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Process Cooling Market in Europe: Assessment of the Final Energy Consumption for the Year 2016

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Abstract: This study analysed one of Europe's most unexplored energy fields: process cooling (PC). The work assessed the final energy consumption (FEC) for PC of the European Union (and United Kingdom) with a 2016 baseline. An extensive literature review of datasets and journal papers was performed to address knowledge gaps by creating a high-quality dataset with factual accuracy, reliability, and completeness. Installed cooling units, equivalent full load hours, energy efficiency levels (seasonal energy performance ratio), and capacities installed were the essential investigated parameters to perform the FEC calculations. The latter were referred to as vapour compression (VC) chillers (air-to-water or water-to-water). Overall, the results of the EU (plus UK) FEC for the PC sector resulted in more than 110 TWh/year, accounting for around 10% of the total energy consumption for electricity in Europe. It is worth mentioning that several non-VC technologies are utilized for PC purposes in various sectors and subsectors primarily in the industry and the tertiary sectors, which are rapidly growing and, therefore, their cooling consumption is increasing. The current research paper aimed to raise awareness of the PC sector by supporting the European Union policies toward a more sustainable and decarbonized industry in the upcoming decades.

Keywords: process cooling; final energy consumption; assessment; Europe

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1. Introduction

The European Union (EU)—please see Table A1 in the Appendix A for all abbreviations utilized—focused its central efforts on achieving shifting goals by 2020, such as a 20% increase in energy efficiency, a 20% in greenhouse gas (GHG) emissions decrease, and a 20% renewable energy sources (RES) share increase in comparison with 1990 levels. Mainly, the energy efficiency targets were initially established in the Energy Efficiency Directive (EED) in 2002 (revised in 2018). The latter resulted in the EED II being updated from 20 to 32.5%, with possible revision in 2023 [1]. More efficient energy use can lead to lower utility bills, decrease the EU's dependence on external oil and gas suppliers, and improve adaptability to climate change. Additionally, the EU intends to drop its emissions by 55% by 2030. In 2018, GHG emissions decreased by 23% from 1990 levels [2]. The EU ambitiously aims to become the first region to reach carbon neutrality by 2050, with a reduction in GHG emissions by at least 80–95% [3]. The Emission Trading System (ETS) is a promising tool that utilizes the "cap and trade" scheme. The ETS covers 45% of GHG emissions in the EU while the remaining 55% of emissions are addressed through country-level emission reduction targets (e.g., through the buildings, agricultural, waste management, and transportation sectors [3]). The Renewable Energy Directive (RED-2009/28/EC), which initially put the mentioned goals into legislation, has been recently revised in 2018 (RED II) for the period 2021–2030 by increasing the RES share target of at least 32% [4]. The RED II envisages a possible revision of that EU goal in 2023 [5]. By 2050, the EU intends to generate in excess of 80% of electricity from RES, which would require a 250% increase versus current levels [1]. Furthermore, the RED II calls for the EU member states (MSs) to increase annual RES shares in the heating and cooling (H&C) sector by an average of 1.3 percentage points (ppt) for the period 2021–2030 [5]. The attention of the RED II to the latter is mainly justified by the fact that, in 2018, it was observed that the largest portion of the EU's primary energy consumption (PEC) was demanded by the H&C sector [5–7]. This large share includes space heating (SH) and space cooling (SC) for buildings comfort, domestic hot water (DHW), and process cooling (PC), accounting for about 800 Mtoe/y, while the EU's total PEC was about 1600 Mtoe/y in 2016. The transportation sector follows with around 490 Mtoe/y, followed by the electricity sector with approximately 310 Mtoe/y. Notably, oil and gas sources are used to produce around 85% of H&C, while RES is only used to produce 15% [8]. Overall, cooling demand is anticipated to rise in the upcoming decades.

Apart from the previously mentioned RED II, EED II, and the European Green Deal aims to reduce GHG by 55% by 2030, the EU MSs are responsible for acting decisively concerning the directives [9]. Therefore, proper energy usage quantification has become an impending necessity resulting in considerable investments from the EU MSs [9–11]. Notably, the EU MSs encountered remarkable data reliability and availability issues during the collection phase in the H&C sector. The encountered issues are of significant concern for SH, DHW, SC, and PC. Research on the EU cooling sector has not been investigated as much as its heating counterpart [12], and there is a lack of information on SC and even more so for PC, the focus of this paper. Based on the study accomplished in the "ENER/C1/2018-493 Renewable cooling under the Revised Renewable Energy Directive" project, a more in-depth analysis has been carried out [13]. In detail, we provide the context of the investigation, an interpretation of the main findings, and a discussion on the barely explored topic of cooling in industry.

The term "cooling" refers to the removal of heat against the second law of thermodynamics. In the following text, the terms SC and PC are used to distinguish one from the other since both contain "cooling". While SC is referred to as ensuring the enclosed space occupants' thermal comfort conditions by removing an amount of heat, PC is referred to as removing heat from processes (e.g., plastic mould cooling [14]), products, or an enclosed spaces that regulate the indoor temperature [13,14]. If SC and PC were summed up together, they solely count for around 4% of the EU's final energy consumption (FEC), which is the total energy consumed by end-users, accounting for around 1200 Mtoe/y [2,15]. It has been estimated that the FEC for SC falls in the range of 134–192 TWh/y and 152–192 TWh/y for PC [16–18]. Overall, PC involves a number of sectors, including industrial buildings, transport (e.g., cooled containers), commercial buildings (e.g., cooled chests in supermarkets), greenhouses, data centres, cold storage, and hospitals (e.g., cooled medical equipment and laboratories), and agriculture applications. Per the limited data mentioned above, little information can be found in the scientific literature regarding PC. Significant retrieving information difficulties have been experienced throughout this analysis. It should be noted that, currently, in the present work, a significant portion of the cooling market in EU27+UK is estimated [16–22].

A number of previous studies evaluated PC energy consumption throughout their research. Notably, in their study, Fleiter et al., 2016 [16] accounted that the FEC for PC could have been in a range of approximately 100 to 160 TWh/y [23–25]. The current study aims to better define the quantification of the FEC for PC in the E27+UK with a specific background dataset from which the parameters essential in the input of the computation can be extracted and further utilized in future research.

Per the fact highlighted above, the PC sector must be further explored through scientific research to raise more awareness of how much the European FEC is dedicated to this sector. The current study has aimed to quantify the PC FEC of the EU (and the UK). The year 2016 has been referenced as a baseline for this study due to the ready access to information for this year. To pursue the aim mentioned above, different objectives have been set, such as investigating and gathering essential data and information to create a high-quality dataset for PC throughout the EU. Therefore, to ensure adequate accuracy, reliability, and completeness, the following aspects have been considered essential to conduct the analysis:

- Data inventory;
- Data reliability;
- Data definition and comparability.

1.1. Data Inventory

The vital phase of establishing an inventory of PC in the EU27+UK data consists of the list creation of all existing information. Notably, if the data are collected on an EU-wide level, they can offer advantages thanks to the extensive territorial view (e.g., EUROHEAT&POWER [26]). However, it is impossible to ensure data completeness. Moreover, large online datasets (e.g., Copernicus Global Land Operations [27], Zambelli et al., 2019 [28], IGA [29], EHPA Stats Tool [30], EUROVENT 2020 [31]) were consulted to close data gaps by an extrapolating and assembling process. In addition, projects (e.g., Horizon 2020 Heat Roadmap Europe 4–HRE4 [32], H2020 HotMaps [33]) were consulted. Besides, for a precise approach, the desk research involved a scouting source-by-source of scientific journal papers (e.g., Evans et al., 2012 [34], Kapoor et al., 2013 [35], Popov et al., 2019 [36], Ebrahimi et al., 2017 [37], Ko et al., 2019 [38], Best et al., 2013 [39], Howard et al., 2023 [40], States et al., 2019 [41]) and industry applications (e.g., SURNA 2016 [42], Stiavelli 2020 [43], UN 2020 [44]) regarding the topic. Further details on which data and information were used in this paper were presented in Section 2.1. Moreover, essential data such as the number of installed cooling units, equivalent full load hours (EFLH), peak capacities installed of the cooling equipment in the industry, and their energy efficiency levels were further discussed in Section 2.2.

1.2. Data Reliability

During the data collection phase, the reliability of the latter was considered. It is worth mentioning that only scientific sources were considered in the current study as the base for the literature review. This premise already enhanced the quality of the sources scouted during the collection phase. Moreover, assessing the collected data's reliability and filling the current studies' gaps with an in-depth investigation required significant efforts. It is essential to mention that data that are lacking or had uncertainties were not considered when creating the dataset. Although the EU27+UK SH market has been broadly researched, there is a need for further data and information regarding the cooling sector. There were significant issues in finding data and information for PC since the most considerable portion of the data regarding the cooling market in the EU27+UK is based on estimated values. Moreover, certain data were retrieved in an aggregated form to recover certain values that are mathematically necessary to filter the latter. The collected information on PC (i.e., the amount of installed capacity values, energy efficiency values, and EFLH per country) was appropriately filtered and statistically evaluated as detailed in Section 2. Besides, additional sources were used to critically validate the outcomes presented in Section 3 and discussed in Section 4 for the EU27+UK to investigate their reliability.

1.3. Data Definition and Comparability

Despite the fact that most data sources present common values, units, and models, the latter could encounter comparability issues. Therefore, the entire data elaboration process necessitates harmonising the results that were produced from varying methods, time references, specifications, measures, and assumptions [45]. It is essential to underline that data over a decade old were collected and processed, and only the most recent records were considered in the present study. The reference year of 2016 was selected for this study to improve the quality and value of existing data and provide the required data for monitoring the development of the EU27+UK's PC market. The latter resulted in being the largest source of information compared to other possible reference years for the barely explored PC sector in the EU27+UK.

Furthermore, once the high-quality dataset for PC based on data inventory, reliability, definition, and comparability was assessed, a precise calculation methodology was established to process the input to obtain the PC FEC assessment regarding the EU27+UK, country-by-country with 2016 as the baseline. Further details on the scouted sources investigated throughout the literature review and the assumed methods in this work were presented in Section 2.

Overall, the given piece follows Section 2 which includes materials and the methodology supporting the study with detailed data and information gathering. Section 3 specified the most important findings and figures. Section 4 provided a critical evaluation of the top results, and Section 5 provided the conclusions and the potential future implications and recommendations.

2. Materials and Methods

2.1. Materials

A thorough bibliographical review was performed for the EU27+UK PC sector. Although this sector is barely analysed in the scientific literature, recent studies' main findings are detailed in this section.

Attention was turned to heat removal methods to cool information technology (IT) equipment and remove heat from the indoor environment. Evans et al., 2012 [34] investigated direct and indirect air methods, which rely on external conditions. Remarkably, the latter was pointed out as the primary means of cooling, and therefore making them more efficient was a requirement. The study aimed to support IT professionals with precision cooling solutions in line with objectives. Notably, the latter involved studies on chiller technologies whose capacities were collected in the present research. In addition, creating an ideal strategy for cooling processes was highlighted by Kapoor et al., 2013 [32]. A mixed-integer nonlinear model was used to estimate the optimal chiller loading strategy. The latter was not considered in the current study due to the hypothetical scenario which does not reflect the current energy market. Besides, Popov et al., 2019 [36] focused their study on cryogenic technologies used for industrial processes, highlighting the advantages of refrigerating food and pharmaceutical warehousing. Although the latter entails the industry sector, attention was turned to refrigeration applications, and therefore it has not been considered useful for this study. Also, with regards to performance and efficiency improvements of cooling fans, the best method to control the latter was proposed by Ko et al., 2019 [35] in their study. This work's primary concerned Industry 4.0. In the latter, a significant number of digital data were used, and therefore data centres regularly handle this large number. Data centres are formed by several components: IT equipment, power systems, and cooling systems, which consume a notable energy amount. A proper method to reduce energy and improve the cooling systems' temperature control performance was investigated in the paper. Best et al., 2013 [39] paid attention to promoting solar energy for cooling in the Agro-Food Industries (AFI). Throughout the simulated-construction model of a case study, they calculated energy savings of around 19% of the total FEC. Also, SURNA 2016 [42] defined the difference between comfort cooling and PC by stating that PC is less familiar to typical consumers. Mainly, the intended use of a PC is to process and remove large amounts of heat from a space, often using a chiller system. The latter is usually found in data centres, plastic injection moulding, airports, and hospitals.

Notably, the sources mentioned above face the topic of PC for certain technical issues, while almost no FEC quantification does. However, the latter provided insights into which types of cooling technologies are most applied in the industry sector: chiller (air-to-water) and chiller (water-to-water). The number of machinery types deployed in the PC sector was collected from the studies by Dittman et al., 2017 [34] and Fleiter et al., 2016 [16] per EU27+UK country [46]. Concerning energy efficiencies, Bertoldi et al., 2021 provided different energy efficiencies and peak capacities values for different types of chillers [25]. Regarding the operative hours of the cooling systems by which it is possible to obtain the yearly FEC, a different methodology apart from data collection was found crucial, presented in Section 2.2.

2.2. Methods

As mentioned above, to assess the PC FEC per technology and EU27+UK MS, a breakdown of vapour compression (VC) technologies, suggested by Dittman et al., 2017 [46] and presented in the Horizon 2020 (H2020) HRE4 project, was followed. The latter-mentioned source was assessed as the most reliable and precise study among scientific literature reports as well as providing data for the PC sector, and thus the classification for the given investigation for this work is as follows:

- Chiller (air-to-water) < 400 kW;
- Chiller (air-to-water) > 400 kW;
- Chiller (water-to-water) < 400 kW; and
- Chiller (water-to-water) > 400 kW.

It is necessary to mention that VC systems provide around 99% of the EU's cooling needs. Regarding the thermally driven heat pumps (TDHPs), it should be noted that the actual market penetration is negligible compared to VC technologies [16,20]. Nonetheless, EUROVENT 2020 [31] data suggested that TDHPs account for around 1% of the EU's cooling market. Based on the VC technology breakdown, further investigation of the PC cooling market was carried out by researching the following for the EU27+UK:

- Number of installed cooling units;
- Equivalent full load hours (EFLHs);
- Installed capacity; and
- Energy efficiency levels (Seasonal energy performance ratio-SEPR).

It is worth mentioning that, with regard to heat load, there is a lower dependence on outdoor temperatures for PC than SC. Therefore, evaluating the seasonal performance of PC equipment is linked to a different set of conditions than the Seasonal energy efficiency ratio (SEER)-Regulations (EU) 1095/2015 [47] and 2281/2016 [48]. The current metric is named the Seasonal energy performance ratio (SEPR). Like the SEER metric, factors such as heat rejection and chilled water temperatures can cause a high degree of variation in SEPR values. The primary advantage of the SEPR metric is that it allows for the comparison of performances on a more representative basis versus using standard rating conditions. Besides, the work input (electricity) for each cooling type was processed, and the average capacities for each PC equipment were categorized for each respective SEPR mean value. Moreover, to acquire dependable data, it is necessary to perform a detailed scientific literature review, although an insignificant amount of information on the PC sector was located. The identified information was filtered and statistically evaluated. The data which lay outside one standard deviation from the assessed data were removed. This analysis could not be performed for at least two data per value due to a lack of data. To conclude, the FEC for PC for each EU27+UK MS was calculated. To obtain the FEC for the year 2016, Equation (1) presents the product of the quantity (number-Nr.) of PC units and average EFLHs (time–T) within a year and the work input (W-electricity):

$$FEC_{cooling} = Nr_{units} \times T_{equivalent\ full\ load\ hours} \times W_{electricity} \quad (1)$$

where:

- Nr_{units} is intended as the number of installed units at EU MS, in the industry sector for a certain type of machinery for PC purposes;

- $T_{equivalent\ full\ load\ hours}$ are intended as the yearly (2016) operative hours of a certain PC system;
- $W_{electricity}$ is considered as the work input of the space PC system. Notably it is considered as the fraction of the system power capacity and its respective energy efficiency level. It is worth noting that electricity is the energy input that allows the cold as output.

The following text aimed to explain how EFLHs were calculated in four steps (i.–iv.), which is the core information for performing the calculations mentioned above.

In the present section, the calculation of the PC's EFLHs was presented. The land surface temperature (LST) hourly profiles for a whole year (8760 h) at the NUTS2 level were used. A constant-linear-constant law was then applied to derive PC EFLHs [49]. The following points expressed the method in detail:

(i.) The LST data were retrieved using the Copernicus Global Land Service [50]. The data collection was based on instantaneous observations. Therefore, the product was computed globally every hour and made available to the user within 4 h. The LST product user manual can be found in further detail [27]. Cloud cover and data consistency issues that affect the LST information were filtered, and only cloud-free areas were selected. Moreover, the CDD (cooling degree days) data were acquired at the NUTS2 resolution from the H2020 HotMaps project's public repositories and were clustered into five different sets to fill incomplete data [28]. The clustering was performed using the k-means algorithm [51]. If no data were available for a defined hour (h) and a specific NUTS2 ($NUTS2_i$), then the missing LST data was estimated by considering the median value of obtainable LST values (for h, i) according to its cluster.

(ii.) The following measures were applied since data related to the elaborated temporal series were missing:
  - The missing LST values were identified.
  - The average value substituted the identified missing values, for the same hour of the day, before and after.
  - A 7-h window and a polynomial order equal to 2 were applied to the Savitzky-Golay filter [52], which was used to create a continuous LST time series.

(iii.) A complete hourly LST dataset was available at each ($_i$) NUTS2 level (LST_{NUTS2}). These data were used to calculate a normalized hourly time series for each ($_i$) NUTS2 ($LOAD_{NUTS2}$). A constant-linear-constant hourly load law was utilized, with LST (temperature and temperature levels) expressed in degrees Celsius (°C) as presented in Equation (2) [49] results in Figure 1.

$$\begin{gathered} LOAD_{Nuts2i} = 0.8\ \{if\ LST_{Nuts2i} < 5\ ^\circ C\} \\ LOAD_{Nuts2i} = 0.8 + \tfrac{0.2}{30}\ x\ (LST - 5)\ \{if\ 5\ ^\circ C\ \leq\ LST_{Nuts2i} < 35\ ^\circ C\} \\ LOAD_{Nuts2i} = 1\ \{if\ LST_{Nuts2i} > 35\ ^\circ C\} \end{gathered} \tag{2}$$

(iv.) Besides, by applying Equation (3) with 8760 (the number of hours in a year), the EFLHs at each ($_i$) NUTS2 level ($EFLHs_{NUTS2}$) were derived:

$$EFLHs_{Nuts2i} = \sum_{i}^{8760} LOAD_{Nuts2i} \tag{3}$$

A national value for each MS was determined ($EFLHs_{National}$) upon the acquisition of the EFLHs values for each ($_i$) NUTS2 region of the EU27+UK ($EFLHs_{NUTS2}$). NUTS2 level values of the EFLHs ($EFLHs_{NUTS2i}$) were weighed according to the gross domestic product

(GDP) at each ($_i$) NUTS2 level (GDP_{NUTS2i}) since cooling can be linked to GDP, according to Equation (4) [53].

$$EFLHs_{National} = \frac{\sum_i (EFLHs_{Nuts2i} \times GDP_{Nuts2i})}{GDP_{National}} \quad (4)$$

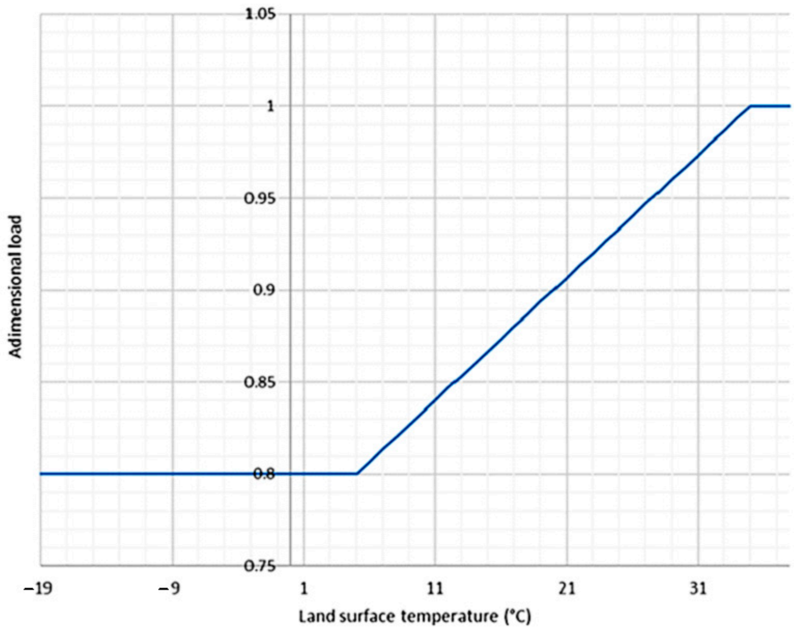

Figure 1. Load curve law for process cooling.

The PC sector's EFLH results at the MS level for the EU27+UK are shown below. Moreover, the average European value was calculated by weighing all national EFLHs using national GDP. The SEPR values were retrieved by following the methods described in the European Standards EN 14825 [49].

3. Results

According to Figure 2, chiller (air-to-water) < 400 kW accounted for most PC units per type with almost 0.5 mil. installed devices; followed by Chiller (water-to-water) < 400 kW, with around 0.08 mil. units. Then, chiller (air-to-water) > 400 kW and chiller (water-to-water) > 400 kW came next with about 0.06 and 0.03 mil. units each.

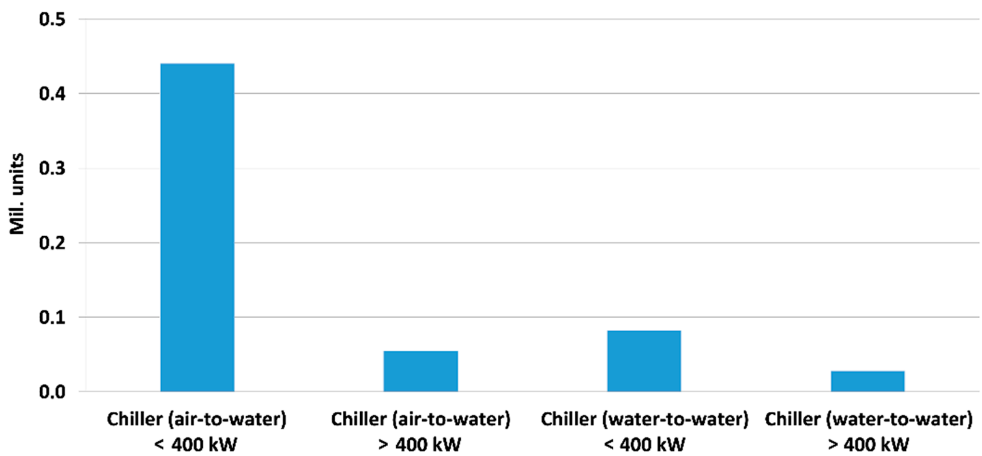

Figure 2. Number of installed units per process cooling type (industrial sector), EU27+UK, the reference year 2016 [16,43,51].

Moreover, Figure 3 shows the average installed capacity per PC in kW.

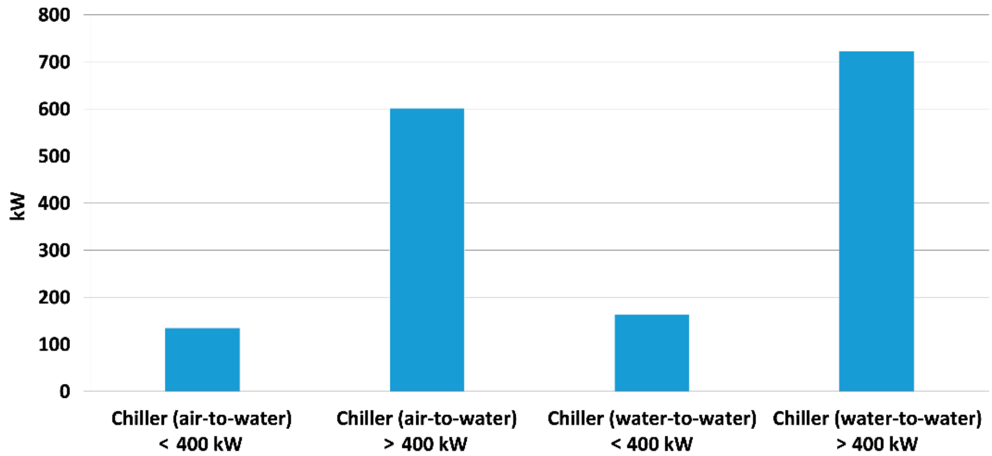

Figure 3. Average installed capacity per process cooling type (industrial sector), EU27+UK, the reference year 2016 [16,43,51].

According to Figure 3, chiller (water-to-water) > 400 kW resulted in the largest installed mean value: more than 700 kW, followed by Chiller (air-to-water) > 400 kW with about 600 kW. Then, it was chiller (water-to-water) < 400 kW with a value greater than 160 kW. Chiller (air-to-water) < 400 kW resulted in having an average installed capacity greater than 130 kW.

Figure 4 demonstrates a visual description of the SEPR values.

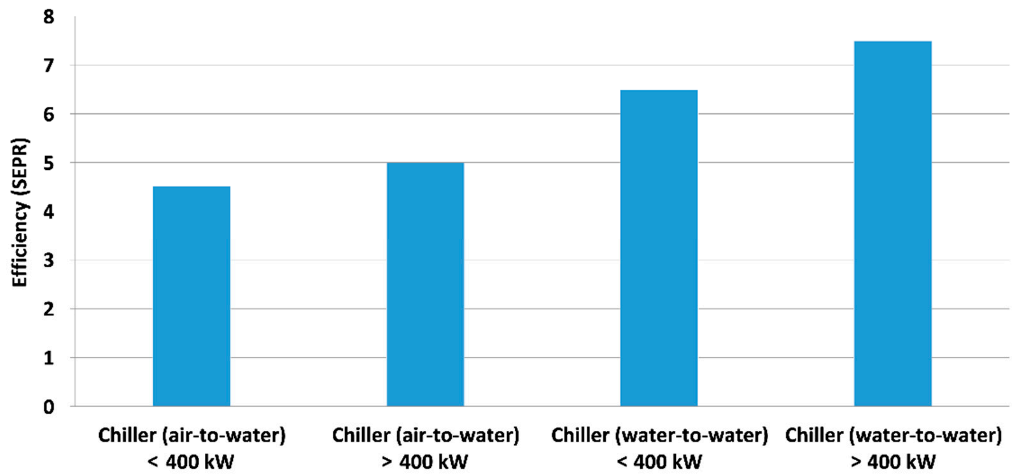

Figure 4. Seasonal energy performance ratio per process cooling type (industrial sector), EU27+UK [54,55] (indicated values refer to the weighted mean per final cooling consumption).

It is worth mentioning that the chiller (water-to-water) > 400 kW resulted as the most efficient PC technology with an SEPR value equal to 7.5. Chiller (water-to-water) < 400 kW ranked next with an SEPR value of 6.5. Chiller (air-to-water) > 400 kW then followed the previous one with a value of 5 and, finally, chiller (air-to-water) < 400 kW came in as the least efficient technology with an SEPR of 4.5. The electricity input values were calculated in kW using average capacities and SEPR values per PC type.

Besides, Figure 5 presents information concerning the equivalent full load hours (EFLHs) of the EU27+UK's industrial sector per country.

As shown in Figure 5, the EFLHs of the EU27+UK's industrial sector were all over 7000. Malta and Cyprus provided peaks. Spain, Portugal, and Greece led all countries. There are no significant differences among the EFLHs of European states, with the exception of Malta and Cyprus, which have higher values than the industrial sector means (about 7450 EFLHs-please see the horizontal line in Figure 5 above).

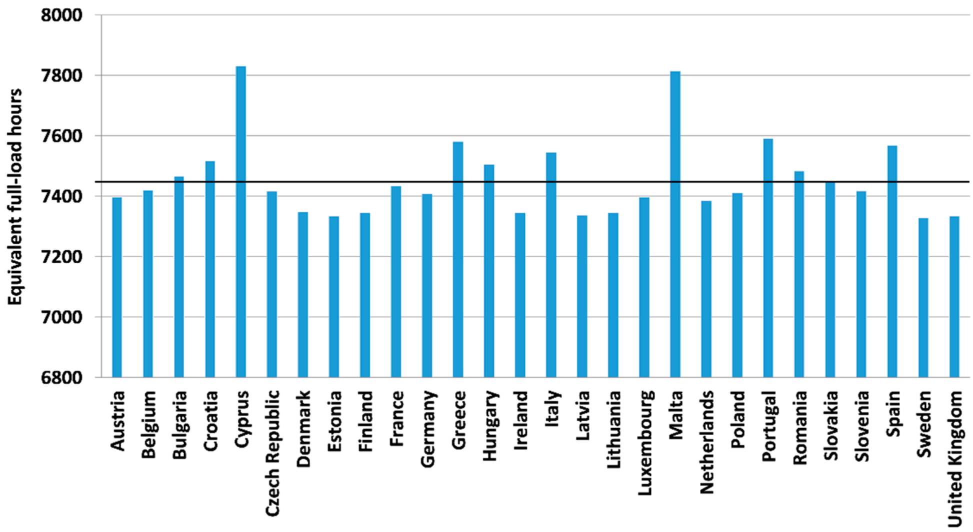

Figure 5. Equivalent full load hours (industrial sector), EU27+UK, the reference year 2016 [20,52,53].

Furthermore, integrating the values, MS by MS, from Figures 1–5, in Equation (1), results in Figure 6 and Table 1.

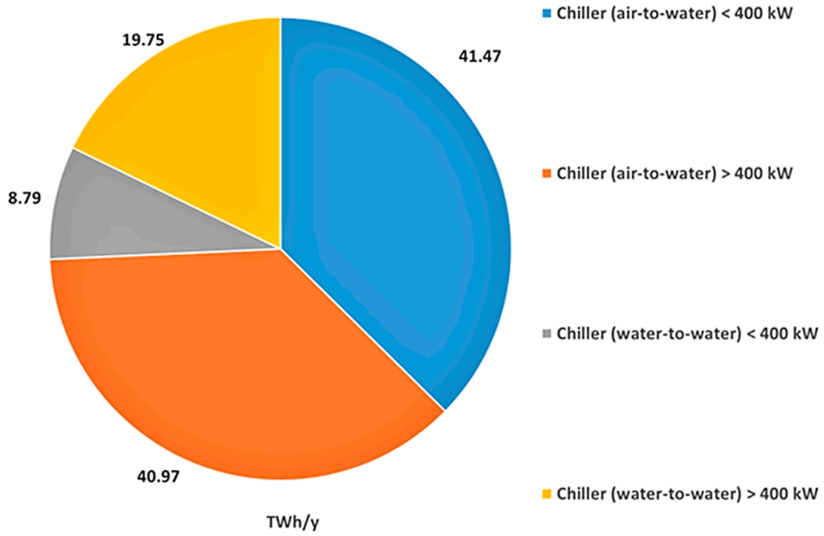

Figure 6. Final energy consumption for process cooling per type (industrial sector), EU27+UK, the reference year 2016 [29,54,55].

Table 1. Final energy consumption for process cooling per type (industrial sector), EU27+UK, the reference year 2016 [29,54,55].

Technology	Final Energy Consumption [TWh/y]
Chiller (air-to-water) < 400 kW	41.47
Chiller (air-to-water) > 400 kW	40.97
Chiller (water-to-water) < 400 kW	8.79
Chiller (water-to-water) > 400 kW	19.75

As shown in Figure 6 and Table 1, the most energy-intensive PC type was chiller (air-to-water) < 400 kW with more than 41 TWh/y. The next most energy-intensive PC type was chiller (air-to-water) > 400 kW with almost 40 TWh/y. Chiller (water-to-water) > 400 kW came next with nearly 20 TWh/y and, finally, chiller (water-to-water) < 400 kW was last with almost 9 TWh/y. The total amount of final PC consumption in Europe's industrial sector was estimated to be greater than 110 TWh/y.

Lastly, Figure 7 and Table 2 show the FEC PC share per EU MS.

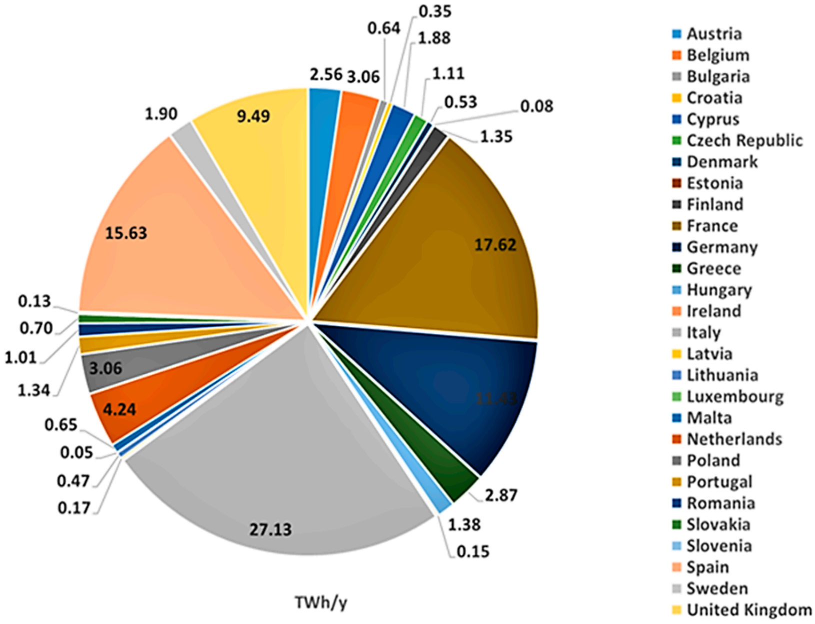

Figure 7. Final energy consumption for process cooling per country (industrial sector), EU27+UK, the reference year 2016 [29,54–56].

Table 2. Final energy consumption for process cooling per country (industrial sector), EU27+UK, the reference year 2016 [29,54–56].

TWh/y per EU27+UK MS–PC–Industrial Sector		Percentage
Austria	2.56	2.31%
Belgium	3.06	2.76%
Bulgaria	0.64	0.57%
Croatia	0.35	0.32%
Cyprus	1.88	1.70%
Czech Republic	1.11	1.00%
Denmark	0.53	0.48%
Estonia	0.08	0.07%
Finland	1.35	1.22%
France	17.62	15.88%
Germany	11.43	10.30%
Greece	2.87	2.58%
Hungary	1.38	1.24%
Ireland	0.15	0.13%
Italy	27.13	24.44%
Latvia	0.17	0.15%
Lithuania	0.47	0.42%
Luxembourg	0.05	0.04%
Malta	0.65	0.59%
Netherlands	4.24	3.82%
Poland	3.06	2.76%
Portugal	1.34	1.21%
Romania	1.01	0.91%
Slovakia	0.70	0.63%
Slovenia	0.13	0.12%
Spain	15.63	14.09%
Sweden	1.90	1.71%
United Kingdom	9.49	8.55%
EU27+UK	110.98	100%

As shown in Figure 7 and Table 2, just a few MSs made up most of the PC FEC for the entire EU27+UK. Italy, France, Spain, Germany, United Kingdom, Netherlands, Greece, Poland, Belgium, Austria, Sweden, Cyprus, Hungary, Finland, and Portugal accounted for more than 90% of the EU27+UK PC FEC. Thus, the remaining 13 countries accounted for the remaining 10%.

The calculation used to estimate the contribution of PC in the EU27+UK included chiller (air-to-water) or chiller (water-to-water) with more or less than 400 kW capacity installed applied to the industrial sector. These chiller's central applications are pharmaceutical, automotive, plastic, bakeries, and process industries related to construction, such as cement, plastic, and glass industries, and the fish and meat industries. In addition, process chiller technology began to be used in close control technologies, such as computer and network rooms in banks, company headquarters, and government departments, for the cooling of IT equipment [57–60].

Nevertheless, different other technologies were utilized for PC purposes in different sectors and subsectors, not solely the industrial sector [58–63]. It follows Table 3, regarding VC technology's further applications in various sectors and subsectors.

Table 3. 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) [64]
	Tobacco	Ambient air control	Packaged [65]
	Paper, pulp, and printing	Cooling of printing machinery	Packaged [66]
TERTIARY	Telecommunications	Shelter cooling	Small split (<5 kW) and Big split (>5 kW) [67]
	Warehouses	Ambient air cooling	Variable refrigerant flow systems [68]
			Rooftop [69]
	Supermarket freezers and cells	Refrigeration and freezing	Small split (<5 kW) and Big split [70]
	Data centres	Electronic equipment cooling	Packaged computer room air conditioners (CRAC) [31,68]

Moreover, in Appendix A, Table A2 provides a complete list by entailing non-VC technologies and different sectors, subsectors, and processes.

It is worth mentioning that the FEC PC values present in each sector and subsector are significant. For instance, Castellazzi et al., 2017 [69] indicated that the FEC for cooling in European data centres was greater than 40 TWh/y [70–72]. However, due to missing data, the quantification of the FEC for PC in the EU27+UK in the sectors and subsectors specified in Tables 3 and A2 was not possible at a greater detail. Besides, regarding the agriculture sector, PC applications are getting a more and more critical need [70–73].

4. Discussion

This study assessed the FEC for the PC sector for the reference year 2016.

While in the H&C sector, SH and DHW were widely investigated in academic literature, PC remained mostly unexplored, and very little information was found regarding the sector. The most essential sources were Copernicus Global Land Operations, which provided LST data, and the H2020 HotMaps project for CDD. The latter was critical for the calculation of the EFLHs. Simultaneously, the study by Dittmann et al., 2017 [46], included in the H2020 HRE4 project, had the highest accuracy for data on the number of cooling units and installed capacity for the PC sector for the EU27+UK. Moreover, the SEPR values were acquired using the calculation methodology indicated in the European Standards EN 14825 [49].

The input data gathered from the above sources were used for Equation (1), which was used to calculate the PC FEC for the EU27+UK, resulting in more than 110 TWh/y in 2016. The EU27+UK countries, listed from the most to least energy consuming, were Italy, France, Spain, Germany, United Kingdom, Netherlands, Greece, Poland, Belgium, Austria, Sweden, Cyprus, Hungary, Finland, and Portugal. They accounted for around 90% of the total FEC, while the other 13 countries made up the remaining 10%.

These calculations mainly entailed chiller (air-to-water) or chiller (water-to-water) equipment with more or less than 400 kW capacity installed since their applications can be found in several industries such as automotive, plastic moulding, pharmaceutical, bakeries, and process industries related to construction, such as cement, plastic, and glass industries. However, several other sectors and subsectors utilize PC in their processes, such as wineries, tobacco, paper, pulp, and printing. In the tertiary sector, PC is utilized, among others, in telecommunications, warehouses, supermarket freezers, and cells and, most importantly, in data centres for electronic equipment cooling. However, the latter mentioned sectors (industry as well as tertiary) involve cooling equipment technologies, such as small split (<5 kW) and big split (>5 kW), packaged, rooftop, VRF, and packaged computer room air conditioners (CRAC), and thus have been excluded from the EU27+UK FEC calculations. The latter also applies to the agriculture sector. It is worth mentioning that the FEC values indicated above do not entail freezing since being out of this study's scope. Therefore, it has not been included in the present work. Overall, in Appendix A, Table A2 provides a complete and precise list by entailing non-VC technologies and different sectors, subsectors, and processes. Potential future studies on this topic might include cooling technologies other than VC for each sector and subsector and refrigeration, although data and information are few. Moreover, regarding the data centres sector, it has to be underlined that the EU27+UK FEC for PC is rapidly growing in need, mainly due to the significant growth of this field [72]. In 2016, the whole EU27+UK industrial sector consumed around 1155 TWh/y of electricity [74–77]. PC accounted for almost 10% of the total electricity consumption. Moreover, final energy consumption affects the prices of the consumables, goods, and services since the electricity (specially purchased from other states) utilized for powering the PC technologies in the industry sector influences the inflation of the prices in a certain country. As described in Section 1, the work by Fleiter et al., 2016 [16] computed that the FEC for PC results fell approximately a limit from 100 to 160 TWh/y [25]. The current research positioned its outcome in that range with a certain value (approximately 110 TWh/y). The results indicated that cooling equipment producers are vital to market participants and that there is a need for higher-quality datasets of the technical parameters of their products. Gathering information from the private sector is often impeded by accessibility issues [78], and smoother accessibility is necessary for research purposes.

The current research was positioned in a context where the aggregation of escalating temperatures, evolving industrial processes, and the increase in demand for goods by the population due to a rise in welfare throughout the EU27+UK, resulted in an increase in PC energy requirements. The PC sector is not a statistically modest operator of electricity; instead, it is an improving sector that provides almost 10% of the general electricity consumption of the whole EU27+UK industrial sector. Therefore, in terms of policies, the EU and its Member States aim to improve the connection between RES and the PC sector under Article 7 (3) of the 2018 Renewable Energy Directive through the renewable cooling calculation methodology, as presented in Section 1. The "renewable cooling" topic is still under development both in terms of definition and quantification. Particularly, regarding the latter, the current paper played an important role as input for understanding how much energy the EU27+UK industry sector spent in 2016 [13].

Lastly, in terms of possible recommendations, cooling in industry, as previously mentioned, entails a large part of the FEC in the EU27+UK, and therefore it can be considered a potentially useful sector for decarbonization. Renewable energy technologies can be better linked to the latter, as well as energy efficiency can be further implemented in the type of machinery utilized in the processes. The combination of new carbon-free technologies with an improvement in the energy efficiency of the current ones can significantly reduce the dependency on the fossil fuel energy supply of the EU27+UK.

5. Conclusions

This section summarizes the primary outcomes of the study. with the European final energy consumption for process cooling in 2016 being the most significant result. Moreover, the present research aims to increase research on the largely unexplored subject of process cooling which can contribute to the assessments for the coming sustainable pathways that the European Union is going to meet in the upcoming decades. The following bullet points are the major findings discovered throughout the present research on the process cooling sector:

- The final energy consumption in the European process cooling sector accounted for more than 110 TWh/year. It is important to state that around half of the European member states make up nearly the entire final energy consumption for process cooling. Notably, the highest percentage, which is about 90%, is detained by Italy, France, Spain, Germany, the United Kingdom, Netherlands, Greece, Poland, Belgium, Austria, Sweden, Cyprus, Hungary, Finland, and Portugal. The remaining 13 member states share the residual of 10%.
- In regard to the applied cooling technologies in the process cooling sector, chiller (air-to-water) < 400 kW accounts for the greatest part of the European process cooling sector with almost 0.5 million installed devices.
- Moreover, chiller (water-to-water) > 400 kW results in having the most considerable installed mean value with more than 700 kW.
- In addition, the most efficient process cooling technology type in this study emerges to be chiller (water-to-water) > 400 kW with a seasonal energy performance factor value of 7.5.
- Lastly, the EFLH of the industrial sector are all over 7000 for each European member state, particularly with peaks reached by Cyprus and Malta.

It is worth stating that the given study encountered significant issues retrieving data and information since data and information was not available or fragmented, contained outdated information, or were inaccessible. The data assembly at the core of the study and its insights showed specific limitations, which were the result of the assumptions mentioned in Section 2. Improved accessibility, reliability, and comparability of data and information on cooling are auspicial in the future, supported by private companies as well as the public sector, on which the funding for further research on process cooling will be a common object of study by the scientific community.

To conclude, it would be interesting to discover the extent that process cooling in the European Union influences the employment rate in the industrial sector since energy expenditures surely influences the final prices of the products. Again, it would be significant to understand its influence on the European Union's severe weather occurrences' impact on the development of the process cooling market. An absence of accurate information was disclosed by the authors regarding this possible research topic.

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

Appendix A

Table A1. Nomenclature.

Acronym	Name
AC	Air conditioning
ASHRAE	American Society of heating, refrigerating and air-conditioning engineers
CACs	Centralized air-conditioners
CDD	Cooling degree day
DC	District cooling
DHW	Domestic hot water
EEA	European Environment Agency
EED	Energy Efficiency Directive
EER	Energy efficiency ratio
EFLHs	Equivalent full load hours
Eq	Equation
ETS	Emission trading system
EU	European Union
FEC	Final energy consumption
GHG	Greenhouse gas
H&C	Heating and cooling
H2020	Horizon 2020
HDD	Heating degree day
IDS	Integrated surface database
NUTS	Nomenclature of territorial units for statistics
PC	Process cooling
R&D	Research and development
RACs	Room air-conditioners
RED	Renewable energy directive
RES	Renewable energy sources
SC	Space cooling
SEPR	Seasonal energy performance ratio
TDHP	Thermally driven heat pump
UED	Useful energy demand
VC	Vapour compression
VRF	Variable refrigerant flow
Wh	Watt-hour

Table A2. Sectors, subsectors, processes, and technologies utilized for process cooling purposes.

Sector	Subsector	Process	Technology
INDUSTRY	Food & Beverages data	Freeze	Mechanical vapour compression freezing [79]
			Cryogenic freezing [79]
		Cold Storage	Mechanical vapour compression refrigeration [80]
		Cooling of products	Absorption (TDHP) [81]
		Condensation	Cryogenic freezing process [82]
		Refrigeration	Rapid evaporative cooling (Vacuum systems) [83]
		Ambient air cooling	Chiller (water-to-water) [14]
	Wineries	Humidification	Evaporative cooling [84]
		Ambient air cooling	Absorption (TDHP) [85]
			Small split (>5 kW) and Big split (<5 kW) [64]

Table A2. *Cont.*

Sector	Subsector	Process	Technology
	Tobacco	Ambient air control	Packaged [65]
		Cooling hydrocarbon rundown	Cooling tower [86] Shall and plate heat exchanger [86]
	Plastic moulding	System or infrastructure cooling	Chiller (air-to-water) [87] Evaporative cooling [88]
		Plastic machine cooling–Hydraulic cooling	Chiller (water-to-water) [83,84] Chiller (water-to-water) [83,84]
		Plastic mould or tool cooling	Chiller (air-to-water) [83,84] Chiller (water-to-water) [83,84]
		Plastic product cooling	Chiller (air-to-water) [83,84] Chiller (water-to-water) [83,84]
	Iron & Steel	Water cooling	Cooling tower [89]
		Waste gas energy recovery	Waste gas cooling plant Hisarna process [90] Cooling plants for converter waste gases oxygen steel plants [90] Sinter cooler for energy recovery sintering plants [90] Waste heat boilers in coke dry quenching plants [90] Cooling stack for Hismelt plants [90]
	Automotive	Temperature control of laser machines	Chiller (air-to-water) [91] Chiller (water-to-water) [91]
		Thermostatic control of painting baths	Chiller (air-to-water) [91] Chiller (water-to-water) [91]
	Cement	Compressors cooling	Chiller (air-to-water) [92]
		Heat neutralization	Chiller (air-to-water) [92]
		Cooling of excess gases	Cooling tower [93]
	Glass	Blowing	Blowers (ventilation) [94]
	Paper, pulp, and printing	Cooling of printing machinery	Mechanical ventilation [95] Evaporative cooling [95] Packaged [96]
	Pharmaceutical	Preservation of thermolabile materials	Evaporative cooling [97] Absorption (TDHP) [63,94]
	Telecommunications	Shelter cooling	Natural convection [98,99] Vortex tube [99] Small split (<5 kW) and Big split [67]
		Internal racks cooling	Mechanical ventilation [99]
TERTIARY	Warehouses	Ambient air cooling	Evaporative cooling [76] Mechanical ventilation [100]
		Adiabatic cooling	Adiabatic cooling [100]
		Ambient air cooling	Variable refrigerant flow systems [81] Rooftop [69]
	Supermarket freezers and cells	Refrigeration and freezing	Small split (<5 kW) and Big split [70]
	Data centres	Electronic equipment cooling	Indirect evaporative cooling [71] Natural conduction (heat exchanger) [71] Natural convection [71] Immersion cooling [71] Packaged computer room air conditioners (CRAC) [34]
TRAN-SPORA-TION	Marine	Cooling of batteries	Absorption (TDHP) [100]
		Engine cooling	Natural conduction (heat exchanger) [100] Natural conduction–Raw water cooling system [100]
AGRICU-LTURE	Greenhouses	Humidification	Evaporative cooling & fans [73]
		Ambient air cooling	Natural ventilation [74]
		Cooling of indoor greenhouse temperature	Absorption (TDHP) [75]
		Ambient air cooling	Mechanical ventilation [76]

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