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Free Cooling for Saving Energy: Technical Market Analysis of Dry, Wet, and Hybrid Cooling Based on Manufacturer Data

Paula M. Wenzel [1,*], Marc Mühlen [2] and Peter Radgen [1]

1 Institute of Energy Economics and Rational Energy Use (IER), University of Stuttgart, 70565 Stuttgart, Germany; peter.radgen@ier.uni-stuttgart.de
2 Faculty 4—Energy, Process- and Bio-Engineering, University of Stuttgart, 70569 Stuttgart, Germany
* Correspondence: paula.wenzel@ier.uni-stuttgart.de; Tel.: +49-711-685-87814

Abstract: In light of energy and climate targets, free cooling unlocks a major resource-saving potential compared to refrigeration. To fill the knowledge gap in quantifying this saving potential, we aim to specify the physical and technical limits of cooling tower applications and provide comprehensive data on electricity and water consumption. For this purpose, we distinguish six types of package-type cooling towers: dry, closed wet, open wet, and three types of hybrid systems; defining one generalized system for all types enables comparability. Subsequently, we collect data from 6730 system models of 27 manufacturers, using technical information from data sheets and additional material. The analysis reveals, for example, specific ranges of electricity demand from 0.01 to 0.06 kW_{el}/kW_{th} and highlights influencing factors, including type and operating point. Refrigeration systems would consume approximately ten times more electricity per cooling capacity. Furthermore, the evaluation demonstrates the functional limits, for example, the minimum cooling temperatures. Minimum outlet temperatures using evaporative cooling are up to 16 K lower than for dry cooling. The collected data have crucial implications for designing and optimizing cooling systems, including potential analysis of free cooling and efficiency assessment of cooling towers in operation.

Keywords: resource efficiency; energy efficiency; descriptive statistics; dry cooling; wet cooling; evaporative cooling; environmental impact; approach temperature; thermal capacity; data center

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1. Introduction

To reduce climate and environmental damage, all sectors must pursue efficiency enhancements. Energy and climate targets necessitate resource-efficient cooling, among others, as the demand for cooling increases continuously [1,2]. For example, digitalization drives the growth of data centers with their significant cooling demands [3,4].

Although waste heat reduction, recovery, or utilization is preferable to cooling towers, which dissipate the heat unused to the environment, cooling is technically or economically unavoidable in many cases. In this case, free cooling is the preferred option, consuming only a tenth of energy compared to refrigeration [5] (pp. 37–38). Hence, cooling tower applications must be exploited to the maximum extent to minimize refrigeration.

Figure 1 charts the theoretical limits of using dry, wet, and hybrid cooling towers as a function of the coolant's required inlet and outlet temperatures, $\vartheta_{w,i}$ and $\vartheta_{w,o}$, on abscissa and ordinate, respectively. The outlet temperature is higher than the inlet temperature; the difference is called the range z and is one limiting factor. Waste heat utilization is typically possible above approximately 35 °C without a heat pump or above 20 °C using a heat pump [6] (p. 32) but does not exclude using cooling towers. Wet and hybrid cooling towers are applicable if the required cooling temperature is above the wet-bulb temperature (*WBT*) plus an interval, which is called the approach. In contrast, the minimum outlet temperature of dry cooling $\vartheta_{w,o,min,dry}$ is the dry-bulb temperature (*DBT*) plus the approach. The *DBT* is the thermodynamic temperature of the air. In contrast, the *WBT* is the temperature that the air can minimally achieve by adiabatic water evaporation to saturation. Consequently, lower cooling temperatures are achievable with wet or hybrid cooling compared to dry cooling.

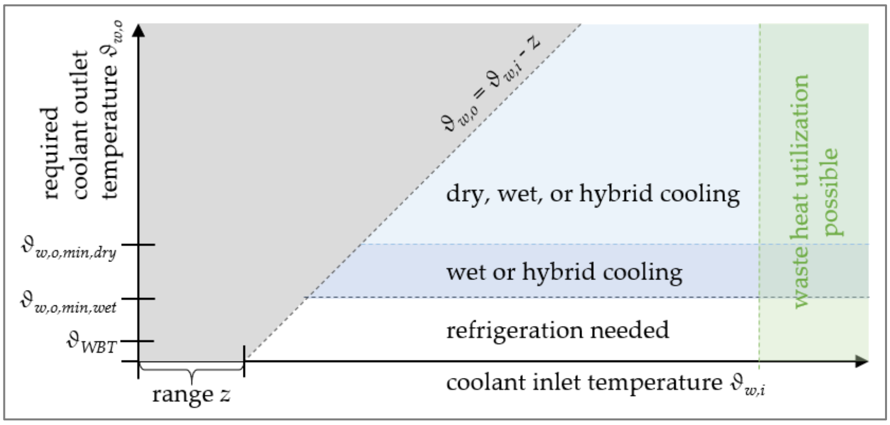

Figure 1. Limits of using dry, wet, and hybrid cooling towers for free cooling.

Quantifying these limiting parameters is crucial to determine and exploit the potential of free cooling by cooling towers. This quantification is one goal of this paper (cf. Section 1.2).

An additional challenge in evaluating the cooling tower efficiency is the dependency of electricity and water consumption on the specific operating point. For example, humid, warm ambient conditions can cause higher electricity demand. Thus, more benchmarks for the limiting parameters, electricity and water consumption are needed to reveal improvement potentials (cf. Section 1.2).

1.1. Previous Research

The free cooling potential depends on physical constraints (ambient conditions) and technical requirements (cooling capacity, temperature requirements). Besides air-side and heat-pipe free cooling, cooling towers serve for water-side free cooling [7]. Liu et al. [8] reviewed the factors affecting the critical temperature between free cooling and the need for refrigeration in data centers, demonstrating that the approach is crucial. Moreover, the ambient conditions and, thus, the climatic zone and the required coolant temperature affect the energy-saving potential through free cooling [9].

Numerous approaches exist to evaluate the energy and water consumption of cooling towers by modeling specific geometries [10–12]. However, the specific geometry is often unknown [13]. Consequently, transferable models, standard energy and water consumption values, and application area indications are lacking.

Geometry-independent, some empirically established values for electricity consumption circulate, which may partly be outdated due to engineering progress. For example, the European Commission (EC) published the most recent reference document on industrial cooling systems in 2001 [14]. The document includes the best available techniques and the water and energy consumption for different cooling systems. In addition, some authors provide data on the approach of different cooling tower types [15,16] (p. 17), [17] (p. 326), [18] (p. 550). Table 1 summarizes the current knowledge on standard values for cooling towers regarding resource consumption and some application area restrictions, such as thermal capacity and coolant outlet temperature.

Table 1. Previous research providing standard values and defining application areas for different types of cooling towers (ns = not specified).

	Analyzed Parameters [1]	Dry	Wet	Hybrid	Operating Points	Reference Object(s)
DIN 15240 [19] (p. 53)	$P_{f,el}$	X	X		ns	example values
EC [14] (p. 40)	$\dot{Q}_i$; $P_{f,el}$; $\dot{m}_{w,i}$; a; $\vartheta_{w,o,min}$	X	X	X	1	example values
Eurovent [20] (p. 9)	$P_{f,el}$		X		3	efficiency targets
Hincke et al. [17]	$\dot{m}_{w,i}$; a	X	X	X	variation	example values
Qi et al. [21]	$\vartheta_{w,o}$		X		variation	neural network
Schlei-Peters [11]	$\dot{Q}_i$; $P_{f,el}$; $\dot{m}_{w,i}$		X		variation	modeling
Schulze et al. [22]	$P_{f,el}$; $\dot{m}_{w,i}$; $\vartheta_{w,o}$		X		variation	simulation
Wang et al. [12]	$\dot{Q}_i$; $P_{f,el}$; $\dot{m}_{w,i}$; a; $\vartheta_{w,o}$		X		variation	experiment + simulation

[1] Among others, the following parameters were analyzed: $\dot{Q}_i$ = nominal thermal capacity; $P_{f,el}$ = fan power; $\dot{m}_{w,i}$ = freshwater consumption; $\vartheta_{w,o}$ = coolant outlet temperature; a = approach; $\vartheta_{w,i}$ = coolant inlet temperature; $\vartheta_{w,o}$ = coolant outlet temperature; $\vartheta_{w,o,min}$ = minimum coolant outlet temperature.

Analyzing market data, serial products, and technical data sheets reveal typical ranges for specific parameters. Such approaches exist for other technologies and scopes. For appliances, Gerke et al. [23] proposed an international cross-market comparison for efficiency deployment and monitoring. Monfet and Zmeureanu [24] used manufacturer data to calibrate a plant model that evaluates the cooling plant, including chillers. Moreover, manufacturer data serve for sizing and selecting specific cooling systems, which Tan and Fok [25] demonstrated for thermoelectric coolers.

1.2. Study's Objective

Filling the knowledge gap of standard values for resource consumption and parameters that restrict the application areas of cooling towers is needed (cf. Section 1). Thus, this study aims to provide the relevant parameters based on a technical market analysis, which comprises comprehensive data acquisition using manufacturers' data sheets and other official information sources. Firstly, we quantify the restricting parameters for the application area of different cooling towers. Secondly, the objective is to provide typical ranges for electricity and water consumption for these types.

The remainder of this paper is structured as follows: Section 2 defines the generalized system and targeted parameters and introduces the systematic data collection method. On that basis, Section 3 presents the results, which we discuss in Section 4. Finally, Section 5 summarizes our conclusions.

2. Materials and Methods

This section first introduces the investigated cooling tower types and the generalized system boundary used to compare these types. Secondly, we describe the systematic method to build the database. Consequently, the statistical evaluation is presented in Section 2.3.

2.1. System Definition

The first step is to clearly describe our object of investigation. Referring to VDI guideline 2047-3 [1] (p. 26), this paper focuses on 'package-type recooler systems', which are serial recirculating systems with less than 200 MW_{th} of nominal power, less than 20 m height, and less than 400 m^2 of footprint. Their purpose is to reduce the temperature of fluid coolants. To this end, these cooling systems include forced ventilation with either forced or induced draft because natural draft is possible only for large-scale cooling towers. We classify the cooling towers into six types:

1. dry cooling towers,
2. wet cooling towers with open circuit (direct),
3. wet cooling towers with closed circuit (indirect),

4. directly wetted hybrid cooling towers,
5. sprayed hybrid cooling towers, and
6. hybrid cooling towers with wetting-mats.

Dry cooling conductively transfers heat to ambient air using a heat exchanger and forced ventilation. Open wet cooling towers enable evaporation as the coolant trickles down fillers directly in contact with ambient air. Wet cooling with closed-loop water circuits uses evaporative heat transfer without direct contact between coolant and ambient air through a coolant–air heat exchanger and separate circulating water that trickles down to evaporate.

Hybrid cooling switches seasonally between dry cooling and indirect wet cooling. Regarding the water distribution, we classify the hybrid systems into directly wetted, sprayed, and wetting-mats hybrid cooling towers. The directly wetted hybrid cooler comprises the wetting circuit: an auxiliary water pump, water trickling down the heat exchanger, and a water collection tank. The spraying system saturates the ambient air for the subsequent cooling in the heat exchanger. Wetting-mats systems combine these water distribution methods, as the auxiliary water trickles down the mats, evaporating to the ambient air that subsequently passes the heat exchanger.

For all investigated cooling tower types, we define the generalized system boundary clarified in Figure 2. This generalization serves to refer all data to a comparable system subsequently. Thus, the system boundary serves to analyze the cooling tower as an isolated unit and as independently as possible from the conditions of the hydraulic integration.

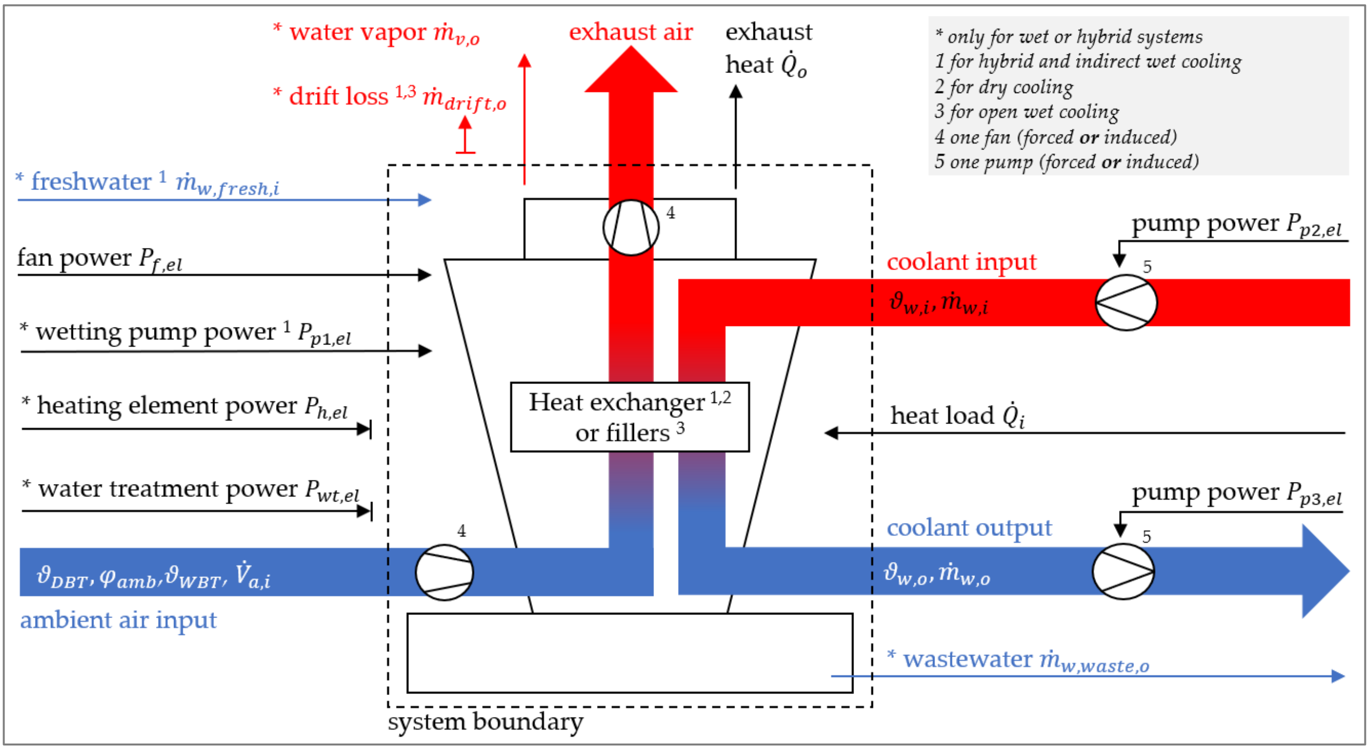

Figure 2. System boundary generalized for the investigated types of dry, hybrid, and wet cooling towers. Accordingly, the coolant-side pump, the wetting pump, heating elements, water treatment, and drift losses are not within the system boundary.

All types include two central mass flows: first, the coolant, the heat flow of which dissipates, and second the ambient air, to which this heat is transferred. In wet cooling, evaporated water accompanies the exhaust air. Furthermore, another output is wastewater. Thus, freshwater compensates for both. We account for all these flows with the system boundary. We neglect the water drift loss as it typically amounts to less than 0.05% of the circulation rate of industrial cooling towers [26] (pp. 1780–1781). The term drift refers to the water droplets carried out with exhaust air, which causes additional water loss.

Regarding energy flows, the system boundary includes the fans and associated electrical power to drive the air volumes. However, the system excludes the pump power to drive the coolant because the pumps are sized and operated independently of the cooling tower, depending on site conditions. For example, the coolant pipes may run across the entire factory site with no necessity on the part of the cooling tower. In contrast, fans are integral components of cooling towers, the same as the wetting pump. Furthermore, we omit the heating elements and water treatment to unify the data, referring to DIN SPEC 15240 [19] (p. 54).

2.2. Data Acquisition

Referring to the system boundary in Figure 2, we gathered specific parameters for the different types of cooling towers in four steps, which is based on Mühlen [27]. Figure 3 illustrates the procedure. The data's primary sources are manufacturers' data sheets.

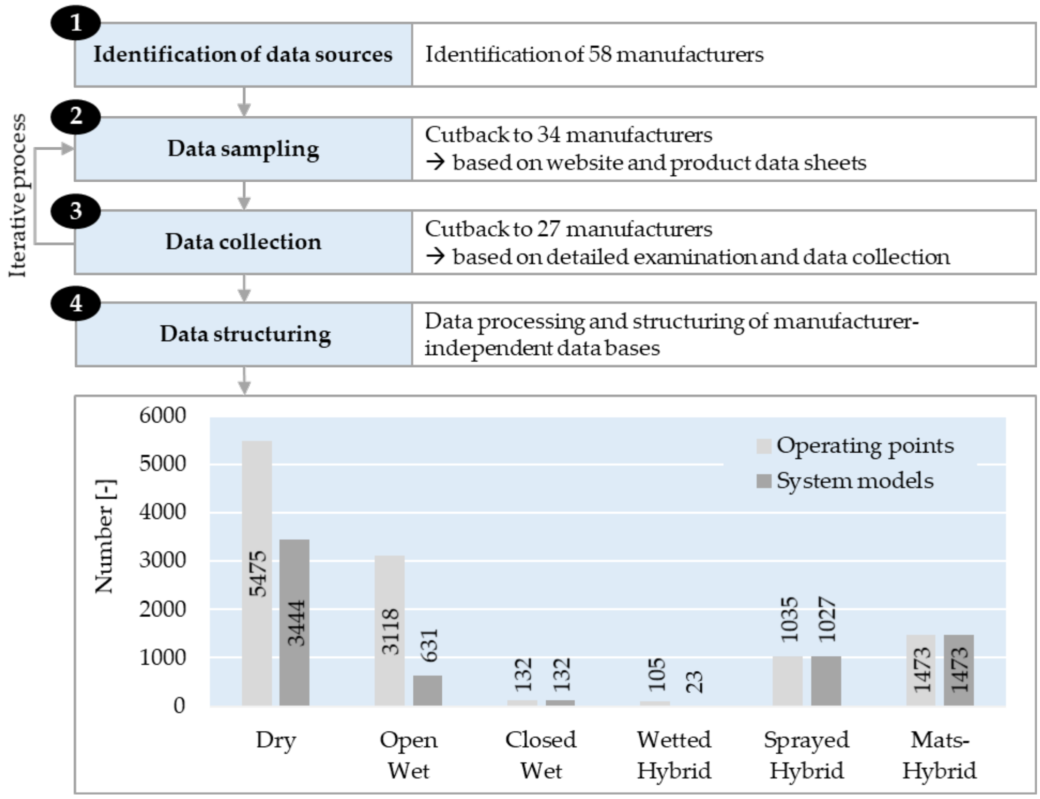

Figure 3. Systematic approach for the data acquisition based on reviewing manufacturer data sheets and data structure regarding the six cooling tower types.

First, we investigated which companies manufacture cooling towers. For this purpose, we conducted exhaustive internet research, searching for companies in refrigeration and cooling technology. Furthermore, we examined the certified products list of the certification body Eurovent [28], which certifies cooling towers and other products internationally. Table S1 in the Supplementary Materials provides the list of 58 identified manufacturers.

The sampling strategy proceeds mainly in the second step but is partly iterative in the third step. The second step was to exclude companies that manufacture products outside the paper's scope. Additionally, we narrowed the data to products sold in the European region. Consequently, we limited the data to 34 companies constructing serial products with liquid heat transfer medium, classifiable in the six cooling tower categories (cf. Section 2.1).

Thirdly, we collected the data and examined the remaining manufacturers in detail. For this purpose, we probed the product catalogs, websites, online tools, technical data sheets, operation and maintenance manuals, economic studies, and the Eurovent database. Mainly, the performance and other technical data refer to specific operating points. Tables S1–S3 in the Supplementary Materials provides the data collection for each manufacturer. The reference section includes the references to all data sources; Table A1 in the Appendix A provides an overview. Due to a lack of data, we excluded seven more manufacturers from the subsequent data analysis within our work.

The fourth step includes the data structuring procedure. We structured the data of the 27 remaining cooling tower manufacturers for specific parameters. As a result, the data include 6730 different system models of cooling towers and 11,338 data points because one or more operating points are given for each model. Figure 3 illustrates the resulting data point distribution regarding the number of system models and operating points of each of the six investigated cooling tower types.

The subsequent data analysis aims to quantify specific parameters for each data point. Given the energy and climate targets, electricity and water consumption are crucial, as are the associated parameters. Thus, we gathered data on freshwater consumption, the fans' nominal power, and the wetting pumps' nominal electricity demand, which manufacturers provide for specific operating points. Subsequently, we analyzed the parameters concerning the cooling tower's technical utility: the nominal thermal load $\dot{Q}_i$, including cooling medium with specific heat capacity c_p, inlet and outlet coolant temperatures with extreme values, and the coolant inlet flow rate $\dot{m}_i$. The difference between the inlet and outlet temperature, $\vartheta_{w,i}$ and $\vartheta_{w,o}$, of the coolant is the range $z = \vartheta_{w,i} - \vartheta_{w,o}$. Therefore, the removed heat $\dot{Q}_i$ that enters the cooling tower is:

$$\dot{Q}_i = \dot{m}_i c_p z \;=\; \dot{m}_i c_p (\vartheta_{w,i} - \vartheta_{w,o}). \tag{1}$$

According to DIN V 18599-7 [29] (p. 64), the specific electricity demand q_{el} of cooling towers is the electricity demand P_{el} per thermal load $\dot{Q}_i$:

$$q_{el} \;=\; P_{el} / \dot{Q}_i. \tag{2}$$

Achieving this technical requirement depends, firstly, on the physical conditions: ambient *DBT* or the *WBT* and the relative humidity φ. Secondly, we ascertain the technical parameters of the cooling tower. The cooling tower approach a_{wet} of wet and hybrid cooling is the difference between the needed coolant outlet temperature $\vartheta_{w,o}$ and the *WBT* ϑ_{WBT}. In contrast, the dry cooling approach a_{dry} refers to the *DBT*:

$$\begin{aligned} a_{wet} &= \vartheta_{w,o} - \vartheta_{WBT}, \\ a_{dry} &= \vartheta_{w,o} - \vartheta_{DBT}. \end{aligned} \tag{3}$$

For hybrid cooling systems, the switchover point ϑ_{switch} is the *DBT* at which the cooler switches between dry and wet cooling. Furthermore, the technical parameters include the fan arrangement, the flow arrangement, size and weight, and the nominal air volume flow rate $\dot{V}_{a,i}$. Table 2 summarizes the parameters collected for our database.

Based on the parameter collection and evaluation, we demonstrate in the results Section (Section 3.3) how the data serve to determine the free cooling potential, using a simplified example for the Stuttgart-Vaihingen site. For this purpose, we use hourly data on the *WBT* and *DBT* of the test reference year of the specific site, which refers to the period between 1995 and 2012 [30]. Subsequently, we calculate the achievable cooling temperature by adding the median approach to the *WBT* for wet cooling or to the *DBT* for dry cooling. Finally, depending on the required cooling temperature, we determine the hours when free cooling is possible for each type of cooling tower.

Table 2. Collected Parameters.

	Parameter	Symbol	Unit
Item Details	name of manufacturer	[-]	[-]
	name of cooler model	[-]	[-]
	type of cooling tower	[-]	[-]
Resource Consumption	fan power [1]	$P_{f,el}$	kW_{el}
	wetting pump power [1]	$P_{p,el}$	kW_{el}
	specific electricity demand (calculated) [1]	q_{el}	kW_{el}/kW_{th}
	freshwater consumption [1]	$\dot{m}_{w,fresh,i}$	m^3/h
	specific freshwater consumption [1]	$\dot{m}_{w,fresh,i}/\dot{Q}_i$	$m^3/h/kW_{th}$
Utility	nominal heat load [1]	$\dot{Q}_i$	kW_{th}
	cooling medium (coolant)	[-]	[-]
	coolant volume flow rate	$\dot{V}_{w,i}$	m^3/h
	coolant inlet temperature	$\vartheta_{w,i}$	°C
	maximum coolant inlet temperature	$\vartheta_{w,i,max}$	°C
	coolant outlet temperature	$\vartheta_{w,o}$	°C
	minimum coolant outlet temperature	$\vartheta_{w,o,min}$	°C
	range z	z	K
Physical Constraints	ambient *DBT* (*DBT*)	ϑ_{DBT}	°C
	relative humidity	φ	%
	ambient *WBT*	ϑ_{WBT}	°C
Technical Constraints	approach a	a	K
	switchover point (hybrid)	ϑ_{switch}	°C
	fan arrangement	[-]	[-]
	flow arrangement	[-]	[-]
	area × height (L × W × H)	$A \cdot H$	$mm^2 \cdot mm$
	weight	m	kg
	thermal capacity per area (calculated) [1]	$\dot{Q}_i/A$	kW_{th}/m^2
	thermal capacity per weight (calculated) [1]	$\dot{Q}_i/m$	kW_{th}/kg
	nominal air volume flow rate [1]	$\dot{V}_{a,i}$	m^3/h

[1] valid for a specific operating point that includes coolant inlet and outlet temperatures, $\vartheta_{w,i}$ and $\vartheta_{w,o}$, ambient temperature ϑ_{amb} or *WBT* $\vartheta_{amb,WBT}$, and relative humidity φ_{amb}.

2.3. Statistical Evaluation

Based on the compiled data, boxplot diagrams illustrate the descriptive statistic. For a specific parameter x, these diagrams highlight the data's median x_{med}, the range between minimum x_{min} and maximum x_{max}, and the interquartile range (IQR) between the 25%-quantile $x_{0.25}$ and the 75%-quartile $x_{0.75}$. The 1.5-IQR value and end determine the minimum and maximum (whiskers) at the most minor or utmost value within the 1.5-IQR intervals.

$$[x_{0.25} - 1.5 \cdot (x_{0.75} - x_{0.25}), x_{0.75} + 1.5 \cdot (x_{0.75} - x_{0.25})] \quad (4)$$

Values outside this range are outliers [31] (p. 28). Figure 4 illustrates the concept.

In addition to the boxplot, we also graph the data points to visualize the quantity of data points. The evaluation tool is *Python*-based.

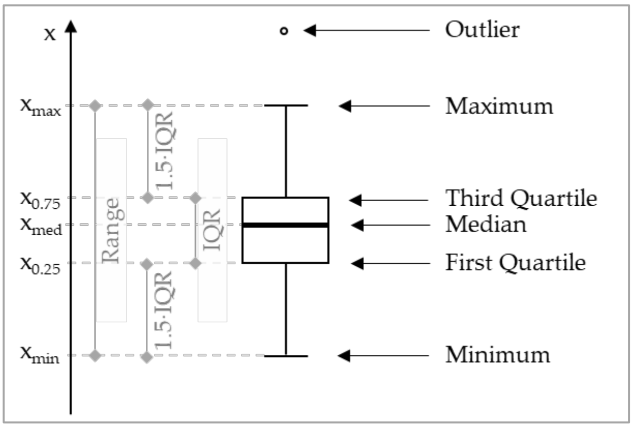

Figure 4. Vertical boxplot diagram.

3. Results

The free cooling potential depends on specific parameters restricting the application area, such as the minimum coolant outlet temperature. Section 3.1. presents the results for the crucial parameters. Secondly, the resource-saving potential is determined from the specific electricity and water consumption, which we evaluate in Section 3.2 for six types of cooling towers. Section 3.3. includes an example of how these findings can be used and interpreted.

The data refer to specific operating points, including ambient temperature or *WBT* and inlet and outlet temperatures of the coolant. Figure 5 illustrates the data of the stated reference temperature, which is the ambient temperature for dry cooling and the *WBT* for wet and hybrid cooling.

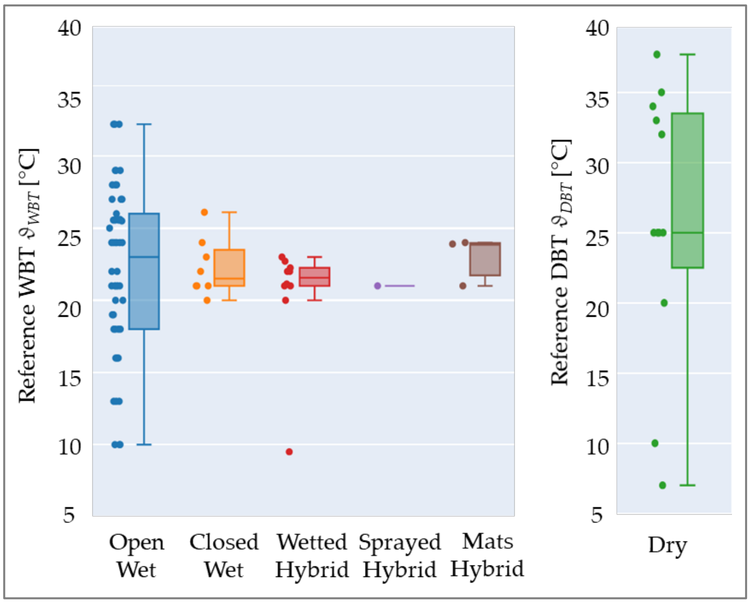

Figure 5. Reference temperatures in the data pool. Dry cooling refers to the *DBT*, whereas wet and hybrid cooling data refer to the *WBT*.

The manufacturers provide data on wet and hybrid cooling that refer to the *WBT*. The median is between 20 and 25 °C. The broadest range of operating points in terms of *WBT* exists for open wet cooling. In contrast, the dry cooling data refer to the *DBT* at 25 °C at the median.

3.1. Limits of Cooling Tower Use

Physically, the cooling process is limited by the laws of thermodynamics. Consequently, the heat transfer of cooling towers is possible only along the temperature gradient. If the process was physically ideal, for example, with an infinitely large heat exchanger surface, dry cooling could reach the ambient *DBT* at the extreme—in theory. Wet cooling could theoretically reach the *WBT* using evaporation. The approach would be zero for the ideal theoretical case.

Beyond the physical constraints, technical limits apply to cooling towers. Thus, in the technical implementation, the dry and wet cooling approach is greater than the one for the physical ideal. Figure 6 graphs the results of our market analysis, showing the nominal design values for the approach of the six types of cooling towers. Moreover, the figure presents the difference between inlet and outlet temperatures as the cooling tower range, the minimum outlet and maximum inlet temperatures of the coolant, and the switchover temperature of hybrid cooling.

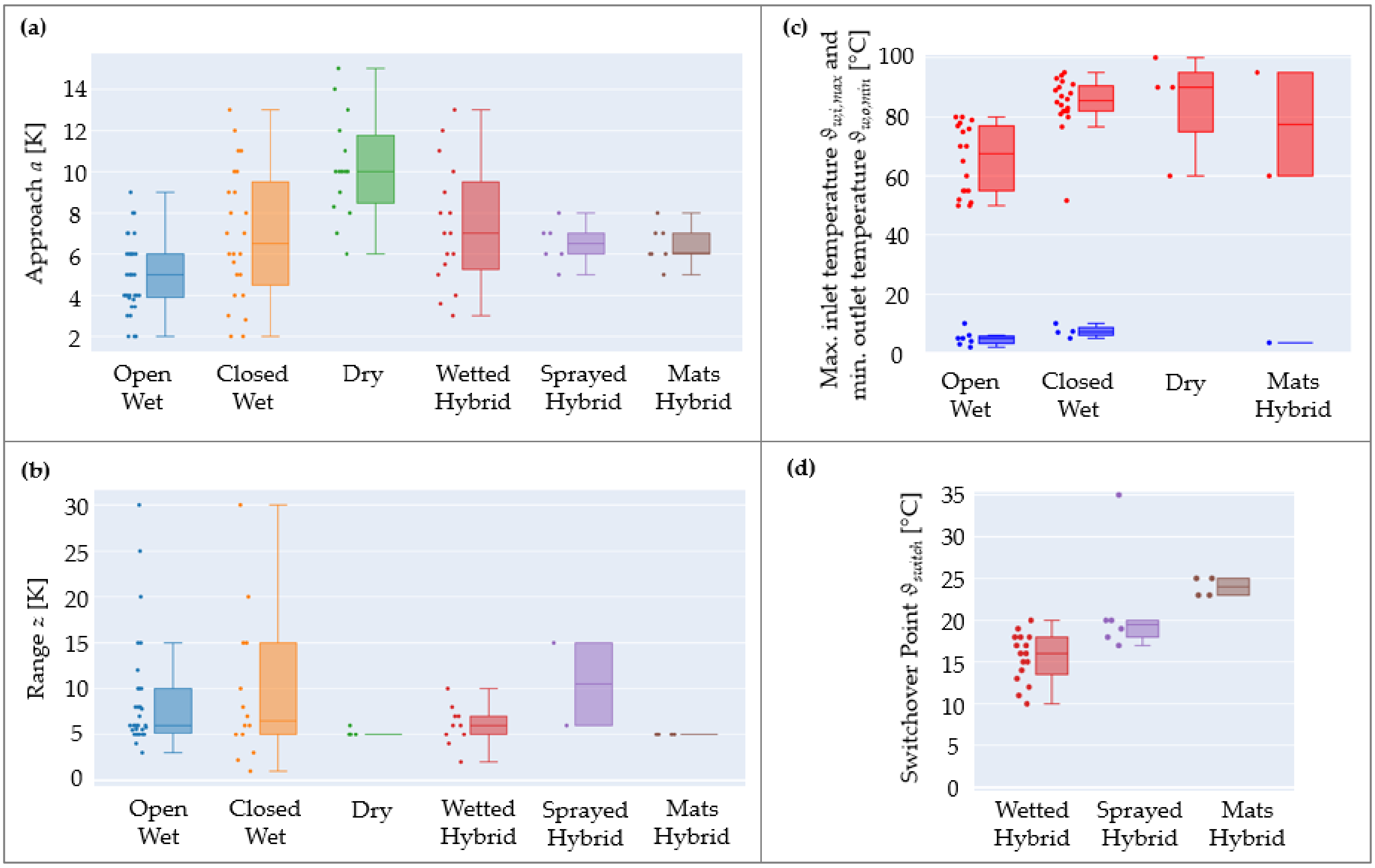

Figure 6. (**a**) Approach a, (**b**) range z, (**c**) maximum coolant inlet temperature $\vartheta_{w,i,max}$, minimum coolant outlet temperature $\vartheta_{w,o,min}$ of different types of cooling towers and (**d**) switchover *DBT* ϑ_{switch} of hybrid coolers within the data pool.

Figure 6a demonstrates that the approach of open wet cooling is tendentially smaller than for dry cooling. For the analyzed data pool, this difference is approximately 5 K. Wet cooling towers with closed circuits have an approximately 3.5 K lower approach than dry cooling at the median. Compared to open wet cooling, closed wet cooling towers have a 1.5 K higher approach at the median because their heat transfer is comparably less effective without direct coolant–air contact. The hybrid coolers' approach heavily depends on whether dry or wet cooling is applied at the operating point. However, the wet and hybrid cooling approach is the distance to the *WBT*, whereas the dry cooling approach is the one to the *DBT*. For this reason, the dry cooling approach is not directly comparable.

The wet cooling range scatters between 1 and 30 K (cf. Figure 6b). The median of all types is between 5 and 6.5 K, except the median of sprayed hybrid coolers, which is approximately 10 K. However, the validity is limited due to limited data availability.

Furthermore, Figure 6c demonstrates the limits of use by inlet and outlet coolant temperatures for wet cooling and hybrid coolers with sprayed mats. The analysis confirms the general result of Figure 6a for the approach data: Open wet cooling enables circa 1.5 K lower outlet temperatures of the coolant than closed-loop wet cooling. The minimum coolant temperature is 5 °C at the median to avoid freezing in wet cooling. The graph also reveals that open wet cooling displays a median inlet coolant temperature of 70 °C, which is 15 K lower than those with closed circuits. The limiting factors are the material properties of fillers or heat exchangers and the water boiling temperature. Moreover, the highest possible coolant inlet temperatures for dry cooling are approximately 90 °C. The graph does not allow statements for hybrid cooling due to the limited availability of data.

The optimal switching point of hybrid cooling between dry and wet cooling depends on the targeted coolant outlet temperatures. Another reason is the differing effectiveness of heat transfer for the different water distribution systems. Hence, the data illustrated in Figure 6d are not universal but reference points for the specific operating points. The ideal switchover ambient temperature for all three types of hybrid coolers would be the required coolant outlet temperature because dry cooling is theoretically possible down to the *DBT* at the minimum. However, in practice, dry cooling has an approach of 10 K to *DBT* at the median, which our results reveal. Consequently, the technical ideal switchover temperature is the required coolant temperature minus the dry cooling approach of a minimum 6 K.

Figure 7 summarizes the findings on the approach, the range, the maximum coolant inlet temperature, and the theoretical switching temperature of hybrid coolers in simplified terms. The figure visualizes the restricting temperatures and the coherencies. For this purpose, the abscissa axis displays the coolant inlet temperature, and the ordinate displays the required coolant outlet temperature. The ambient *WBT* is lower than this cooling temperature by at least the approach. The minimum approach for dry cooling is around 5 K larger than the evaporative cooling approach, as illustrated. Furthermore, the minimum dry cooling temperature is higher than that of wet cooling because the approach refers to the *DBT*. Below the approach of open wet cooling, refrigeration will be needed if waste heat utilization via a heat pump is excluded for economic or other practical reasons. Another limitation is the range, which leads to the diagonal limitation of cooling towers because the outlet temperature is approximately 5 K higher than the inlet temperature. Consequently, further cooling below the range would require refrigeration as well. In practice, higher ranges than 30 K are uncommon. As a result, the application areas of the cooling tower types are parallelograms in practice.

According to Figure 8, wet cooling towers have the largest thermal capacities per unit; the other types of cooling towers are manufactured in smaller sizes. Multi-unit installations enable the realization of higher capacities.

Furthermore, the thermal capacity per cooling tower can be a limiting factor. However, installing multiple items enables scalable capacity to a certain extent. Figure 8 graphs typical values for the thermal capacity for each cooling tower type.

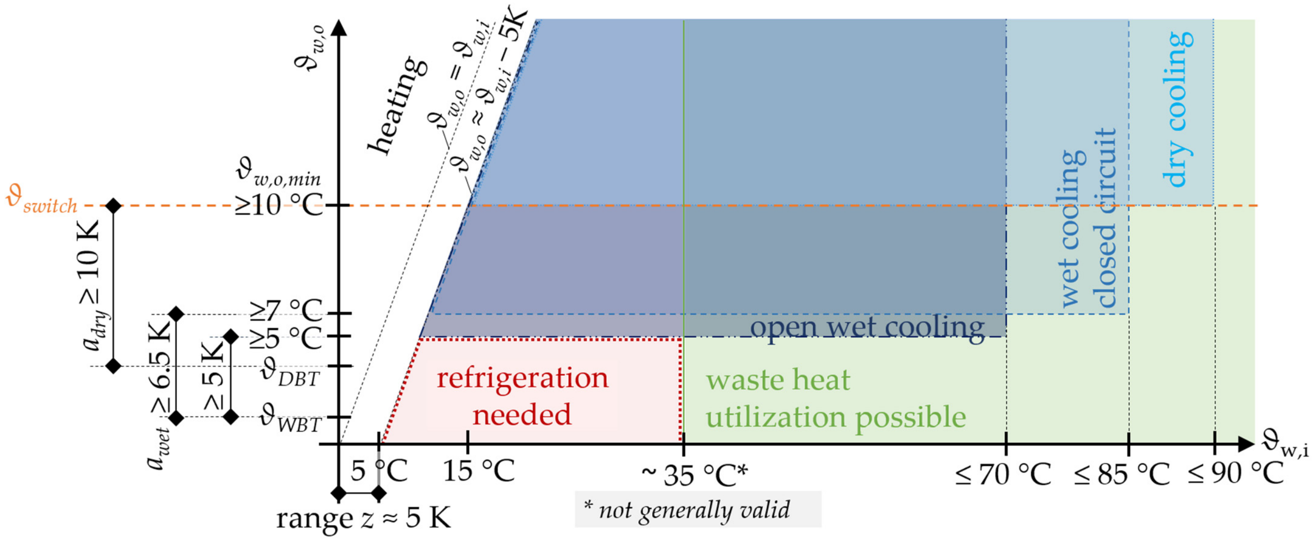

Figure 7. Summary of the findings on the technical application limits of cooling systems using the medians of values within the dataset. The limit of utilizing waste heat is not universally valid but to clarify the concept.

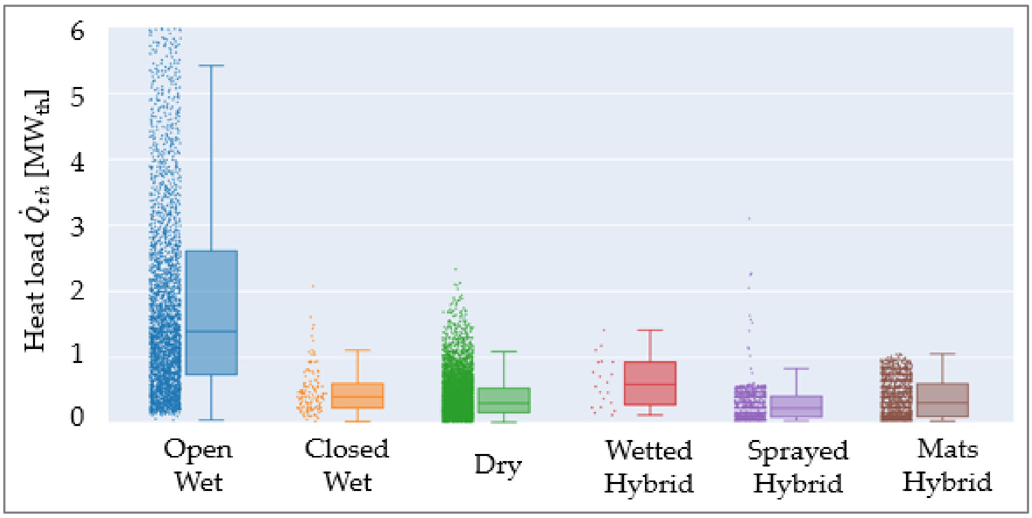

Figure 8. Thermal load ranges of the cooling tower types in the data pool. The axis or ordinates is capped at 6 MW_{th}, although the data points reach up to 20 MW_{th}, to make the data points more perceptible.

3.2. Electricity and Water Consumption

Regarding resource consumption, this section presents the amount of electricity and water consumed by the cooling tower types. Figure 9 graphs the specific electricity demand of the six cooling tower types over the cooling capacity. As these data points are nominal values for the stationary operating points, direct comparison between different operating points is limited.

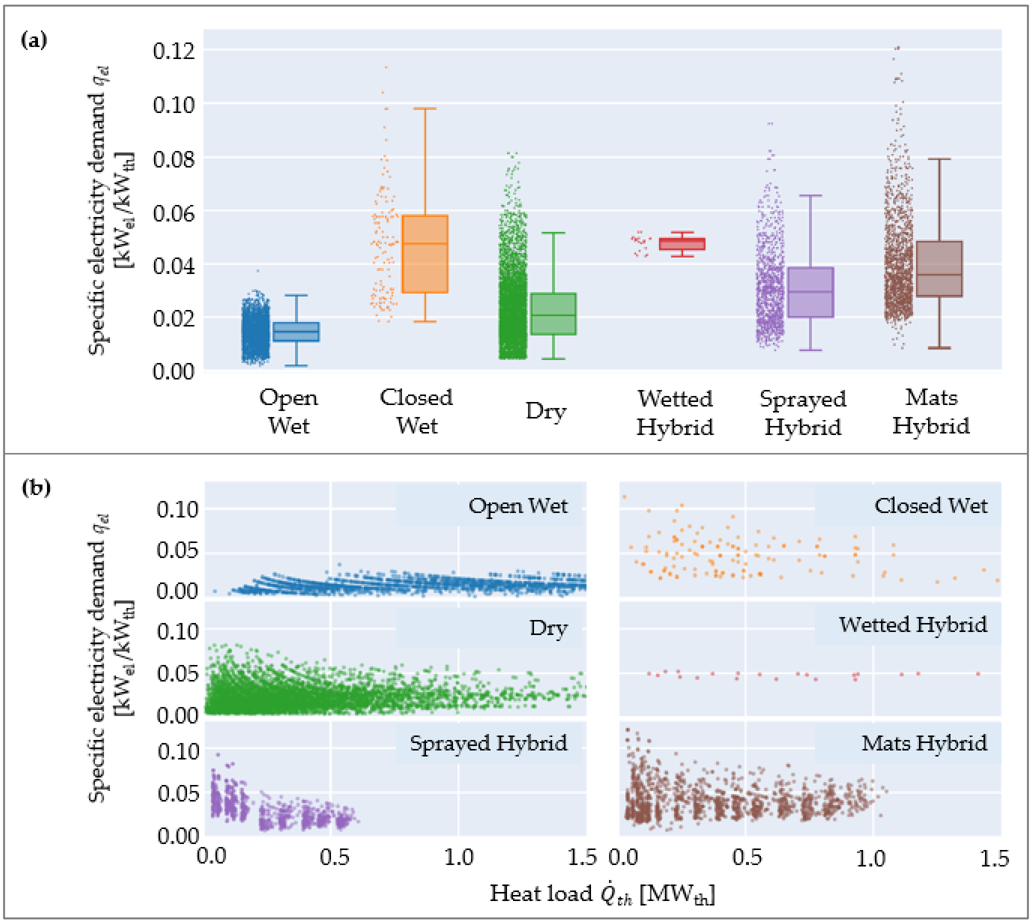

Figure 9. Specific electricity demand of each type of cooling tower (**a**) as a boxplot diagram and (**b**) over the thermal capacity below 1.5 MW$_{th}$. The data points amount to: 3118 for open wet cooling, 132 for closed wet cooling, 5475 for dry cooling, 105 for directly wetted hybrid cooling, 1035 for sprayed hybrid cooling, and 1473 for hybrid cooling with wetting-mats.

Despite the limited comparability due to different operating points, Figure 9 confirms that, with up to 0.03 kW$_{el}$/kW$_{th}$, open wet cooling consumes on average less electricity per kW$_{th}$ than all other types. Wet cooling with closed circuit and spayed or wetting-mats hybrid cooling exhibit wide ranges up to approximately 0.10 kW$_{el}$/kW$_{th}$, including higher specific electricity demand values than dry cooling. The data points for directly wetted hybrid coolers are around 0.05 kW$_{el}$/kW$_{th}$ but comparatively few. The specific electricity demand tends to decrease with increasing thermal loads. Some data points form strictly monotonically decreasing lines due to the same number and nominal power of fans.

Examining specific operating points allows the comparison of systems. For this purpose, Table 3 outlines the electricity demand of cooling tower types for five clearly defined operating points.

Regarding hybrid cooling, the specific electricity demand refers to an ambient *WBT* of 21 °C. The corresponding *DBT* is unknown but is generally higher than or equal to the *WBT*. As hybrid cooling switches to dry cooling below a maximum *DBT* of 25 °C (cf. Figure 6), the data of electricity demand in Table 3 mostly correspond to the dry cooling mode of hybrid coolers.

Table 3. Ranges of specific electricity demand between the 25% and 75% quartiles regarding specific operating points for thermal capacities of less than 2.4 MW_{th} (ns = not specified).

Operating Point [1]	Dry	Open Wet	Closed Wet [2]	Wetted Hybrid [2]	Sprayed Hybrid [2]	Mats Hybrid [2]
$\vartheta_{w,i}/\vartheta_{w,o}/\vartheta_{D/WBT}$ [°C]	$P_{el}/\dot{Q}_i$ [kW_{el}/kW_{th}]	$P_{el}/\dot{Q}_i$ [$kW_{el}kW_{th}$]	$P_{el}/\dot{Q}_i$ [kW_{el}/kW_{th}]	$P_{el}/\dot{Q}_i$ [kW_{el}/kW_{th}]	$P_{el}/\dot{Q}_i$ [kW_{el}/kW_{th}]	$P_{el}/\dot{Q}_i$ [kW_{el}/kW_{th}]
32/27/21	ns	0.012–0.018	ns	ns	0.020–0.039	0.028–0.050
32/26/21	ns	0.013–0.021	0.045–0.058	ns	ns	ns
35/30/24	ns	0.012–0.018	0.025–0.031	ns	ns	ns
36/30/21	ns	ns	ns	0.045–0.05	ns	ns
40/35/25	0.014–0.029	ns	ns	ns	ns	ns

[1] $\vartheta_{w,i}/\vartheta_{w,o}/\vartheta_{WBT}$ for wet and hybrid cooling and $\vartheta_{w,i}/\vartheta_{w,o}/\vartheta_{DBT}$ for dry cooling. [2] including electricity demand of spray water pump.

Not all types are tested for these five operating points because the main fields of application differ. Direct comparison is only reasonable line by line, not across different operating points. Consequently, open wet cooling, wet cooling with closed circuits, sprayed hybrid cooling, and wetting-mats hybrid cooling are comparable. The direct comparison of specific operating points reveals that the regarded open wet coolers consume less electricity than the compared hybrid coolers. Dry cooling and directly wetted hybrid cooling are incomparable to the other types using this data. Conclusions on closed wet cooling and directly wetted hybrid cooling are comparatively less reliable because of fewer data points.

Like electricity demand, water consumption depends on the thermal load, coolant temperatures, ambient temperature, and humidity. The dataset comprises the water consumption of sprayed and wetting-mats hybrid cooling. Table 4 summarizes the data results.

Table 4. Ranges of specific water consumption per MW_{th} between the 25% and 75% quartiles.

Operating Point [1]	Dry	Open Wet	Closed Wet	Wetted Hybrid	Sprayed Hybrid [1]	Mats Hybrid [1]
$\vartheta_{w,i}/\vartheta_{w,o}/\vartheta_{WBT}$ [°C]	$\dot{m}_{w,i}/\dot{Q}_i$ [$l/h/kW_{th}$]	$\dot{m}_{w,i}/\dot{Q}_i$ [$l/h/kW_{th}$]	$\dot{m}_{w,i}/\dot{Q}_i$ [$l/h/kW_{th}$]	$\dot{m}_{w,i}/\dot{Q}_i$ [$l/h/kW_{th}$]	$\dot{m}_{w,i}/\dot{Q}_i$ [$l/h/kW_{th}$]	$\dot{m}_{w,i}/\dot{Q}_i$ [$l/h/kW_{th}$]
32/27/21	0	ns	ns	ns	3.32–4.60	2.06–2.69

[1] $\vartheta_{w,i}$ = 32 °C/$\vartheta_{w,o}$ = 27 °C/ϑ_{WBT} = 21 °C/φ = 36%.

The sprayed hybrid coolers and those with wetting-mats are comparable because this data refers to the same operating point. The analysis demonstrates that the sprayed type consumes around 76% more water than the equivalent with wetting mats.

3.3. Exemplary Application

The potential for free cooling is demonstrated in the following example of applying the manufacturer data analysis. The reachable coolant outlet temperatures depend on the dynamic ambient conditions. Exemplary, we examine the free cooling potential in Stuttgart-Vaihingen using the temperature profile of the test reference year (cf. Section 2.2). The achievable coolant outlet temperature is approximately the *WBT* or *DBT* plus the approach median determined in Section 3.1. (cf. Figure 6). As a result, Figure 10a demonstrates that the reachable temperature with dry cooling is higher than with all other types of cooling. Consequently, dry cooling exceeds the required coolant outlet temperature more frequently than the other cooling types, which results in a longer duration where refrigeration is needed (cf. Figure 10b).

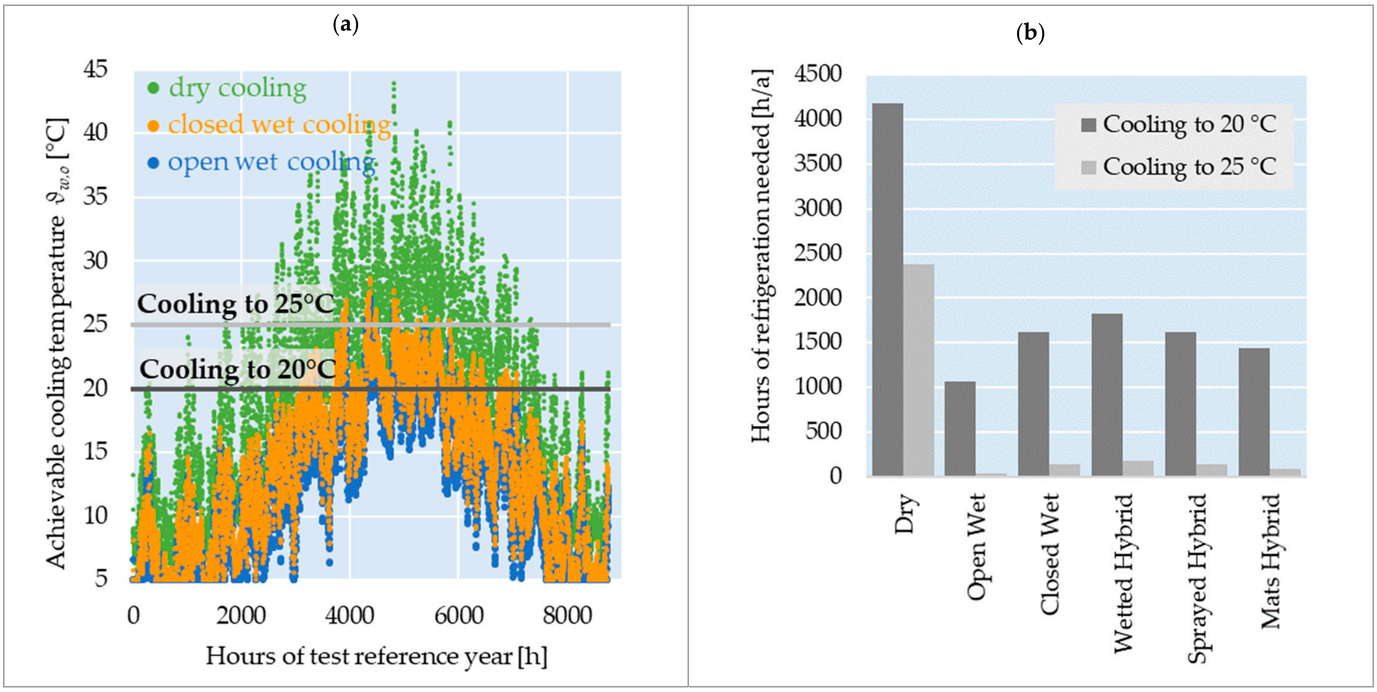

Figure 10. An exemplary application of our results that highlights (**a**) the achievable coolant outlet temperature using different cooling tower types located in Stuttgart-Vaihingen compared to two exemplary required coolant outlet temperatures and (**b**) the free cooling exceedance duration in which refrigeration is required. Table S4 in the Supplementary Materials provides the underlying data.

Figure 10 demonstrates that the free cooling potential using dry cooling is significantly smaller than for the other cooling tower types. For example, with the required cooling temperature of 25 °C, dry cooling suffices for approximately 72.8% of the year's hours. In contrast, wet and hybrid cooling can cover between 98.0% and 99.6% of the annual cooling demand. A lower required cooling temperature of 20 °C leads to a free cooling potential of 52.2% with dry cooling or from 79.2% to 87.9% with wet or hybrid cooling. The higher the required cooling temperature is, compared to the ambient *DBT*, the greater the free cooling potential and the dry cooling potential. Thus, wet or hybrid cooling becomes more beneficial for required cooling temperatures closer to the *WBT*.

4. Discussion

Reflecting the resulting application areas, our findings confirm what is qualitatively well-known but also reinforce the expectations with quantitative data (cf. Figure 7). The data serve to complement and update previous literature values for cooling tower design and modeling.

Generally, the ranges found within this study are more precise than the compared literature values because the data distribution becomes clear with given quartiles and medians. Nevertheless, the uneven data distribution over the cooling tower types (cf. Figure 3) results in varying soundness of the types' results. The results on dry cooling are comparably more robust because most data we collected refer to dry cooling (5475 operating points, 3444 models). Data quantity for open wet (3118 operating points, 631 models), sprayed hybrid (1035 operating points, 1027 models), and wetting-mats hybrid cooling (1473 operating points, 1473 models) lies in the middle range. In contrast, closed wet cooling (132 operating points, 132 models) and directly wetted hybrid cooling (105 operating points, 23 models) have the smallest database. Consequently, the results are less reliable for open wet, sprayed hybrid, and wetting-mats hybrid cooling and the least reliable for closed wet and directly wetted hybrid cooling compared to dry cooling. Therefore, some parameters are still missing for these types.

One general limitation is the data's dependency on weather conditions and operating points. Different locations determine the cooling tower operation by specific weather conditions, so the location can be considered an indirect influencing factor. However, the cooling tower cannot 'sense' the location but depends only on the current ambient air properties. Consequently, the cooling tower will operate identically at different locations if the incoming air has the same thermodynamic characteristics. For this reason, we refer only to the humid air properties instead of the location.

Regarding operating points, the data are sound for the typical nominal-value measurement ranges. For wet and hybrid cooling, the data refer mainly to a *WBT* between 20 and 25 °C and, for dry cooling, to a *DBT* of around 25 °C (cf. Figure 5). The data for open wet cooling have the most comprehensive ranges of *WBT* comparatively. These reference temperatures are higher than the annual mean temperature in most countries. The data are reliable for lower temperatures than the reference ones because free cooling is applicable with larger temperature gradients. In contrast, for higher temperatures, the results' transferability is limited. Future studies should additionally address the consequences of global warming on free cooling.

As illustrated in Figure 5, the median of the reference *WBT* of wet and hybrid cooling ranges between 21 and 24 °C. For dry cooling, the median of *DBT* is 25 °C, which equals the standardized temperature for nominal power measurement [32] (p. 7). As most data points do not include the humidity, dry, wet, and hybrid cooling are comparable to a limited extent. A total of three manufacturers provide humidity data for the operating points. For these specifications, the relative humidity ranges from 31 to 49% [33] (p. 3), [34] (pp. 14,16,18–19), [35] (p. 7), [36] (p. 10), [37] (p. 3), [38] (p. 3).

In addition to the ambient conditions, the coolant inlet and outlet temperatures affect the investigated parameters, especially electricity consumption, because a smaller approach requires a greater air volume flow for heat transfer of the same heat load. Alternatively, heat transfer could be achieved with a larger heat exchanger. Thus, the data apply rather to higher outlet temperatures with higher temperature gradients. Deviations are expectable for cooling towers with a variable frequency drive.

Table 5 summarizes our results (grey lines) and compares them to the previous standard values (white lines). The data in the white originate from literature sources, while the superscript leads to the literature reference in the footer. Furthermore, the specific electricity demand applies to specific operating points, which are also stated in the footer. For example, we found a dry cooling approach of 10 K at the median, where the 25%-quartile is 8.5 K and the 75%-quartile is 11.8 K. We compare our results to those from the literature, where a range from 7 to 8 K is provided; and the superscript "1" leads to the literature source [18] (p. 550).

Regarding the dry cooling approach in Table 5, the two literature sources show two discrepant results. Our 25%-to-75%-quartiles result is within the range given by Freiherr [39] but outside the one provided by Dehli [18]. The results for open wet, sprayed hybrid, and wetting-mats hybrid cooling display greater overlapping with the literature values. In contrast, the literature values for closed wet and directly wetted hybrid cooling are smaller than our results.

The results for the cooling ranges mostly correspond to the compared literature, except for the sprayed hybrid cooling's result, which is larger than the literature ranges.

Table 5. Results of this study (grey rows: 25% quartile—75% quartile; median) compared with literature values.

Parameter	Source	Dry	Open Wet	Closed Wet	Wetted Hybrid	Sprayed Hybrid	Mats Hybrid
approach a [K]	this study	8.5–11.8; 10	3.9–6; 5	4.5–9.5; 6.5	5.3–9.5; 7	6–7; 6.5	ns–7; 6
	literature	7–8 [1] 8–15 [2]	4 [1] 4–7 [3]	3 [2]	4–7 [3] 4–5 [4]	6–8 [2]	5–8 [2]
range z [K]	this study	5–5; 5	5–10; 6	5–15; 6.5	5–7; 6	7–15; 10.5	5–5; 5
	literature	4–10 [5] 5–6 [3]	4–10 [5] 5–6 [3]	4–10 [5] 5–6 [3]	4–10 [5] 5–6 [3]	4–10 [5] 5–6 [3]	4–10 [5] 5–6 [3]
$\vartheta_{w,i,max}$ [°C]	this study	75–95; 90	55–78; 68	82–91; 85	ns	ns	60–95; 78
	literature	ns	85 [6]	ns	40 [4]	ns	ns
$\vartheta_{w,o,min}$ [°C]	this study	38.5–41.8	24.9–27	25.5–30.5	26.3–30.5	27–28	ns
	literature	40–45 [7]	27–31 [7]	28–35 [7]	28–35 [7]	ns	ns
ϑ_{switch} [°C]	this study	-	-	-	13.5–18; 16	18–20; 19.5	23–25; 24
	literature	-	-	-	20–25 [8] 2–18 [4]	20–25 [8] 26 [3]	20–25 [8]
q_{el} [kW$_{el}$/kW$_{th}$]	this study	0.014–0.029 [a]	0.012–0.018 [b] 0.013–0.021 [c] 0.012–0.018 [d]	0.045–0.058 [c] 0.025–0.031 [d]	0.045–0.050 [f]	0.020–0.039 [a]	0.028–0.050 [a]
	literature	0.045 [9]	0.018–0.021 [9] 0.014–0.028 [b,10]	0.033–0.040 [9] 0.031–0.067 [e,10]	ns	ns	ns
$\dot{m}_{w,fresh,i}/\dot{Q}_i$ [l/h/kW$_{th}$]	this study	0	ns	ns	ns	3.32–4.60/3.97	2.06–2.69/2.25
	literature		2.5–4.5 [4] 2 [7]	2.5–4.5 [4]	1.6–2.0 [4] 1.5 [7]	ns	ns

[1] [18] (p. 550); [2] [39] (p. 38); [3] [15]; [4] [17] (pp. 327–331); [5] [40] (p. 88); [6] [41] (p. 1938); [7] [14] (p. 40); [8] [42] (p. 114); [9] [19] (p. 53); [10] [20] (pp. 9–10). [a] operating point: $\vartheta_{w,i}$ = 40 °C/$\vartheta_{w,o}$ = 35 °C/ϑ_{DBT} = 25 °C; [b] operating point: $\vartheta_{w,i}$ = 32 °C/$\vartheta_{w,o}$ = 27 °C/ϑ_{WBT} = 21 °C; [c] operating point: $\vartheta_{w,i}$ = 32 °C/$\vartheta_{w,o}$ = 26 °C/ϑ_{WBT} = 21 °C; [d] operating point: $\vartheta_{w,i}$ = 35 °C/$\vartheta_{w,o}$ = 30 °C/ϑ_{WBT} = 24 °C; [e] operating point: $\vartheta_{w,i}$ = 35 °C/$\vartheta_{w,o}$ = 30 °C/ϑ_{WBT} = 21 °C; [f] operating point: $\vartheta_{w,i}$ = 36 °C/$\vartheta_{w,o}$ = 30 °C/ϑ_{WBT} = 21 °C.

The literature rarely provides typical values for the maximum inlet temperature, so our data analysis can partly supplement these values. Contradictorily, Erens and Reuter [41] state 85 °C as the maximum inlet temperature for open wet cooling. However, as the fillers material restricts the maximum inlet temperature, our result based on manufacturers' data is accurate for the investigated system models.

The smallest possible cooling temperature is also crucial for the application area of each type. Thus, our results demonstrate that previous studies overestimated the minimum outlet temperature for almost each cooling tower type. Consequently, the free cooling potential is greater than estimated with these literature values, depending on the specific system model.

Brunner et al. [42] state the same ranges for the switchover point for all types of hybrid cooling. In comparison, we found lower values for directly wetted and sprayed hybrid cooling and coinciding values for hybrid coolers with wetting-mats. Hincke and Hainbach [17] state 2–18 °C as the switchover point of directly wetted hybrid cooling, which confirms our finding. In contrast, Pfeiffenberger [15] found 26 °C as the switchover point of sprayed hybrid cooling, which varies from our result.

Regarding the specific electricity demand of the different types, dry cooling would be expected to consume significantly higher amounts since this type uses only convection but no evaporation. However, dry cooling is typically applied for higher coolant temperatures where the larger temperature gradient to the ambiance enhances the heat transfer. Thus, these typical operating points require less electricity than expected compared to wet cooling. In contrast, the expectation is met for comparing open and closed wet cooling because open wet cooling enables the greatest heat transfer without an additional heat exchanger.

The data on hybrid cooling are rarely available in previous literature. Thus, our study provides new reference points. However, these values are only valid for the regarded system models and the specific operating points. Furthermore, a comparison of wet, dry, and hybrid cooling methods initially shows discrepancies in the results, particularly for hybrid cooling. One significant economic advantage of hybrid cooling is energy saving compared to dry cooling. Thus, lower electricity demand is expected compared to dry cooling. However, in this comparison, the hybrid cooling data refer to lower cooling temperatures than the regarded dry cooling operation. Hence, future studies should investigate typical values for hybrid cooling to depict other operating points.

Compared with values presented in the literature, the resulting specific electricity demand of dry cooling is smaller. The wet cooling results mostly coincide with the given standard ranges. Nevertheless, the comparability with different operating points is limited. One reason why the German Institute for Standardization [19] states a higher electricity demand for dry cooling than we found is that this document states the average consumption, enabling simplified modeling of the cooling system as part of an overall building system. In contrast, manufacturers measure the nominal electricity demand for specific nominal operating points. While the manufacturers refer to the nominal conditions, the standard values include average inefficiency causes, such as increased pressure drops through fouling, to model actual electricity demand in practice.

The data within our manufacturer database should be completed for the water consumption of wet and directly wetted hybrid cooling in the future. Nevertheless, our study can supplement the literature values for sprayed and wetting-mats hybrid cooling. The reason that sprayed towers consume approximately 76% more water than hybrid coolers with wetting-mats (cf. Table 4) is that the sprayed type has higher water loss by evaporation due to the higher surface of the sprayed water to air compared to the water trickling down wetting-mats. As the advantage of hybrid cooling compared to wet cooling is water saving through partially dry cooling, our data confirm that water consumption of hybrid cooling is slightly lower than the wet cooling values presented by Hincke and Hainbach [17]. Nevertheless, the European Commission [14] states a lower value for open wet cooling than we found for hybrid cooling. As this literature source is from 2001 and the exact framework conditions are unclear, the discrepancy appears not too suspect. Nonetheless, future studies are needed to provide comparable standard values for water demand of all types.

Furthermore, the system boundary excludes drift loss (cf. Figure 2). Drift eliminators typically reduce drift losses to less than 0.001% of nominal coolant flow [43] (p. 6). However, these losses should be considered if a detailed analysis is targeted.

When analyzing the potential of free cooling (cf. Figure 10), factors such as hydraulic integration must be considered, as they can impact the achievable cooling temperature in practice. For example, an additional heat exchanger between the cooling tower and the heat source leads to a temperature increase of around 2.7 K [44] (p. 5). Moreover, irregularities in the air and water flow distribution in the cooling tower play a decisive role in practical application and further restrict the application area provided in this study [45].

This example confirms the expectation that dry cooling has a significantly lower free cooling potential than wet and hybrid cooling, especially for achieving low cooling temperatures, as demonstrated by the quantitative values.

5. Conclusions and Outlook

With the aim of quantitatively specifying application areas of cooling towers, this study contributes to quantifying the resource-saving potential through free cooling with dry, wet, and hybrid cooling towers. Quantifying the restricting temperatures concretely helps exploit the free cooling potential to the maximum. The key findings from analyzing 6730 cooling tower models are:

- The free cooling potential with cooling towers depends on whether the required cooling temperature is achievable, which the cooling tower approach and ambient temperature determine. Dry cooling has a median approach of 10 K towards ambient

DBT. In contrast, open wet cooling enables a median approach of 5 K towards ambient *WBT*, while the median of wet cooling with a closed circuit is 6.5 K. Additionally, a safety gap of around 5 K towards freezing applies to wet cooling.

- All cooling tower types exhibit a typical coolant temperature range of at least 5 K. Thus, free cooling with cooling towers is mostly not feasible if the desired coolant outlet temperature is less than 5 K higher than the inlet temperature.
- Open wet cooling has the lowest specific electricity demand, ranging approximately from 0.012 to 0.021 kW_{el}/kW_{th}. The data of the other cooling tower types vary widely depending on factors such as design, size, and operating point.
- Data on water consumption are scarce but indicate that sprayed hybrid cooling towers use less water per MW_{th} than hybrid systems with wetting-mats.

In light of resource scarcity and climate change, free cooling must substitute refrigeration, where technically realizable, given that refrigeration consumes about ten times more electricity than the examined cooling towers. Additionally, the data presented in this study provide benchmarks and serve for more precise modeling of the regarded cooling tower types and their resource-saving potential.

Based on this study, further research should investigate benchmarks for a broader range of operating points. Furthermore, future studies should propose and discuss possible efficiency indicators that consider the dynamic external conditions. Such indicators are essential for monitoring the cooling tower operation in corporate environmental and energy management. On this basis, manufacturers and operators can identify efficiency potentials and undertake the respective measures, representing a small yet essential contribution towards energy and climate targets.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16093661/s1, Table S1: Overview of identified manufacturers and data sampling (steps 1 to 3); Table S2: Database of operating points, containing information on parameters necessary to describe operating ranges based on the operating points from manufacturers' performance data and all information extracted from the investigated documents); Table S3: Database of specific product information on the cooling performance, including electricity demand, water consumption, and additional investigations, such as installation area and weight; Table S4: Data from Figure 10 in the manuscript.

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Data Availability Statement: The data presented in this study are either available within the article or the Supplementary Materials in Tables S1–S4.

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Disclaimer: We acquired the manufacturer data for this project from publicly available sources in 2022. While we have made every effort to ensure the accuracy and reliability of the data, we cannot guarantee its completeness or correctness. Therefore, we do not assume any responsibility for errors or omissions in the data nor any consequences arising from its use. Accordingly, users of this data are advised to exercise caution and verify the information before relying on it for any purpose.

Nomenclature

Abbreviations		Subscripts	
DBT	dry-bulb temperature	0.25	25%-quartile
EC	European Commission	0.75	75%-quartile
IQR	interquartile range	*a*	air
ns	not specified	*DBT*	ambient *DBT*
VDI	Association of German Engineers (German: Verein Deutscher Ingenieure)	*el*	related to electricity
		h	heating element
WBT	wet-bulb temperature	*i*	input, inlet
		o	output, outlet
Symbols		*p*	pump
c	heat capacity [kJ/(kgK)]	*th*	thermal
H	enthalpy [J]	*v*	vapor
p	pressure [Pa]	*w*	water
Q	heat [J]	*WBT*	ambient *WBT*
q	specific electricity consumption [kW_{el}/kW_{th}]	wt	water treatment
T	temperature [K]		
V	volume [m^3]		
ϑ	temperature [°C]		
φ	relative moisture [%]		

Appendix A

Table A1 outlines all detailed data sources of the 27 manufacturers of which data were processed. The data sources include websites, technical documentation, product brochures, operating and maintenance manuals, and other official information sources.

Table A1. Overview of the examined manufacturer data sources.

Manufacturer's Name	Name of Data Source	Ref.
Alfa-Laval AB	Niagara Wet Surface Air Coolers—Website	[46]
Alfa-Laval AB	Niagara Wet Surface Air Coolers—Product brochure	[44]
Baltimore Aircoil International nv	Operating points PTE—Technical documentation	[47]
Baltimore Aircoil International nv	Operating points VT0-VT1—Technical documentation	[48]
Baltimore Aircoil International nv	Operating points VTL-E—Technical documentation	[49]
Baltimore Aircoil International nv	TVCF Cooler—Product brochure	[50]
Baltimore Aircoil International nv	Adiabatic Cooler—Model TRF—Website	[51]
Baltimore Aircoil International nv	FXVS—Operating and maintenance manual	[52]
Baltimore Aircoil International nv	FXVT—Operating and maintenance manual	[53]
Baltimore Aircoil International nv	HFL—Operating and maintenance manual	[54]
Baltimore Aircoil International nv	NXF—Operating and maintenance manual	[55]
Baltimore Aircoil International nv	PFI—Operating and maintenance manual	[56]
Baltimore Aircoil International nv	PTE—Operating and maintenance manual	[57]
Baltimore Aircoil International nv	S1500E—Operating and maintenance manual	[58]
Baltimore Aircoil International nv	S3000E—Operating and maintenance manual	[59]
Baltimore Aircoil International nv	VFL—Operating and maintenance manual	[60]
Baltimore Aircoil International nv	VT0—Operating and maintenance manual	[61]
Baltimore Aircoil International nv	VTL-E—Operating and maintenance manual	[62]
Baltimore Aircoil International nv	VXI—Operating and maintenance manual	[63]
Baltimore Aircoil International nv	FXT—Operating and Maintenance Instructions	[64]

Table A1. *Cont.*

Manufacturer's Name	Name of Data Source	Ref.
Baltimore Aircoil International nv	HXI—Operating and Maintenance Instructions	[65]
Baltimore Aircoil International nv	Operating points S1500E—Technical documentation	[66]
Carrier Global Corporation	09PE- 09 VE—Manual for control system	[67]
Decsa S.r.l	TMA—EU—Product catalog	[68]
Decsa S.r.l	TMR—Product catalog	[69]
Decsa S.r.l	REF-A—Product catalog	[43]
Decsa S.r.l	REF-C—Product catalog	[70]
Decsa S.r.l	SQA—Product catalog	[71]
ENGIE Refrigeration GmbH	Re-cooling systems—Product catalog	[72]
EUROCONFORT GRUP (JACIR-GOHL)	Adiabatic Cooler—Topaz—Product brochure	[73]
EUROCONFORT GRUP (JACIR-GOHL)	Product Overview	[74]
EUROCONFORT GRUP (JACIR-GOHL)	Dunstturm EcoTec—Product brochure	[75]
EUROCONFORT GRUP (JACIR-GOHL)	LW Air-cooled Water Cooler—Website	[76]
EUROCONFORT GRUP (JACIR-GOHL)	Cooling Tower DT—Product brochure	[77]
EUROCONFORT GRUP (JACIR-GOHL)	Cooling Tower SK—Product brochure	[78]
EUROCONFORT GRUP (JACIR-GOHL)	Evaporative Cooler VK—Product brochure	[79]
EUROCONFORT GRUP (JACIR-GOHL)	Hybrid Water Cooler HK—Product brochure	[80]
Evapco Europe GmbH	LPT—Product brochure	[81]
Evapco Europe GmbH	LSTE—Product brochure	[82]
Evapco Europe GmbH	LSWA-H/LRW-H—Product brochure	[83]
Evapco Europe GmbH	ATWB—Product brochure	[84]
Evapco Europe GmbH	Air-cooled and adiabatic liquid coolers—Installation, operating, and maintenance manual	[85]
Evapco Europe GmbH	AT Thermal Performance—Technical documentation	[86]
Evapco Europe GmbH	AT Atlas—Product brochure	[87]
Evapco Europe GmbH	AT, AT Atlas, AXS, SUN, LPT, LSTE—Operating and maintenance manual	[88]
Evapco Europe GmbH	Closed Circuit Coolers—Product brochure	[89]
EWK Kühlturm GmbH	EWK-A—Operating and maintenance manual	[90]
EWK Kühlturm GmbH	EWK-I—Operating and maintenance manual	[91]
EWK Kühlturm GmbH	EWK-C—Operating and maintenance manual	[92]
EWK Kühlturm GmbH	EWB—Operating and maintenance manual	[93]
EWK Kühlturm GmbH	EWK—Operating and maintenance manual	[94]
EWK Kühlturm GmbH	EWK-D—Operating and maintenance manual	[95]
EWK Kühlturm GmbH	Cooling tower Ty p. EWK—Website	[96]
EWK Kühlturm GmbH	Cooling tower Ty p. EWK-A—Website	[97]
EWK Kühlturm GmbH	Cooling tower Ty p. EWK-C—Website	[92]
EWK Kühlturm GmbH	Cooling tower Ty p. EWK-D—Website	[98]
EWK Kühlturm GmbH	Cooling tower Ty p. EWK-DC—Website	[99]
EWK Kühlturm GmbH	Cooling tower Ty p. EWB—Website	[100]
EWK Kühlturm GmbH	Cooling tower Ty p. EWK-I—Website	[101]
Frigosystem S.r.l.	Corema—Product catalog	[102]
Frigosystem S.r.l.	ACE—Website	[103]
Frigosystem S.r.l.	Performance of adiabatic hybrid coolers—Website	[104]
Frigosystem S.r.l.	DCS—Website	[105]
Friterm AS	Horizontal- and vertical-type dry coolers with axial fans—Product catalog	[106]
Gohl-KTK GmbH	ERD—Product information	[107]
Gohl-KTK GmbH	WRD—Product information	[108]
Gohl-KTK GmbH	KAHV—Product flyer	[109]
Gohl-KTK GmbH	Product information Topaz—Website	[110]
JACIR SAS	Performance Table DTC—Technical documentation	[111]
JACIR SAS	Performance Table VAP—Technical documentation	[112]
JAEGGI Hybridtechnologie AG [1]	Re-cooling systems in the cooling circuit, presentation, evaluation, calculation of economic efficiency—Technical article	[34]
JAEGGI Hybridtechnologie AG [1]	Operating cost reduction in the data center—Presentation	[113]

Table A1. *Cont.*

Manufacturer's Name	Name of Data Source	Ref.
JAEGGI Hybridtechnologie AG [1]	Innovative and sustainable cooling with hybrid or adiabatic dry coolers—Technical article	[114]
JAEGGI Hybridtechnologie AG [1]	ADC—Product information	[115]
JAEGGI Hybridtechnologie AG [1]	HTK—Product information	[116]
JAEGGI Hybridtechnologie AG [1]	Data center cooling with hybrid coolers—Technical article	[33]
JAEGGI Hybridtechnologie AG [1]	HTK-SE—Product information	[36]
JAEGGI Hybridtechnologie AG [1]	Efficient cooling of data centers with hybrid dry coolers—Technical article	[117]
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