hotels. One interesting example of free cooling in the services sector is the space cooling system of the Hotel Victoria (Freiburg – Germany) [187]. In 2007 a new free cooling system has been installed. Coldwater (10-13°C) is extracted from the ground at a depth of about 16-24 m and circulated in heat exchangers removing the heat load of the rooms. The cooling medium is then rejected again to the ground at a temperature not higher than 16°C (maximum 6°C temperature difference). This system allows only the use of the electric energy to feed circulating pumps for cooling the whole hotel [190].

6.6. Aquifers Thermal Energy Storage

Aquifer Thermal Energy Storages (ATES) use suitable aquifers for (seasonal) storage of the thermal energy: in winter, the water is chilled to be used for cooling in summer. In summer, the heat can be stored for heating purposes during winter. This water is used directly or through heat exchangers for removing or adding a heat load. Special attention needs to be set on the typology of the aquifer used: to allow the storage of thermal energy, the aquifers need to have minimal exchanges with the external environment given by low-speed water movement. Furthermore, a too high-temperature difference between extraction and rejection streams is typically not allowed. Seasonal storage in aquifers for space cooling is usually used in combination with space heating. ATES as cooling (and heating) technology is mainly used for large commercial buildings and apartment buildings larger than 50 units. For smaller buildings, ATES is not economically feasible since the investments exceed the benefits of the technology [190].

Aquifer Thermal Energy Storages are a widely spread technology in the Netherlands, where the potential of aquifer storage and aquifer cooling is also very high. About 90% of the aquifers in the country are suitable for ATES projects. In 2015, around 2 PJ (0.56 TWh) of final energy consumption for cooling purposes in the Netherlands was provided by almost

2000 ATES (Bosselaar, 2017, Renewable Cooling in the Netherlands) [190]. Please find in the following sections below two study cases implementing ATES technology in Europe.

6.6.1. Stockholm Arlanda Airport

The Stockholm Arlanda airport cooling/heating system is fed by the world's largest aquifer storage unit. A natural cycle located in the nearby boulder ridge is used, allowing energy savings equivalent to a year's electricity use for two thousand single-family homes [188]. The aquifer is so divided into a hot and a cold part and used as a water thermal storage both for winter and summer: during the summer, cold water is pumped into the airport's district cooling network. Water running through the system gets warmer, increasing its temperature till about 20°C. This heated water is then pumped underground and used in the winter to melt snow on the aircraft parking stands and to preheat the ventilation air in buildings. Using the aquifer, the airport can reduce its annual energy use by 19 GWh/year [188].

6.6.2. German federal state parliament (Berlin)

The German federal state parliament energy supply is based on a cogeneration system: electricity is mainly produced by thermal engines where the excess of heat is used for heating in winter and feed some absorption cooling machines. The free cooling component is based on an ATES system where the excess energy produced by cogeneration is stored. Aquifer Thermal Energy Storages are fed also by cooling energy provided by the thermal exchange between hotter water of the aquifer and cooler external air during the winter season. The top priority in connection with cold production is in fact to store ambient cold in winter, which is dissipated into the groundwater via heat exchangers. This process lasts the whole winter period, after which the cold water is tapped by reversing the direction of flow at the start of early summer, initially being drawn from the respective cold well at approx. 6 °C. The temperature variation between extraction and injection wells is strongly dependent on the heat load to remove. The temperature at the exhaust can rise to the natural temperature of 11 °C in the course of the summer. If the Bundestag buildings simultaneously require more cold than can be taken from the cold storage wells, this cold is generated by conventional cooling machines [189], [190].

6.7. Seasonal Snow or Ice Storage

Seasonal snow or ice storage systems (SSIS) are used to store cold solid material (snow or ice) during the winter season, prevent their rapid meltdown, and use the melted water to feed cooling systems. These kinds of cooling systems are more suitable for cold climates characterized by winter snowfalls and colder temperatures.

One of the most famous and biggest SSIS applications is the space cooling system of the Hospital of Sundsvall (Sweden) [191]: Sundsvall´s hospital cooling system is operating since 2000. Snow is stored in a sealed pond structure (140x60 m) built of water-tight asphalt and covered with a 0.2 m thick layer of woodchips for insulation and prevention of snow melting. The total capacity of snow storage is 60000 m^3 (40000 tons of snow). Melting water is then cleaned and transferred to the hospital and after cooling is recirculated to the snow storage at a slightly higher temperature. The cold is extracted by direct contact of the circulating water with the snow. During the first summer, the total amount of cooling energy required by the hospital (space cooling) was 655 MWh with a maximum power of 1366 kW [190], [191]. The use of 19000 m^3 of snow in the SSIS cooling system was enough to cover 93% of the total cooling need (609 MWh). The remaining 7% of cooling energy was provided by traditional VC cooling machines (46 GWh). About 75% of the snow used was natural snow, while the remaining 25% had been produced using snow guns. Concerning the COP, a running COP of 10.5 (lowered to 8.6 considering the material depreciation) has been evaluated with a correspondingly COP for the chiller of 2.2 [191].

7. Quantification of the actual contribution of thermally driven heat pumps

7.1. Introduction

According to EUROVENT [52], approximately 99% of the final cooling consumption in Europe is provided by traditional VC cooling systems. The remaining 1% of the total share is provided basically by thermally driven heat pumps (TDHPs, absorption, and adsorption equipment). In this section, an assessment of the final cooling consumption of TDHPs for every country of the EU has been performed. The values of final cooling consumption have also been divided according to the sources used for providing cooling energy and to the type of technology utilized (e.g. absorption or adsorption technologies [196]).

7.2. Thermally driven heat pumps final cooling consumption

In section 3 the final cooling consumption for the single EU27+UK countries had been assessed and is reported in Table 51. As already mentioned above, according to EUROVENT [52], 99% of the final cooling consumption is provided by traditional vapour compression cooling systems while the remaining 1% is provided by thermally driven heat pumps (TDHPs). Thus, the amount of final cooling energy given by TDHPs, country-by-country, has been assessed in Table 58, by simply applying the latter mentioned 1% of final cooling consumption to each country.

Table 58 Final cooling consumption, EU27+UK countries (TWh/y, %) - total and thermally driven heat pumps contribution

TWh/y per country – Space cooling + Process cooling		Percentage on total (EU27+UK)	TDHPs contribution
Country	[TWh/y]	[%]	[TWh/y]
Austria	4.29	1.99%	0.04
Belgium	4.53	2.10%	0.05
Bulgaria	0.94	0.43%	0.01
Croatia	0.94	0.44%	0.01
Cyprus	2.68	1.24%	0.03
Czech Republic	2.53	1.17%	0.03
Denmark	1.67	0.77%	0.02
Estonia	0.33	0.15%	0.003
Finland	1.51	0.70%	0.02
France	30.61	14.16%	0.31
Germany	11.74	5.43%	0.12
Greece	9.53	4.41%	0.10
Hungary	2.28	1.05%	0.02
Ireland	0.66	0.30%	0.01
Italy	51.39	23.78%	0.51
Latvia	0.48	0.22%	0.005
Lithuania	0.48	0.22%	0.005
Luxembourg	0.41	0.19%	0.004
Malta	1.21	0.56%	0.01
Netherlands	4.99	2.31%	0.05
Poland	5.52	2.55%	0.06
Portugal	4.41	2.04%	0.04
Romania	2.78	1.29%	0.03
Slovakia	0.81	0.38%	0.01
Slovenia	0.45	0.21%	0.00
Spain	52.07	24.09%	0.52
Sweden	3.93	1.82%	0.04
United Kingdom	12.95	5.99%	0.13
Sum	216.13	100%	2.16

According to Kuehn et al. [197], [198] the main source-related plants for the generation of cooling energy in Europe are solar cooling systems (SCS) (34%), combined heat-and-power-cooling plants (CHPC, 44%), district heating (DH) networks (8%) and waste heat recovery systems (14%). These data have been collected by the Green Chiller members, which have produced and commissioned together about 630 absorption and adsorption chillers with an accumulated cooling capacity of around 18.8 MW between 2006 and 2012. The Green Chiller members association brings together about 60% of all European manufacturers of sorption chillers in the small and medium cooling capacity range. The data collected by the Green Chiller Members Association have been extended for the whole TDHPs market. The data obtained by the assessments done in this paragraph are reported in Table 59.

Table 59 Thermally driven heat pumps' final cooling energy consumption distribution according to the data provided by the Green Chiller members (marked in green you can see the solar cooling shares for Spain, Germany, and Italy described by [197] as well as marked in yellow we evidence the sum for final cooling consumption of the whole EU27+UK)

Country	2006-2012 Green Chiller Members TDHPs sells (small-medium scale)			
	Solar Cooling	CHPC	DH networks	Waste heat
	34%	44%	8%	14%
	[TWh/y]	[TWh/y]	[TWh/y]	[TWh/y]
Austria	0.34	0.44	0.08	0.14
Belgium	0.01	0.02	0.003	0.01
Bulgaria	0.02	0.02	0.004	0.01
Croatia	0.003	0.004	0.001	0.001
Cyprus	0.003	0.004	0.001	0.001
Czech Republic	0.01	0.01	0.002	0.004
Denmark	0.01	0.01	0.002	0.004
Estonia	0.006	0.007	0.0013	0.002
Finland	0.001	0.001	0.0003	0.0005
France	0.005	0.01	0.001	0.002
Germany	0.10	0.13	0.02	0.04
Greece	0.04	0.05	0.01	0.02
Hungary	0.03	0.04	0.01	0.01
Ireland	0.01	0.01	0.002	0.003
Italy	0.002	0.003	0.0005	0.001
Latvia	0.17	0.23	0.04	0.07
Lithuania	0.002	0.002	0.000	0.001
Luxembourg	0.002	0.002	0.0004	0.001
Malta	0.001	0.002	0.0003	0.001
Netherlands	0.004	0.005	0.001	0.002
Poland	0.02	0.02	0.004	0.01
Portugal	0.02	0.02	0.004	0.01
Romania	0.01	0.02	0.004	0.01
Slovakia	0.01	0.01	0.002	0.004
Slovenia	0.003	0.004	0.0006	0.001
Spain	0.002	0.0020	0.0004	0.0006
Sweden	0.18	0.23	0.04	0.07
United Kingdom	0.01	0.02	0.003	0.01
Sum	0.73	0.95	0.17	0.30

Concerning solar cooling systems, a subdivision of the technologies employed for generating cooling energy has been provided by Kuehn et al. [197]. The final cooling consumption for solar cooling at EU27+UK level shown in Table 59 has been so redistributed for the different technologies as shown in Table 60.

Table 60 Final cooling consumption at EU27+UK level by solar cooling technologies

SOLAR COOLING EU27+UK	[%]	[TWh/y]
Absorption TDHPs	71%	0.52
Adsorption TDHPs	13%	0.10
DEC Solid TDHPs	14%	0.10
DEC Liquid TDHPs	2%	0.01

8. Passive cooling solutions

8.1. Introduction

In the context of our project, passive cooling has been defined as actions aiming to reduce the cooling load not requiring an external energy input, and cooling systems using air as the only heat transportation medium and not containing a cooling generator[14]. This means having the possibility of reducing the initial SC load by a zero or very low energy consumption method. There are different applications concerning passive cooling, mainly based on options such as shading devices, envelope design, airstreams, and other solutions. Several passive cooling solutions, such as ventilative passive cooling, can be considered as free air cooling when electrically driven pumps are used to enhance the airflow.

8.2. Night ventilation

Night ventilation is a passive cooling method mainly related to the temperature gradient between night and day and the thermal capacity and thermal mass of the envelope of a building. The working principle is simple: during the night external cold air is used for space cooling, cooling down both the internal temperature of the building and the structure of the building itself, which stores in this way potential SC energy. When during the day the external temperature starts to rise and the internal air of the building requires to be cooled down, the thermal energy stored in form of cold in the building mass is released so to reduce the SC final energy demand. This method provides a solution for reducing the final SC consumption especially in the first hours of the morning. Seen from another perspective, this SC method creates a lag between outdoor and indoor temperatures. Night ventilation systems can be divided into two categories: direct night ventilation, based on the direct circulation of air in the building, and indirect night ventilation, based on the circulation of fresh air in thermal storage at night [199].

An example of direct night ventilation passive cooling is the one applied in the Pleiade dwelling in Belgium, a passive building using also other SC useful energy demand reduction technologies such as passive (or extensive) solar gains in winter. In this case, the thermal mass of different structural components of the building is important to optimize the ventilation strategy. The air changes per hour in this building have been measured and resulted to be of about three air changes per hour (ASHRAE recommends in its Standard 62.2-2016 - "Ventilation and Acceptable Indoor Air Quality in Residential Buildings" - that homes receive 0.35 air changes per hour, which is a value about ten times lower than the one measured in the case study). Despite the high temperature reached in summer (till 30 °C) the internal temperature of the building has been kept under 25 °C without the use of active SC machines, confirming the great potential of night ventilation and other passive cooling strategies [200].

The second example of night ventilation passive cooling is the Open house in Seville. In this case, no active cooling system has been installed (not usual for houses in such climates). In Seville however, the potential for night ventilative cooling is high given the diurnal temperature variation of about 17 °C in summer. The structure of the building has been designed to optimize the solar gains during winter and the shape of the building has been

[14] Cooling systems using air as the only heat transportation medium and not containing a cooling generator" are air based free cooling systems.

designed to catch the night breezes coming from the southwest. Breezes effect is maximized by an appropriate internal design of the spaces and by a smart design of the envelope itself: walls are made of two layers of massive brick with an intermediate air layer and 4 cm of polyurethane foam. All thermal bridges have been eliminated so that the columns of the structure are incorporated into the internal inertia of the building [199].

8.3. Ground cooling

Ground cooling is a passive cooling strategy using the ground as a heat sink during the summer and as a heat source during the winter season. The temperature of the ground once reached a minimum depth, is almost constant along the year, so to allow attenuation of the external air temperature. For SC two different strategies can be used: in the first one, direct ground cooling, the ground system is directly set in contact with the envelope of the building (floor and part of the walls). In the second one, indirect ground cooling, the connection with the building takes place through properly positioned buried pipes and air/water-driven heat exchangers. This type of passive cooling is generally used for preheating ventilation air [199], [201].

An example of this application is the Jaer primary school in Norway [202]. The ventilated building is connected employing a concrete duct (20 m long and with a diameter of 1.6 m) to an air intake tower. After transporting external air through the ground, where it gets cooled, it is distributed on vertical shafts through the whole building. A fan in the duct permits a higher flow rate and so a higher useful energy demand reduction. Buried ducts can provide positive effects on the rising cooling loads, especially in northern countries climates, where the useful energy demand for cooling is lower and night temperatures are colder, air generally remains in the comfort range.

The second example of ground passive cooling is the Aggelidis building in the outskirts of Athens (paper warehouse) [147]. The structure of the building has been properly designed to exploit ground cooling: in the basement parking and mechanical equipment are placed, while on the ground floor there is only storage. On the first floor, it is instead possible to find further storage and offices. The Earth to air heat exchanger used for SC mainly consists of two tubes of 0.31 m diameter and 50 m length buried at a 2 m depth around the building. The use of the Earth to air heat exchangers has permitted to keep the indoor temperature inside the comfort levels without the use of further SC technologies.

8.4. Evaporative cooling

Evaporative cooling is a cooling solution exploiting the sensible heat that can be extracted by the water in fine droplets mixed with air. More specifically, some water is sprayed and mixed with fresh air [199], [201]. Air gets more humid since part of the droplets are evaporated by using the latent heat of vaporization of the air itself thus reducing the temperature of the air used. The movement of air can happen naturally or mechanically driven (hybrid evaporative solution). A further division can be done according to the type of circuit used: it can be direct or indirect. In the former, the water content of the cooling air increases, being the air in contact with the evaporated water. In the latter, the evaporation takes place inside a heat exchanger, without a change in the water content of the air.

One example of an evaporative cooling system can be the one used by the Stock Exchange building in Valletta, Malta [204]. Its structure has been designed so to try to catch the north-western winds blowing during the day and generally resting during the night. Evaporative cooling solution was designed only for dray air climatic conditions, while for humid air conditions, usually traditional chilled water coils are applied. Ventilation is ensured by openings at the ground floor for the intake and openings on the roof for air outtake. Passive downdraught cooling is implemented by 14 hydraulic nozzles operating in dry air conditions.

This last strategy requires a total volume of water of 90 litres per hour at a pressure of 25 bar. To enhance the cooling effect, some fans can be used.

The second example of evaporative cooling, interesting since the humidity of the air is not increased even though the cooling system is direct, is the one implemented in Midershet Ben Gurion, Israel for the Blaustein Institute for the Desert research [204]**.** From a climatic point of view, the area is characterized by dry summers and strong daily temperature variations. The building has been designed so to have a central large atrium directly connected by lateral rooms and laboratories. The downdraught SC was built, thanks to a shower tower incorporated in the centre of the atrium. The shower tower works providing water at low pressure to the top and partly sprayed as droplets into the open shaft. Thanks to the downdraught forces cooled air is provided to the atrium and water, which does not evaporate given the low pressure, is simply collected in a pool below the tower. Given the hot climate, this solution is usually used only as an SC useful energy demand reduction strategy, and further SC systems are integrated.

8.5. Cool roofs

This type of passive cooling mainly consists in the use of higher performances construction materials having lower absorptances and thus reducing the solar gains through the opaque envelope components. Materials used are so characterized by high reflectance but also high emittance, so to favour the radiation of the stored heat in the building. The material used has different properties and they get chosen according to different parameters such as climate, building use, building geometry, and insulation [199].

An example of a cool roof application for cooling can be the one of a single building hosting offices and laboratories of a school in Trapani (Italy), where the original dark concrete tiles covering the roof (0.25 reflectance estimated) have been treated with a white coating increasing the solar reflectance to about 0.85. Effects of the coating have been monitored and it has been found that before the cool roof applications the indoor air temperature was 1.8°C higher than the outdoor one (26.2 and 24.4 °C, respectively). After the cool roof application, the indoor temperature was 1.1 °C cooler than the external one (27.1 and 28.2 °C, respectively). The main difference introduced by the white coating is related to the temperature of the external surface of the roof, which has been sensibly lowered. With the building not being insulated, the impact of the cool roof is very strong; in fact, it was discovered that by increasing the solar reflectance by 0.6 (from .25 to 0.85), the useful energy demand for cooling would be reduced by 54 %.

A second application for cool roofs has been reported [205]. It is the case of a primary school building in Kaisariani, Athens, Greece. The building is not insulated and has a flat roof of 400 square meters. The roof was covered with cement and gravel screed, having an estimated albedo of 0.2. The application of the coating led to the increase of the albedo to an estimated value of 0.89, inducing a radical change in the cooling load. The SC effect of the cool roof reaches its maximum during the peak solar conditions when a temperature difference in the surfaces of about 12 °C has been registered. The analysis demonstrated that the potential SC energy savings of the building were about 40 % concerning the initial useful energy demand and that the SC peak load was reduced by 20 %.

8.6. Green roofs

A further solution for passive cooling is the use of green roofs (also called eco-roofs) [199]. This solution does not only guarantee a reduction in the cooling load but also guarantees positive effects in terms of aesthetic, ecological impact, air quality control, and urban heat island effect mitigation. Usually, green roofs are kept in a high humidity condition, so to exploit the majority of the solar radiation heat for evaporating the water contained in the soil, so to reduce the amount of heat entering the building and enhancing the cooling load. The efficacy of this solution is strictly related to the material used, the humidity of the soil, climatic conditions, and the type of vegetation used. This solution for passive cooling is widely used and there are a lot of different case studies in the literature. Green roofs generally allow a high reduction in the SC load but need to be coupled with other solutions for satisfying the remaining SC load. It is important to remember that the use of green roofs has also some drawbacks, such as the water consumption for keeping the roof in a wet condition and the higher maintenance costs.

8.7. Phase change materials in the building envelope

The use of phase change materials for SC in the envelope of a building is nowadays not so common. Its working principle is simple: the phase change materials (PCM) installed in the building acts as a battery, storing energy using the phase change process and releasing it by exploiting the same but opposite process. Phase change materials batteries practically use the latent heat property of materials to store energy: for example, during the night, when the external air is colder, it is used to freeze the PCM batteries, while during the day the PCM melts extracting heat from external hotter air which gets so cooled. The PCM battery can be simply bypassed by the stream of external air when cooling is not required. To enhance the flow rate of air, it is also possible to increase the performance of the system. The indoor air quality is generally controlled by CO_2 sensors while the bypassing and opening of the air ducts is instead provided by temperature sensors and control rules. An example of a PCM application is a seminar room at a university campus in West England, containing various IT equipment producing high internal gains [206]**.** The seminar room was not the only one presenting this SC system, but it was the one monitored for several periods so to assess the performances of the system. Results showed how the PCM batteries could provide just a minimal part of the cooling load required and as a result, a second cooling system had to be installed. Passive cooling through PCM batteries can be more effective in climates characterized by high night/day temperature variations and moderately warm summers (moderate cooling load).

8.8. Windows and shading systems

One of the most effective solutions for reducing the SC need of a building is to reduce the solar gains, especially in the residential sector, where the internal gains are less relevant. The main effect gained by shading systems is the screening from direct solar radiation, having one of the most important roles in the heating effect on a building. Sunlight can still have an effect using its reflected and diffuse component, but the direct one is blocked reducing dramatically the SC need. Shading can also reduce the peak-SC load in buildings, thus reducing the size of the SC equipment. Energy savings can range between 10 – 40 % [207] and in moderate climates, it can even help to avoid an active cooling system.

8.8.1. Shading by overhangs, louvers, and awnings

A proper design of the shading systems, directly integrated into the structure of the building or separately placed, guarantee a dramatic SC useful energy demand reduction given by a strong peak solar heat gains reduction. The use of shading systems can also improve the peak load hours a positive effect on the natural lighting quality. The proper design of a shading system allows the screening from direct solar radiation in summer but allows the solar rays to reach the building during the winter period, so to reduce the heating need. For example, simply fixed overhangs are very effective at shading south-facing windows in the summer when sun angles are high [208].

8.8.2. Shading of roof

Also, the roof can be shaded blocking the direct solar radiation to hit the surface of the roof itself. The shading effect can be reached utilizing concrete covering, plants, canvas, or other methods. Using a covering of the roof, however, does not permit escaping of heat to the sky at night-time. Another option for covering the roof is the use of green roofs on which deciduous plants are planted or the use of coatings/coverings having high reflectance and low absorbance [208].

8.8.3. Shading by trees and vegetation

The landscape surrounding a building affects the SC load, too: placing trees for example in the right positions could avoid direct radiation hitting certain parts of the building itself. Shading and evapotranspiration (the process by which a plant actively releases water vapor) from trees can reduce surrounding air temperatures by as much as 5 °C [207]. Their effect however is difficult to regulate between winter and summer seasons. The use of deciduous trees can allow the shading in summer when leaves are hanging on the trees, and allow sunrays to hit the building in winter when leaves fall.

Proper Landscaping can be one of the important factors for energy conservation in buildings. Vegetation and trees in particular, very effectively shade and reduce heat gain. Trees can be used with the advantage to shade roofs, walls, and windows. Different types of plants (trees, shrubs, vines) can be selected based on their growth habit (tall, low, dense, light-permeable) to provide the desired degree of shading for various window orientations and situations. The following points should be considered for summer shading [153].

- Deciduous trees provide summer shading and allow winter access. They should be located on the south and southwest side of the building.
- The heavier the foliage the higher the obstructing effect of the sun’s rays. Dense shade is cooler than filtered sunlight.
- Evergreen trees on the south and west sides afford the best protection from the setting summer sun and cold winter winds, however, they cause an increase in the winter heating demand since the sunrays screening.
- Plants adhering to the walls can provide an additional shading and insulation effect.

8.8.4. Shading by textured surfaces

Integrated buildings structures and elements can provide an interesting shading effect too. In this case, only newly built buildings are interested. The creation of a wall surfaces texture can guarantee an increased outer surface coefficient, keeping the surface itself cooler during the whole day.

8.9. Selective coating for glazed surfaces

There is a wide choice of new glazing systems integrated with selective coatings, able to screen from undesired frequencies of solar rays and letting pass the one desire to have. In this way, it is possible to exploit the frequencies responsible for the lighting effect avoiding the one only providing an external thermal load to the conditioned building. The only problem with these glazing systems is that they do not distinguish between winter and summer seasons [210].

Annex

Annex: Experts' indications per factors – Porter five forces analysis and Multiple criteria decision analysis

The following tables resume the answers provided by the contacted experts during the 56 interviews carried out for the data/information collection. The interquartile range (IQR) of each factor is provided as well at the bottom of the following tables - Table 61 and Table 62.

Table 61 Porter five forces analysis – marks for factors

	Force 1										Force 2						
	Treat of new entrants										Threat of Substitute Products and services						
	Economics of scale	Costs of market entrance	Legislations	Technology protection	Market saturation	Market image	Market importance	Substitution of services	Transportation costs	Export duties	Ventialtion	Thermally driven Heat Pumps	Natural ventialtion	Renouncement	District Cooling	Other technologies	Energy efficiency of buildings
1	8+	8+	6+	5+	6-	7.5-	5-	9+	3+	3+	1-	3-	1-	3+	3+	3+	2-
2	8+	9+	7+	6+	6-	5-	4-	6+	3+	4.5+	1-		2-	4+	3+	1+	2-
3	7+	9+	8+	6+	7-	5-	2-	7+	4+	4+	2-	1-	0	5+	2+	4+	1-
4	2+		7+		8-	6-		2+	1+	4+	3-	1-	0	3+	1+	3+	1-
5	9+	8+	5+	7+	4-	3.5-	6-	8+	2+	3+	1-	2.5-	1-	2+		4+	2-
6	7+	7+	3+	5+	5-	4-	5-	9+	5+	5+	2-	5-	2.5-	4+	0	2+	
7	4+	9+	7+		6-	7-	3-	6+	6+	7+	0		1-	6+	0	2+	0
8		8+	8+	4+	8-	2-	5-	7+	4+	4+	4-	1-		5+	4.5+	1+	1-
9	8+		6+		4-		4-	8+	1.5+	5.5+			0	3+	1.5+		2-
10	9+	7+	4+	7+		4.5-	2-	9+	3+	5+	0	4-	2-	4+	0	0	1-
11	8+	7+		8+		4-	5-		4+	4.5+	2-	3-	0	7+	6+	3.5+	
12	9+	9+	9+			3-	6-	8+	9+	6+	3-	4-	3-	6+		2+	0
13	7+	9+	7+		6-	7.5-	4-	6+	5+	4+	1-	3-	2-	4+	3+	5+	0
14	4+				6-	5-	3-	5+	2+	5+	0	0		5+	1.5+	1+	1.5-
15	8+		9+	7+	5-	7-	2-	7+	3+	5.5+	2-	3-	0	3+	1+		3-
16	8+	8+	8+		7-			9+	5+		1-	2-	0	5+		0	2-
17	9+	9+	7+	5+	6-	4-	2-	9+	0	3+	0-	2-	3-	4+	0	0	3-
18	7+	5+	9+		7-		4-	6+	4+	5+	0-	3-	2-	5+	2+	3+	1.5-
19	5+	7+		6+	5-		3-	8+	6.5+	9+	0-	0	2.5-	4+	1.5+	2.5+	0
20	9+	9+	8+			4-		5+	0	4+		5-	2-	3+	0	3+	1-
21	10+		10+	8+	7-	6-	5-		3+	3+	0-	3.5-	1-	4+		6+	0
22	6+	9+			5-	3-	4-	1+	1+	4+	2-			4+	2+		
23	7+		9+	6+		4.5-	3-	7+	3+		1-	2-	0		1+	4+	0
24	8+	9+	7+	8+	7-		5-		4+	1+	3-	2-	4-	4+	5+	5+	1-
25	9+	8+	8+	7+		4-	6-	8+	5.5+	4+	1.5-	3-	0	5+	0	5+	1-
26	6+	8+	7+		5-	6-	3-	9+		7+	1-		2-	3+	1.5+	1.5+	
27	6+	7+		8+	4-	7.5-	5-		1+	6+	0	1.5-	1.5-		1+	2+	1.5-
28	7+	4+	8+	2+	2-	2-	2.5-	2.5+	2.5+	5+	2-	2-	2-	2.5+	1+	1+	4-
Number of answers	27	22	23	17	22	23	25	24	27	26	26	23	25	26	24	25	24
	Force 1										Force 2						
	Treat of new entrants										Threat of Substitute Products and services						
Evaluated forces	Economics of scale	Costs of market entrance	Legislations	Technology protection	Market saturation	Market image	Market importance	Substitution of services	Transportation costs	Export duties	Ventialtion	Thermally driven Heat Pumps	Natural ventialtion	Renouncement	District Cooling	Other technologies	Energy efficiency of buildings
First Quartile	7	7	7	5	5	4	3	6	2	4	0	2	0	3	1	1	1
Third Quartile	9	9	8	7	7	6	5	8	4.5	5	2	3	2	5	2	4	2
Interquartile Range	2	2	1	2	2	2	2	2	2.5	1	2	1	2	2	1.5	3	1
Final result	7+	8+	7+	6+	6-	5-	4-	7+	3+	5+	1-	2-	1-	4+	2+	3+	1-

	Force 3										Force 4			
	Bargaining Power of Suppliers										Burgaining Power of Buyers			
	Competitiveness	Size and concentration of suppliers relative to the industry participants	Possibility to forward integration of suppliers	Fragmentation of customers	Market support	Investors' interest	Climate change	Multifunctionalities	Customer loyalty measures	Comfort	Sale price reduction	Concentration of customers	Differentiation of technologies	Risk of failure
1	3-	7+	7+	1+	6+	6+	8.5+	4+	3+	7+	6-	3-	3-	4+
2	0	9+	5+	1+	5+	7+	7.5+	2+	2+	4+	4-			7+
3	1-	9.5+	6+	2+		6+	8+	4+	3+	9+	6-	2-	2-	4.5+
4	2-	9+	7+	1+	4+		10+	3+	5+	7+	9-	1-		5+
5	2-	6.5+	5+	3+	3.5+	5+	10+	1+	4+	6+	2-	5-	2-	2.5+
6	3-		6+	2+	2.5+	1.5+	9+	4+	1+	10+	4-	4-	3-	
7	1-	8+	4+		6+	6+	9+	5+	3+	9+	5-		6-	7+
8	0	7+	5+	0	7.5+		8.5+	6.5+	2+		6-		0	6.5+
9	0	10+	8+		5+	3+	10+	4+		8.5+	8-	0	8-	2+
10	2-	7.5+	7+	2+	4+	5+	9+	3+	5+	9+	7-	2-	3-	3+
11	1-	9+	9+	3+		4+	9+		3+	10+	9-	4-	4-	7+
12	1-	3+	+	1+		9+		4+	2+	9.5+		1-	2-	4+
13			7+		7+	6+	8+	1.5+	5+		4-	2-	5-	8+
14	1-	8+	2.5+	1+	5.5+		9+	3+	3+	10+	5-		1-	5+
15	2-	9+	6+	1+	6+	2.5+	10+	4+	5+	9+		5-		2+
16	0	4.5+	5+	1+	0+	5+	10+	2+	3+	8+	7-		0	
17	2-	7+	6+	0	3+	7+	8+	0	2+	8.5+	8-	6-	6-	5+
18	1-	6+	7+			4.5+	8.5+		3+	10+		7-	3-	3+
19		8+	8+	1+	5+		9+	5+	4+	10+	7-	-	4-	
20			7+	3+		7+		5.5+		7+	5-	2-	0	6+
21	1-	8+	1.5+	0+	0+	5+	9+	4+	3+	9+	2-		2-	3.5+
22	0	10+	5+	0+	2+	7.5+	9+			8+	4-	2-		
23	0	3.5+			3+	5+		4+	2+	9+		1-	2-	6+
24	0		5+	2+		+	10+	4+		9+				3+
25	6-	9+	7+	3+	5+	5+	9+	1.5+	3+		7-	3-	5-	+
26	1-	7+	8+	1+	4.5+		9+	2+	4+	9+	4-	5-	5-	6+
27	2-	8.5+	9+	2+	6+	4+	9.5+	5+	5+	10+	6-		6-	
28				2+		6+	8+		2+	9+	7-		3-	3+
Number of answers	24	23	25	23	21	22	25	24	24	25	23	19	24	22

	Force 3										Force 4			
	Bargaining Power of Suppliers										Burgaining Power of Buyers			
Evaluated forces	Competitiveness	Size and concentration of suppliers relative to the industry participants	Possibility to forward integration of suppliers	Fragmentation of customers	Market support	Investors' interest	Climate change	Multifunctionalities	Customer loyalty measures	Comfort	Sale price reduction	Concentration of customers	Differentiation of technologies	Risk of failure
First Quartile	0	7	5	1	3	5	8.5	2	2	8	4	2	2	3
Third Quartile	2	9	7	2	6	6	9.5	4	4	10	7	5	5	6
Interquartile Range	2	2	2	1	3	1	1	2	2	2	3	3	3	3
Final result	1-	8+	6+	1+	4+	5+	9+	3+	3+	9+	6-	3-	3-	5+

Table 62 Multiple criteria decision analysis – marks for goals and sub-goals

	Goals										
	EU Directives				EU Regulations		EU Standards	Income max.		Benefit to cost max.	
N°	2010/31 EU: EPBD	2018/2001EU: REDII	2009/125 Ecodesign Dir.	EU - EED 2018/2002	66/2010: EU Ecolabel	EU Reg. N° 517/2014 (F-Gas)	Test requirements	Earnings generation	Expenses reduction	Gain max.	Cost min.
1	3+	7+	2.5+	5.5+	7+	4+	6+	9+	8+	7+	7+
2	3+	6+	1+	7+	6+	2.5+	7+	7+	7.5+	8+	8+
3		4+	6+		7+	9+	8+	8+	10+	8+	10+
4	8+	1+	2+	5+	6+	0		9+		9.5+	8+
5	7+	5+	3+	3+	5+	4+	8+		9+	6+	7+
6		6+		4+	6+		2.5+	9+	8+	7+	9+
7	2+	3+	2+	2+	7+	6+	7+	8+	7.5+	8+	7+
8	6+	4+	4+	6+	3+	7+	7+	8+	7+	9+	6.5+
9	5+	4+	5.5+	3.5+	4+	4+	3.5+	7+	9.5+	8+	8+
10	8+	6+	1.5+	1+	5+	5+	7+	7+	10+	7+	7+
11		8+	3+	5+		2.5+	5+	5.5+	8+	8+	9+
12	9+	6+	4+	6+	5.5+	5+	7+	9+		9.5+	4+
13	6+	2+	5+	3.5+	7.5+	3.5+		3+	8+		
14		4.5+	3+	6+	6+	6+	6+	8+	8+	7+	6+
15	5+	7+	6+	4+	7+	4+	9+	9+	6+	8+	7+
16	5+	5.5+	2.5+	3.5+		7+	8+	9.5+	7+	7+	9.5+
17	4+		7+	6+	7.5+	7.5+	3+	8+	8+	8+	7+
18	2.5+	6+	5+	2.5+	3+	2.5+	7+	8+	+	9+	9+
19	5+	3+	1+		9+	4+	7+	6.5+	9+	8+	7+
20	6+		5+	5+	4+	5+		7.5+	8+	0+	9.5+
21	5+	6+	4+	6+	6+	0		10+	3+		
22	8+	8+	0+	4.5+	3.5+	7+	7+	9+	9+	9+	7+
23	7.5+		6+				6+	7+	8+	8+	9+
24	9+	6+	3+	1.5+	5+	3+	7+	2.5+	7+	7+	6.5+
25	4.5+	7+	4+	2+	8+	4+	8+	9+	5.5+		9+
26	6+	5+	1+	4+	3+	5+	4+	5+	9.5+	7+	7+
27		4+		6+	6+		7+	9+	8+	8+	8+
28	7+	7+	3+	5+	6+	4+		7+	7+	6.5+	6.5+
Number of answers	23	25	26	25	25	25	23	27	25	25	26
	EU Directives				EU Regulations		EU Standards	Income max.		Benefit to cost max.	
Evaluated goals & factors	2010/31 EU: EPBD	2018/2001EU: REDII	2009/125 Ecodesign Dir.	EU - EED 2018/2002	66/2010: EU Ecolabel	EU Reg. N° 517/2014	Test requirements	Earnings generation	Expenses reduction	Gain max.	Cost min.
First Quartile	5	4	2	4	5	3.5	6	7	7	7	7
Third Quartile	7	6	5	6	7	6	7	9	9	8	9
Interquartile Range	3	2	3	3	2	3	1	2	2	1	2
Final result	6+	5+	3+	4+	6+	4+	6+	8+	8+	8+	8+

	Factors														
	Development		R&D	Habits	Weather	Costs				Replacement	Comfort	Competition		Building
N°	Number of installed units	Energy Efficiency	R&D funding	Energy consumption for cooling purposes	Climate change	Customers´ investemt costs	Running costs	Disposal costs	Transportation costs	Life span of cooling equipment	Comfort requests	Size and concentration of the cooling market	Customer loyiality measures	Buildings efficiency
1	6+	7+	7+	4+	8.5+	3-	4-	1.5-	1-	2+	8+	4+	1+	2-
2	7+	6+	6+	5+	7.5+	2-	2-			3+	7+	3+	1+	4-
3	5+	7+		7+	8+	5-	4-	5-	2-	4+	6+	2+	0	3-
4	4+	8+	8+	3+	10+	4-	5-	1.5-	5-	1+	4+	4+	0	5-
5	8+	8+		6+	10+	4.5-	6-	4-	1-	2+	8+	5+		1-
6	6+	7+	5+	6+		1-	4-	4-	1-	3+	9+	3+	3+	0
7	6+	6+	8+	4+	9+	8-	5-	2-	2-	4+	9+	4+	2+	
8	5+	7+	9+	7+	8.5+	7-	1-	3-	3-	2+	9+	6+	1+	0
9	7+	8+	10+	5+	10+	8.5-	0	2-	4-		9+	5+	3+	
10	7+	6+	8+	6+	9+	5-	7-	2-	2-	2+	6+	3+	3+	2.5-
11	7+	7+	8+	3+	9+	4.5-	6-	7-	3-	3+	7+	4+	0	3-
12	5+	6+	7+	4+		4-	7-	2-	1-	4+	8+	2+	0	1.5-
13	7+	7+	7+	6+	9+	2-	4-	4-	0	4+	6+	2+		1-
14		8+	6+	3+	7.5+	7.5-	5-	3-	0	5+		1+	0+	
15	8+	7+	3+	7+		3-				3+	8+			1-
16		6+	8+	9+	8+					4+	6+	4+	1+	3-
17	7+		8+		9+	7.5-	3-	3-	0		7+		2+	0
18	7+	8+	7.5+	7+		4-	4-	2-	2-	2+	9+	5+	1+	
19	6+	8+	6+	8+	8.5+	3-	5-	3.5-	1-	4+	9+	4+	3+	0
20	8+	7+	7+	8+	8+	6.5-	4-	5-	3-	2+	8+	3+	2+	1-
21	7+	6+	9+	5+	9+	1-	3-	6-	2-	3+	7+	4+	1+	2.5-
22	6+	7+	9.5+	3+	10+					5+	8+	5+	1+	
23		6+	6+	6+		7-	2-	3-	1-	3+	9+	4+		5-
24		7+	7+	6+	7.5+	6.5-	3-	2-	0	5+	9+	3+	0	3-
25	6+	7+	4.5+	5+	9+	7-	2-	7-	0		6+	5+	0	2-
26	6+	7+	7+	6+	9+	4.5-	5-	2-	0	1+		3+	0	2-
27	7+	8+	10+	6+		3-	4-	3-	1-	3+	7+	5+	2+	
28					8+	7-	7-	3-	2-	1+	7.5+	4+	1+	3-
Number of answers	23	26	25	26	22	26	25	24	24	25	26	26	24	22
	Development		R&D	Habits	Weather	Costs				Replacement	Comfort	Competition		Building
Evaluated goals & factors	Number of installed units	Energy Efficiency	R&D funding	Energy consumption for cooling purposes	Climate change	Customers´ investemt costs	Running costs	Disposal costs	Transportation costs	Life span of cooling equipment	Comfort requests	Size and concentration of the cooling market	Customer loyiality measures	Buildings efficiency increase
First Quartile	6	6	6	4	8	3	3	2	1	2	7	3	0	1
Third Quartile	7	8	8	7	9	7	5	4	2	4	9	5	2	3
Interquartile Range	1	1.5	2	2.5	1	4	2	2	1	2	2	2	2	2
Final result	6+	7+	7+	6+	9+	5-	4-	3-	2-	3+	8+	4+	1+	2-

Annex: Process cooling - sectors, subsectors, processes, and technologies

The following Table 63 categorise the cooling technologies by process, subsector and sector for process cooling purposes.

Table 63 Sectors, subsectors, processes, and technologies utilized for process cooling purposes

SECTOR	SUBSECTOR	PROCESS	TECHNOLOGY
INDUSTRY	Food & Beverages	Freeze	Mechanical vapour compression freezing [211]
			Cryogenic freezing [211]
		Cold storage	Mechanical vapour compression refrigeration [212]
		Cooling of products	Absorption (TDHP) [132]
		Condensation	Cryogenic freezing process [213]
		Refrigeration	Rapid evaporative cooling system (Vacuum systems) [214]
	Wineries	Ambient air cooling	Chiller (water-to-water) [215]
		Humidification	Evaporative cooling [216]
		Ambient air cooling	Absorption (TDHP) [217]
			Small split (<5 kW) and Big split (>5 kW) [130]
	Tobacco	Ambient air control	Packaged [131]
		Cooling hydrocarbon rundown	Cooling tower [218]
			Shell and plate heat exchanger [218]
	Plastic moulding	System or infrastructure cooling	Chillers (air-to-water) [8]
			Evaporative cooling [219]
		Plastic machine cooling - Hydraulic oil cooling	Chiller (air-to-water) [8], [219]
			Chiller (water-to-water) [8], [219]
		Plastic mould or tool cooling	Chiller (air-to-water) [8], [219]
			Chiller (water-to-water) [8], [219]
		Plastic product cooling	Chiller (air-to-water) [8], [219]
			Chiller (water-to-water) [8], [219]
	Iron & Steel	Water cooling	Cooling tower [220]
		Waste gas energy recovery	Waste gas cooling plant Hisarna process [221]
			Cooling plants for converter waste gases oxygen steel plants [221]
			Sinter cooler for energy recovery in sintering plants [221]
			Waste heat boilers in coke dry quenching plants [221]
			Cooling stack for Hismelt plants [221]
INDUSTRY	Automotive	Temperature control of laser machines	Chiller (air-to-water) [222]
			Chiller (water-to-water) [222]
		Thermostatic control of painting baths	Chiller (air-to-water) [222]
			Chiller (water-to-water) [222]

SECTOR	SUBSECTOR	PROCESS	TECHNOLOGY
	Cement	Compressors cooling	Chiller (air-to-water) [223]
		Heat neutralization	Chiller (air-to-water) [223]
		Cooling of excess gases	Cooling tower [224]
	Glass	Blowing	Blowers (ventilation) [225]
	Textile	Humidity control	Evaporative cooling [226]
			Chiller (air-to-water) [226]
			Absorption (TDHP) [226]
	Paper, pulp and printing	Cooling of printing machinery	Mechanical ventilation [227]
			Evaporative cooling [228]
			Packaged [132]
	Pharmaceutical	Preservation of thermolabile materials	Evaporative cooling [229]
			Absorption (TDHP) [230]
TERTIARY	Telecommunications	Shelter cooling	Natural convection [231]
			Vortex tube [231]
			Small split (<5 kW) and Big split [133]
		Internal racks cooling	Mechanical ventilation[231]
	Warehouses	Ambient air cooling	Evaporative cooling [143]
			Mechanical ventilation [232]
		Adiabatic cooling	Adiabatic cooling [233]
		Ambient air cooling	Variable refrigerant flow systems [134]
			Rooftop [135]
	Supermarket freezers and cells	Refrigeration and freezing	Small split (<5 kW) and Big split [136]
	Data centres	Electronic equipment cooling	Indirect evaporative cooling [137]
			Natural conduction (heat exchanger) [137]
			Natural convection [137]
			Immersion cooling [137]
			Packaged computer room air conditioners (CRAC) [138]
TRANSPORTATION	Marine	Cooling of batteries	Absorption (TDHP) [234]
		Engine cooling	Natural conduction (heat exchanger) [235]
			Natural conduction - Raw water cooling system [236]

SECTOR	SUBSECTOR	PROCESS	TECHNOLOGY
AGRICULTURE	Greenhouses	Humidification	Evaporative cooling & fans [140]
		Ambient air cooling	Natural ventilation [141]
		Cooling of indoor greenhouse temperature	Absorption (TDHP) [142]
		Ambient air cooling	Mechanical ventilation [143]

Annex: Building stock analysis - complete results for final space cooling consumption in the residential and service sectors

The following Table 64 summaries the results of the space consumption in the residential sector for the EU27+UK divided by single-family, multifamily and apartment blocks obtained by the Building stock analysis of section 5. While, Table 65 entails the space cooling energy consumption in the services sector.

Table 64 EU27+UK countries space cooling consumption in the residential sector [112], [179], [180]

Nation		SPACE COOLING ENERGY CONSUMPTION - RESIDENTIAL [TWh/y]			
		Total	Single-family- Terraced houses	Multifamily houses	Apartment Blocks
Austria		0.12	0.059	0.026	0.028
Belgium		0.12	0.036	0.081	0.003
Bulgaria		0.20	0.127	0.020	0.049
Croatia		0.67	0.456	0.084	0.127
Cyprus		2.32	1.806	0.189	0.070
Czech Republic		0.02	0.011	0.002	0.006
Denmark		0.02	0.013	0.010	0.001
Estonia		0.00	0.003	0.001	0.001
Finland		0.04	0.028	0.002	0.002
France		3.45	1.063	1.768	0.458
Germany		0.87	0.524	0.258	0.081
Greece		6.07	3.420	1.087	1.561
Hungary		0.14	0.091	0.010	0.034
Ireland		0.01	0.008	0.000	0.002
Italy		7.13	1.276	4.650	1.222
Latvia		0.01	0.003	0.010	0.001
Lithuania		0.00	0.001	0.000	0.000
Luxembourg		0.00	0.000	0.000	0.000
Malta		0.26	0.214	0.007	0.039
Netherlands		0.14	0.126	0.005	0.003
Poland		0.04	0.021	0.004	0.012
Portugal		0.24	0.174	0.097	0.105
Romania		0.01	0.007	0.001	0.003

Nation		SPACE COOLING ENERGY CONSUMPTION - RESIDENTIAL [TWh/y]			
		Total	Single-family- Terraced houses	Multifamily houses	Apartment Blocks
Slovakia		0.01	0.003	0.001	0.002
Slovenia		0.26	0.223	0.021	0.024
Spain		8.10	3.004	1.102	2.068
Sweden		0.15	0.062	0.085	0.010
United Kingdom		0.19	0.152	0.038	0.005
EU27+UK		30.60	12.908	9.558	5.919

Table 65 EU27+UK space cooling energy consumption in the services sector [112], [179], [180]

Nation	SPACE COOLING ENERGY CONSUMPTION - TERTIARY [TWh/y]						
	Total	Offices	Trade	Education	Health	Hotels and Restaurants	Other non-residential buildings
Austria	0.63	0.106	0.220	0.019	0.029	0.086	0.208
Belgium	0.65	0.191	0.181	0.105	0.035	0.062	0.075
Bulgaria	0.20	0.056	0.055	0.037	0.014	0.004	0.036
Croatia	1.25	0.270	0.089	0.112	0.062	0.450	0.277
Cyprus	0.36	0.240	0.123	0.099	0.036	0.164	0.018
Czech Republic	0.75	0.250	0.132	0.115	0.046	0.009	0.202
Denmark	0.21	0.074	0.033	0.034	0.006	0.008	0.052
Estonia	0.02	0.013	0.003	0.002	0.000	0.000	0.001
Finland	0.35	0.037	0.139	0.036	0.024	0.015	0.091
France	9.87	1.945	3.104	2.190	1.249	0.715	0.671
Germany	0.75	0.404	0.051	0.118	0.020	0.058	0.038
Greece	3.70	0.587	0.974	1.129	0.047	0.601	0.378
Hungary	0.72	0.034	0.190	0.121	0.076	0.197	0.096
Ireland	0.20	0.047	0.057	0.037	0.011	0.022	0.030
Italy	12.93	1.112	5.535	2.177	0.756	1.078	2.243
Latvia	0.07	0.014	0.015	0.019	0.005	0.006	0.095
Lithuania	0.05	0.013	0.008	0.013	0.003	0.002	0.011
Luxembourg	0.02	0.005	0.007	0.004	0.001	0.002	0.003
Malta	0.19	0.048	0.054	0.027	0.011	0.022	0.029
Netherlands	1.06	0.202	0.311	0.042	0.015	0.040	0.455
Poland	2.25	0.200	0.743	0.740	0.067	0.285	0.347
Portugal	1.10	0.215	0.212	0.123	0.054	0.109	0.139
Romania	0.10	0.015	0.024	0.012	0.013	0.007	0.017
Slovakia	0.63	0.094	0.007	0.241	0.104	0.089	0.090
Slovenia	0.22	0.062	0.067	0.027	0.008	0.020	0.047
Spain	21.63	3.837	6.381	2.477	1.028	2.671	5.114
Sweden	0.86	0.123	0.108	0.313	0.122	0.040	0.162
United Kingdom	7.02	1.645	3.390	0.487	0.082	0.641	0.491

Nation	SPACE COOLING ENERGY CONSUMPTION - TERTIARY [TWh/y]						
	Total	Offices	Trade	Education	Health	Hotels and Restaurants	Other non-residential buildings
EU27+UK	67.79	11.839	22.215	10.856	3.923	7.401	11.416

Annex: Equivalent full load hours for cooling and free cooling

Annex I Tmax values in Meteonorm data files

In the current annex, the difference of the Cooling Degrees Day and the maximum temperature are summarized in the Table 66 below.

Table 66 CDD (Copernicus 2018 and Meteonorm) and maximum yearly temperature (Meteonorm)

	Weather data city for Armines	CDD18 Armines	CDD18 EURAC	Tmax Armines
Austria	Wien	282	250	33.8
Belgium	Brussels	108	321	32.1
Bulgaria	Sofia	303	517	35.2
Croatia	Zagreb	624	556	36.5
Cyprus	Nicosia	1424.7	1860	37.6
Czech Republic	Praha	118	356	32.1
Denmark	Copenhaguen	65.6	184	27.4
Estonia	Tallinn	35.6	186	27.7
Finland	Helsinki	47.5	163	28
France	Paris	230	357	33.6
Germany	Berlin	172	335	31.5
Greece	Athens	965	862	37.8
Hungary	Budapest	378	630	34.6
Ireland	Dublin	0.7	157	23.6
Italy	Roma	734	594	34.8
Latvia	Riga	83.6	220	31.8
Lithuania	Vilnius	76.5	157	31.8
Luxembourg	Luxembourg	131	279	32.3
Malta	Valletta	1038	1485	36.5
Netherlands	Amsterdam	78.2	255	29.8
Poland	Warsaw	147	316	32
Portugal	Lisboa	538	873	36.5
Romania	Bucharest	477	524	35.1
Slovakia	Bratislava	322	402	34.5
Slovenia	Ljubjana	293	343	32.1

Spain	Madrid	707	710	38.6
Sweden	Stockholm	70.9	186	30
United kingdom	London	121	117	31.1

Annex II Inertia

The estimation of the infiltration rate and the inertia of the buildings is estimated based on the year of the construction of the buildings according to the Table 67 below.

Table 67 Estimation of the inertia and the infiltration rate of the tertiary buildings

Period of construction	Inertia (J/(k.m²))
Before 1945	432000
1945-1969	210240
1970-1979	126000
1980-1989	180000
1990-1999	180000
2000-2010	216000
Post 2010	216000

Annex III Years of construction

To present the repartition of the years of construction, a visualization of the years of construction of buildings has been implemented, comparing the stock building modeled in Smart-E and the original data. The repartition of the sources is based on the HotMaps calculation for trade and offices buildings. The results are shown in Figure 95 and Figure 96 below.

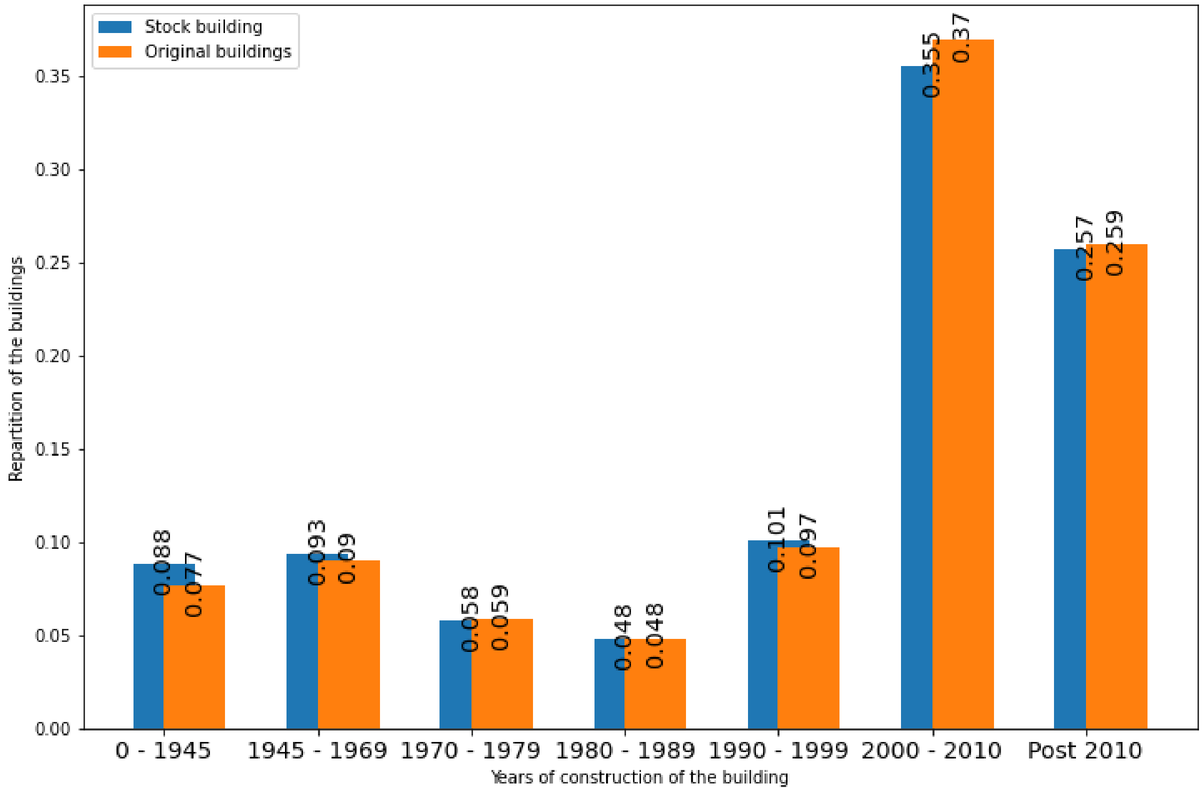

Figure 95 Repartition of the years of construction of trade buildings in Latvia.

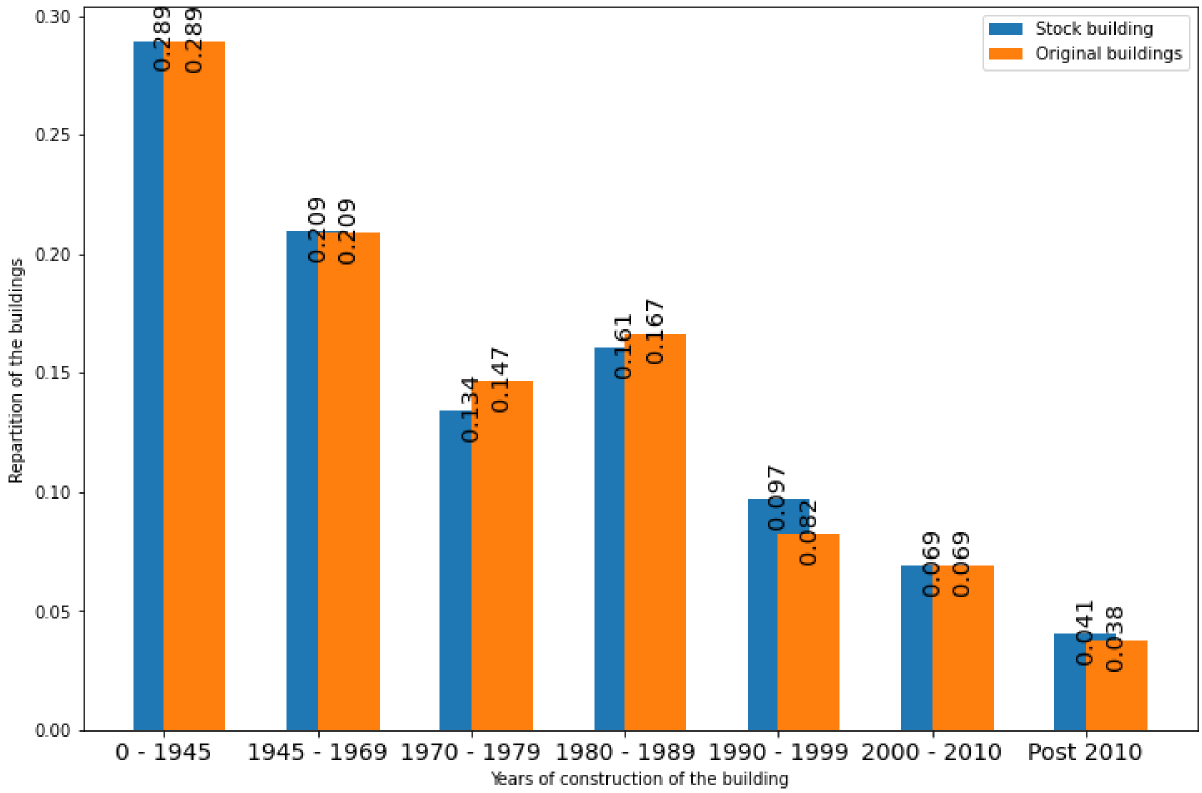

Figure 96 Repartition of the years of construction of offices buildings in Latvia.

Based on the different charts, we can assume that the absolute difference between the simulated and the original data are not significant. We can also have a statistics overview of the absolute difference with Table 68 shown below.

Table 68 Statistic overview of the difference of the year of construction repartition between the stock model and the source.

Statistics treatment	Absolute value
Average difference	<1%
Standard deviation of differences	<1%
Median difference	<1%
Minimal difference	<1%
Maximal difference	1.50%

The results of the statistics treatment confirm that the difference between the simulated and the original data are not significant.

Annex IV Number of employees

The objective of this chapter is to compare the repartition of the number of employees of the stock buildings with the repartition of the number of employees of the buildings from the source [237].

As the number of employees is estimated by the source of the French Institute INSEE and then it is transcribed for the EU27+UK, the repartition is the same for each country.

The results of the comparison for trade and office buildings are shown in Figure 97 and Figure 98:

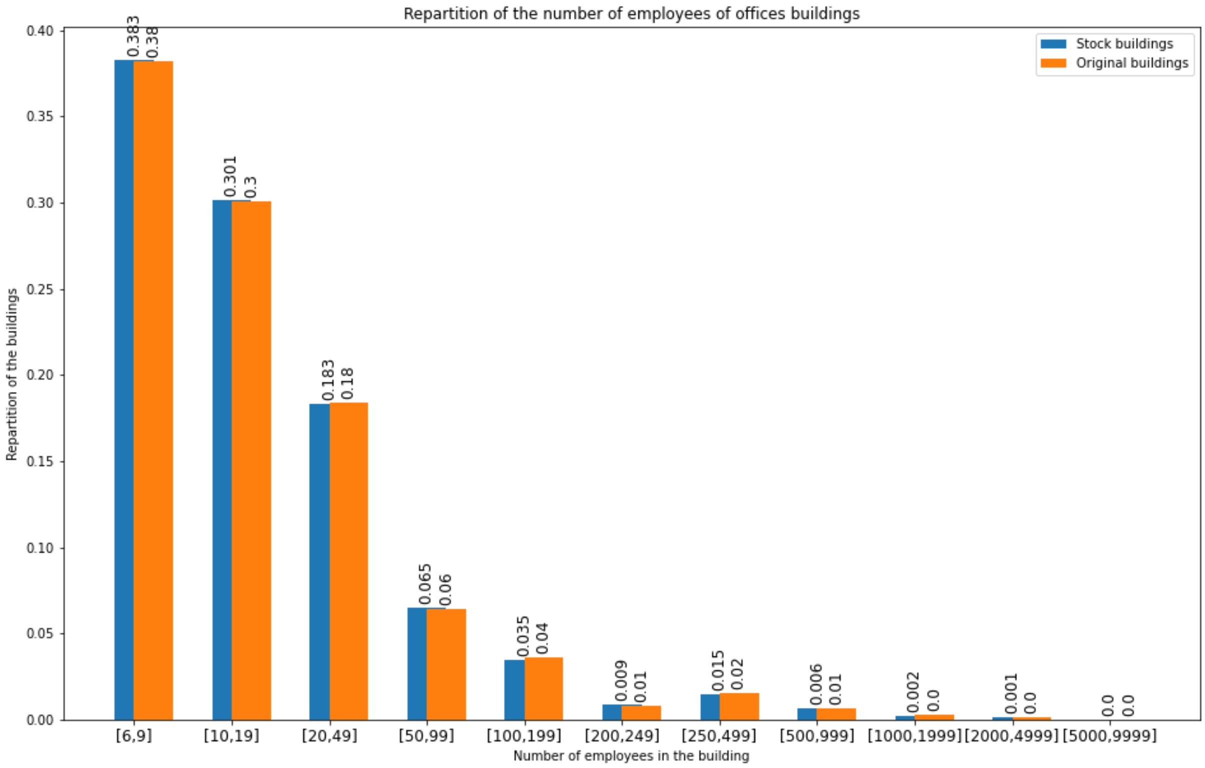

Figure 97 Repartition of the number of employees of office buildings from simulated data

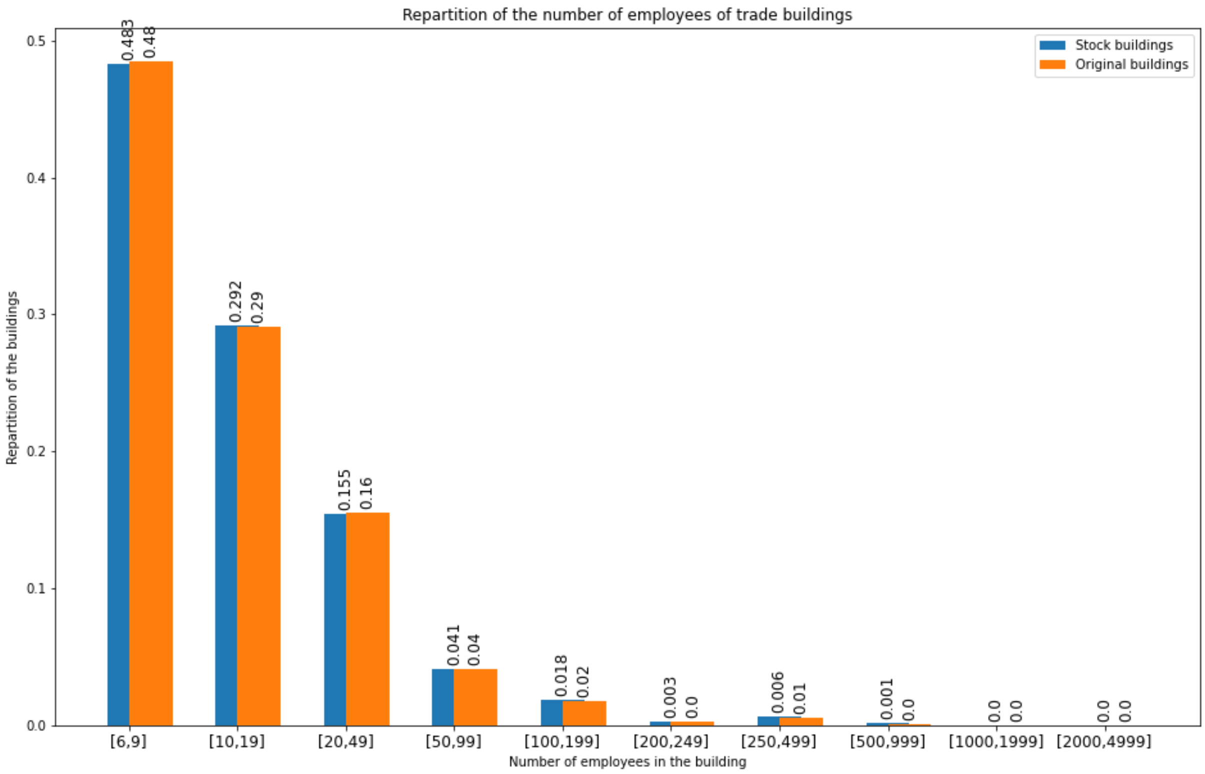

Figure 98 Repartition of the number of employees of trade buildings

Based on the different charts, we can assume that the absolute difference between the simulated and the original data are not significant. We can also have a statistics overview of the absolute values in Table 69 below.

Table 69 Statistics overview of the difference of the number of employee repartition between the stock model and the source

Statistic treatment	Absolute value
Average difference	<1%
Standard deviation of differences	
Median difference	
Minimal difference	
Maximal difference	

Annex: Case study of process cooling use per subsector in Denmark and the EU27+UK

In the current annex, Table 70 summarises the distribution of final energy consumption for process cooling per subsectors.

Table 70 Distribution of final energy consumption for process cooling per subsectors

Subsector	Upscaling		Process cooling			Temperature intervals		
	Prod. value	GDP	Other sources	TWh/y	%	<5°C [TWh/y]	5-30°C [TWh/y]	>30°C [TWh/y]
Crop and animal	X			4.17	3.1%	0.90	3.27	0.00

Subsector	Upscaling		Process cooling			Temperature intervals		
	Prod. value	GDP	Other sources	TWh/y	%	<5°C [TWh/y]	5-30°C [TWh/y]	>30°C [TWh/y]
production, hunting and related service activities								
Forestry and logging	X			0.47	0.3%	0.00	0.47	0.00
Processing and preserving of meat and production of meat products	X			13.05	9.6%	13.05	0.00	0.00
Processing and preserving of fish, crustaceans and molluscs	X			1.14	0.8%	0.91	0.23	0.00
Manufacture of dairy products	X			6.44	4.7%	6.12	0.32	0.00
Manufacture of bakery and farinaceous products	X			1.91	1.4%	0.00	0.00	1.91
Other food industry	X			6.37	4.7%	3.18	3.18	0.00
Manufacture of beverages	X			2.47	1.8%	0.49	1.97	0.00
Printing and reproduction of recorded media	X			0.31	0.2%	0.00	0.31	0.00
Manufacture of industrial gases	X			0.47	0.3%	0.00	0.00	0.47
Manufacture of other organic basic chemicals	X			2.30	1.7%	0.69	1.61	0.00
Manufacture of other basic chemicals	X			2.29	1.7%	1.83	0.46	0.00
Manufacture of paints and soap, etc.	X			1.94	1.4%	0.00	0.97	0.97
Manufacture of basic pharmaceutical products and pharmaceutical preparations	X			1.30	1.0%	0.13	0.91	0.26
Manufacture of rubber and plastic products	X			3.99	2.9%	0.00	3.99	0.00
Manufacture of fabricated metal products, except machinery and equipment	X			0.38	0.3%	0.00	0.00	0.38
Manufacture of other electronic equipment, electric motors, etc., as well as wires and cables	X			0.09	0.1%	0.00	0.00	0.09
Manufacture of engines, wind turbines and pumps	X			0.23	0.2%	0.00	0.00	0.23
Manufacture of	X			0.25	0.2%	0.00	0.00	0.25

Subsector	Upscaling		Process cooling			Temperature intervals		
	Prod. value	GDP	Other sources	TWh/y	%	<5°C [TWh/y]	5-30°C [TWh/y]	>30°C [TWh/y]
other machinery								
Toys and other manufacturing	X			0.08	0.1%	0.00	0.08	0.00
Wholesale and retail trade and repair of motor vehicles and motorcycles		X		0.15	0.1%	0.00	0.00	0.15
Wholesale on a fee or contract basis		X		11.04	8.1%	11.04	0.00	0.00
Retail trade, except of motor vehicles and motorcycles		X		25.07	18.4%	25.07	0.00	0.00
Hotels and similar accommodation		X		2.66	2.0%	2.66	0.00	0.00
Food and beverage service activities		X		6.84	5.0%	6.84	0.00	0.00
Information and communication		X	X	40.09	29.3%	0.00	0.00	40.09
Knowledge service		X		0.22	0.2%	0.00	0.22	0.00
Travel agency, cleaning, and other operational services		X		0.10	0.1%	0.00	0.10	0.00
Culture and leisure		X		0.38	0.3%	0.00	0.38	0.00
Total				136.19		72.91	18.49	44.80

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