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METHODS ARTICLE

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Extending effectiveness to efficiency

Comparing energy and environmental assessment methods for a wet cooling tower

Paula M. Wenzel | Peter Radgen

Institute for Energy Economics and Rational Use of Energy (IER), University of Stuttgart, Stuttgart, Germany

Correspondence
Paula M. Wenzel, Institute for Energy Economics and Rational Use of Energy, University of Stuttgart, Heßbrühlstr. 49a, 70565 Stuttgart, Germany.
Email: paula.wenzel@ier.uni-stuttgart.de

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Abstract

Improving the environmental performance and energy efficiency of cooling towers requires systematic evaluation. However, methodological challenges emerge when applying typical environmental assessment methods to cooling towers. Hence, this paper compares the methods, analyzes their strengths and weaknesses, and proposes adaptions for evaluating cooling towers. As a case study, we applied five methods for assessing the wet cooling system of the high-performance data center in Stuttgart. These are material flow analysis (MFA), life cycle inventory, life cycle assessment (LCA), exergy analysis, and life cycle exergy analysis (LCEA). The comparison highlights that the LCA provides the most comprehensive environmental evaluation of cooling systems by considering several environmental impact dimensions. In the case of the wet cooling tower, however, electricity and water consumption cause more than 97% of the environmental impacts in all considered impact categories. Therefore, MFA containing energy flows suffices in many cases. Using exergy efficiency is controversially debated because exergy destruction is part of the technical principle applied in cooling towers and, therefore, difficult to interpret. The LCEA appears inappropriate because construction and disposal barely affect the exergy balance and are associated with transiting exergy. The method comparison demonstrates the need for further methodological development, such as dynamic extensions or the efficiency definition of cooling towers. The paper highlights that the methodological needs depend on the specific application.

KEYWORDS
cooling tower, data center, exergy analysis, industrial ecology, life cycle assessment, material flow analysis

1 | INTRODUCTION

1.1 | Background of effectiveness and efficiency evaluation of cooling towers

Cooling towers are indispensable in many cases to transfer heat from technical processes to the environment to close the overall energy balance. In 2021, space cooling required 2000 TWh of electricity worldwide (IEA, 2022). Moreover, the energy demand for cooling increases with rising outside temperatures (Deroubaix et al., 2021). Especially the required removal of low-grade heat from data centers significantly increases (Cannistraro et al., 2016; Turek & Radgen, 2021; Zhang et al., 2021). For decades, research has focused on the effectiveness of heat transfer

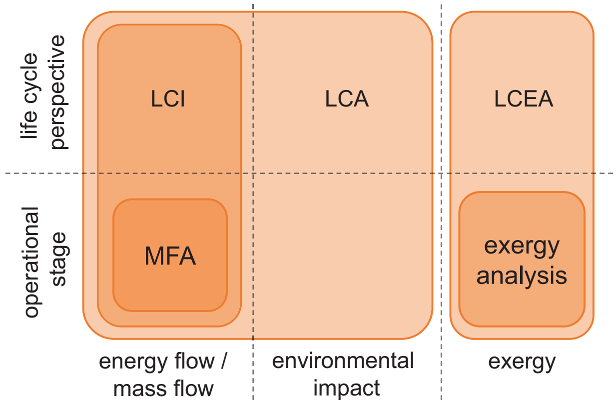

FIGURE 1 Intersections and relationships between material flow analysis, life cycle inventory, life cycle assessment, exergy analysis, and life cycle exergy analysis.

(Kloppers & Kröger, 2005; Sun et al., 2019). However, some cooling towers consume up to 45 kW_{el}/MW_{th} of electricity (DIN SPEC 15240, 2019, p. 53) or up to 4.5 $m^3/h/MW_{th}$ of water (Hincke & Hainbach, 2018, pp. 330–335), whereas once-through cooling requires 10 to 100 times more water than cooling towers (European Commission, 2001, p. 72; Macknick et al., 2012, p. 6). Therefore, beyond the effectiveness assessment of cooling systems, systematic efficiency assessment is needed to identify and implement necessary measures for energy efficiency improvements and environmental protection and, thus, achieve energy and climate targets. Nevertheless, the cooling tower characteristics make the efficiency assessment difficult, with efficiency as the ratio of useful output to useful input. Quantifying the useful output of cooling towers is the main challenge due to different technical requirements and ambient conditions.

1.2 | Methods overview and previous research

An almost infinite number of methods, method extensions, and combinations exist for environmental and sustainability assessment. Each method has a different focus, so the selection can significantly impact the conclusions. Therefore, previous studies developed approaches to systematically select an assessment method at the beginning of the study (Ness et al., 2007; Rodríguez et al., 2019; Wenzel & Radgen, 2022). Additionally, case study comparisons are essential for the application area of cooling towers since only practical use reveals the specific advantages and disadvantages, and these rarely exist for cooling towers hitherto. With the energy and climate targets in mind, we focus on environmental assessment methods applicable to process scale. Like Loiseau et al. (2012), we exclude methods for economic evaluation, such as life cycle costing or material flow cost accounting, and methods for social impacts, such as social life cycle assessment (LCA). These are complementary methods for sustainability assessment considering the triple bottom line (social, environmental, and economic aspects). Furthermore, we limit the study to input–output approaches for a specific system boundary because the system's evaluation is usually conducted before the optimization and simulation. Due to these reasons, we choose the following five methods.

Material flow analysis (MFA) and LCA are essential methods in the field of industrial ecology (Clift & Druckman, 2016, p. xviii). The MFA systematically quantifies material flows and stocks of a temporally and spatially defined system (Brunner & Rechberger, 2004, p. 3). MFA serves mainly for broader perspectives, such as sectors, regions, and nations, but also for industrial processes, such as cooling towers (Cullen & Cooper, 2022, pp. 527, 529; Schlei-Peters et al., 2017). Extending MFA to a life cycle perspective and up to elementary flows leads to the life cycle inventory (LCI). Elementary flows enter or leave the system from or into the environment without human intervention, such as natural resources and emissions. LCI bridges to LCA, which additionally includes the impact assessment, among others. To evaluate the environmental impact of services, processes or products throughout the life cycle, the LCA methodology has four stages: (1) definition of goal and scope, (2) LCI, (3) impact assessment, and (4) interpretation (ISO 14040 (2021) and 14044 (2021)). Beyond MFA, exergy analysis uniformly evaluates material, electricity, and heat (Cullen & Cooper, 2022, p. 529). Exergy is the work obtainable by the reversible interaction of matter or energy with the natural surroundings. Using exergy units enables the combined and equal evaluation of material and energy efficiency (Hernandez et al., 2018). The life cycle exergy analysis (LCEA) combines the concepts of exergy analysis and LCA to evaluate the exergy flows of a product or service during its life cycle, including construction, operation, and disposal. The key indicator of the LCEA is the natural resource consumption during each life cycle stage using the exergy analysis (Gong & Wall, 1997). MFA, LCA with LCI, and exergy analysis are significantly more common than LCEA. Nevertheless, we use LCEA for completing the exergy evaluation from a life cycle perspective. Figure 1 illustrates the methodological linkages.

While the method's general strengths and weaknesses are largely known (Angelakoglou & Gaidajis, 2015; Baars et al., 2022; Loiseau et al., 2012), we anticipate additional aspects and challenges when applying them to cooling towers, some of which appear in previous studies.

These studies have used MFA, LCI, LCA, and exergy analysis to evaluate cooling towers. Schlei-Peters et al. (2017) applied the MFA to reveal the energy and water-saving potentials of an industrial cooling tower. Moreover, they examined ecological aspects, defining the functional unit (FU) as the "provision of 1-megawatt heat rejection (cooling) capacity (MW_{th}) for a period of 1 year" (Schlei-Peters et al., 2017, p. 50). Schulze et al. (2019) conducted an LCA of industrial cooling towers considering all life cycle stages with the FU "cooling of 1 kg water from 35°C to 28°C in Germany for the overall usage time," meaning the entire life cycle (Schulze et al., 2019, p. 140). Furthermore, several studies evaluated cooling towers using exergy analysis (Ghazani et al., 2017; Farmahini-Farahani et al., 2012; Muangnoi et al., 2007; Peng et al., 2017; Singh & Das, 2017). In general, exergy input, the exergy of the useful product, and exergy loss are distinguished, leading to the exergy efficiency as the ratio of exergy of the useful product and exergy input. For cooling towers, however, other definitions of exergy efficiency have been discussed, such as the ratio between exergy output and exergy input, the ratio between desired exergetic effect and exergy use, and the change in products exergy and supply exergy (Madlool et al., 2012, p. 925; Qureshi & Zubair, 2007, p. 190).

1.3 | Objective of this study

This study aims to fill the gap in standardizing environmental and energy efficiency assessment for cooling towers (cf. Section 1.2) by examining the capability of five methods: MA, LCI, LCA, exergy analysis, and LCEA. Based on Section 1.2, we chose these five methods to investigate the mass, energy, exergy flows, and environmental impacts, either with or without a life cycle perspective. The study provides new case study data and offers a rare interdisciplinary perspective across the different fields of these methods to demonstrate how they can supplement each other. Additionally, the study aims to reveal the hotspots of mass, energy, exergy, and environmental impact of the wet cooling tower. Thus, we analyze whether construction and disposal contribute significantly less than the operational phase. Furthermore, we examine the share of electricity consumption in the hotspots and to what extent the changing German electricity mix toward higher shares of renewable electricity affected the cooling tower's environmental impacts over the past 20 years. Finally, based on these results, we discuss how targeted MFA, LCI, LCA, exergy analysis, and LCEA are for the efficiency assessment of cooling towers in terms of the results achieved, necessary data and assumptions, remaining challenges, and required methodological development. The study is structured as follows: Section 2 includes the methods and case study data, Section 3 presents the results for each method, and Section 4 discusses the case study results, and the method comparison before Section 5 presents our conclusions.

2 | APPLIED METHODS AND CASE STUDY DATA

2.1 | Methods overview

As MFA, LCI, LCA, exergy analysis, and LCEA overlap to a certain extent, they partly require the same definitions, data, and assumptions. This section introduces the essential methodological parts to achieve our goals, with Table 1 highlighting which methods require which elements. Section 2.2 provides the goal and scope definition, including the FU, the system definition, and the impact assessment methodologies. Only LCI and LCA usually require a standardized goal and scope definition. Nevertheless, the system definition is essential for every analysis independent of the method applied. Furthermore, Section 2.3 presents the data and assumptions for the case study evaluation, Section 2.4 contains the calculation of exergy values, and Sections S1 and S3 in the Supporting Information S1 provide further calculation details.

2.2 | Goal and scope

For the long-term goal of standardized environmental and efficiency assessment of cooling towers, the application of the methods in this study aims to identify the hotspots of environmental impacts, energy and mass flows, and exergy flows from cradle to grave. Since Schulze et al. (2019) identified electricity consumption as the most significant parameter and the electricity mix (shares of energy sources) and thus the environmental impact changes significantly over the years, we additionally model the impact change from 2000 to 2021. Comparing the operational phase (MFA and exergy analysis) and life cycle perspective (LCI, LCA, and LCEA) shall reveal the relevance of the life cycle perspective for assessing cooling towers.

The scope of the analysis depends on each method (cf. Figure 1). In our study, all methods refer to a specific FU, although a FU definition is standardly only intended for LCI and LCA. This consistent FU allows comparability between the methods within the scope of this paper. In this study, the FU is the cooling throughout 2019 with 2,450,000 m^3 of circulating water cooled from 21.21 to 14.87°C on average and under ambient conditions in Stuttgart-Vaihingen. The data was measured at 5 min intervals.

The examined wet cooling system is situated at the High-Performance Computing Centre (HLRS) of the University of Stuttgart. The cooling system operates in counterflow while the air is drawn in by forced-draft ventilation. The investigated system consists of four cooling towers with

TABLE 1 Comparison of requirements for different assessment methods: an overview of which methods require which definitions, data, and other methodological parts, which are described in Sections 2.2 to 2.4. For material flow analysis and exergy analysis, the functional unit definition is not necessary as standard but optionally applicable.

	MFA	LCI	LCA	Exergy analysis	LCEA
Goal and scope definition (Section 2.2)					
FU definition	(X)	X	X	(X)	X
System definition and description	X	X	X	X	X
Life cycle impact assessment methodology	–	–	X	–	–
Case study data (Section 2.3)					
Construction and disposal materials [kg]	–	X	X	–	X
Freshwater (kg)	X	X	X	X	X
Circulating water (kg)	X	X	X	X	X
Water additives (kg)	X	X	X	X	X
Electricity (GJ)	X	X	X	X	X
Electricity mix (shares of energy sources)	–	X	X	–	–
Cooling water inlet/outlet temperatures (K)	X	X	X	X	X
Ambient temperature and pressure (K, Pa)	–	–	–	X	X
Chemical composition of the environment	–	–	–	X	X
Exergy calculation (Section 2.4)	–	–	–	X	X

a nominal cooling capacity of 1.2 MW_{th} each, providing a total cooling capacity of 4.8 MW_{th} (Brodbeck et al., 2020, p. 32). In this dimensioned case, at a wet-bulb temperature of 5.5°C, a water volume flow of 400 m^3/h can be cooled from 20 to 10°C (Spindler et al., 2016, p. 5). In 2019, the average outside temperature was 10.40°C, and the relative humidity amounted to 70% (IWS, 2021). Furthermore, in 2019, the measured average water inlet and outlet temperatures were 21.21 and 14.87°C, respectively. The mean water flow rate amounted to approximately 280 m^3/h, of which 0.8% evaporated (M. Brodbeck et al., personal communication, 2021). The cooling tower removed 65,006 GJ_{th} of heat in 2019 (cf. Supporting Information S1 Section S1).

The system boundary of the wet cooling system includes the four wet cooling towers, each with two 22-kW fans, and the cooling water circuit with, in total, two 22-kW pumps (at 50 Hz) operating continuously. The fans and pumps are speed controlled with temperature as a control variable. Figure 2 illustrates the structure and system boundary of the system. LCI, LCA, and LCEA cover the entire life cycle starting from the material extraction and ending with the disposal (cradle-to-grave up to elementary flows). In contrast, the MFA and the exergy analysis include only the operational phase. In this study, we define the life cycle stage "disposal" from the time of disposal of the cooling tower. Hence, the life cycle stage "operation" includes wastewater disposal during operation. As the wastewater is not treated within the cooling tower facility, the wastewater enters the wastewater market, meaning the average European treatment options provided by the ecoinvent database (cf. Supporting Information S2 Section S12).

To examine the environmental impacts of the wet cooling system, we perform an LCA according to DIN EN ISO 14040 (2021) and 14044 (2021) using the software GaBi (version 8.7.0.18 by thinkstep AG, Sphera) with ecoinvent (2018) database (version 3.5) with the cut-off allocation system model. The impact categories, classification, and characterization are carried out according to the Centrum voor Mileuwetenschappen Leiden (CML) with version 4.8, 2001–August 2016 (CML Department of Industrial Ecology, 2016; Guinée et al., 2002). In this study, the impact assessment comprises the following characterization factors: the potentials of abiotic depletion, acidification, eutrophication, freshwater aquatic ecotoxicity, global warming, human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical ozone creation, and terrestric ecotoxicity. With the CML methodology, global warming potential refers to the effect of greenhouse gases over 100 years, considering the lifetime of each gas. Additionally, we examine the temporal variation on global warming potential and global temperature change potential of the Intergovernmental Panel on Climate Change fifth assessment report (AR5) (Myhre et al., 2014), comparing the time horizons of 20, 50, and 100 years of carbon equivalent impacts. For accuracy estimation and comparability with other studies, we supplementarily conduct the impact assessment with two other methodologies: ReCiPe 2016 version 1.1 (Midpoint Hiearchist) (Huijbregts et al., 2017) and TRACI 2.1 (Bare, 2014).

2.3 | Case study data

This section presents the underlying data and assumptions for the evaluation of the wet cooling tower. The measurement series refer to the year 2019. Table 2 provides the physical inputs and outputs related to the wet cooling system per year or per life cycle, as stated. The assumed life span

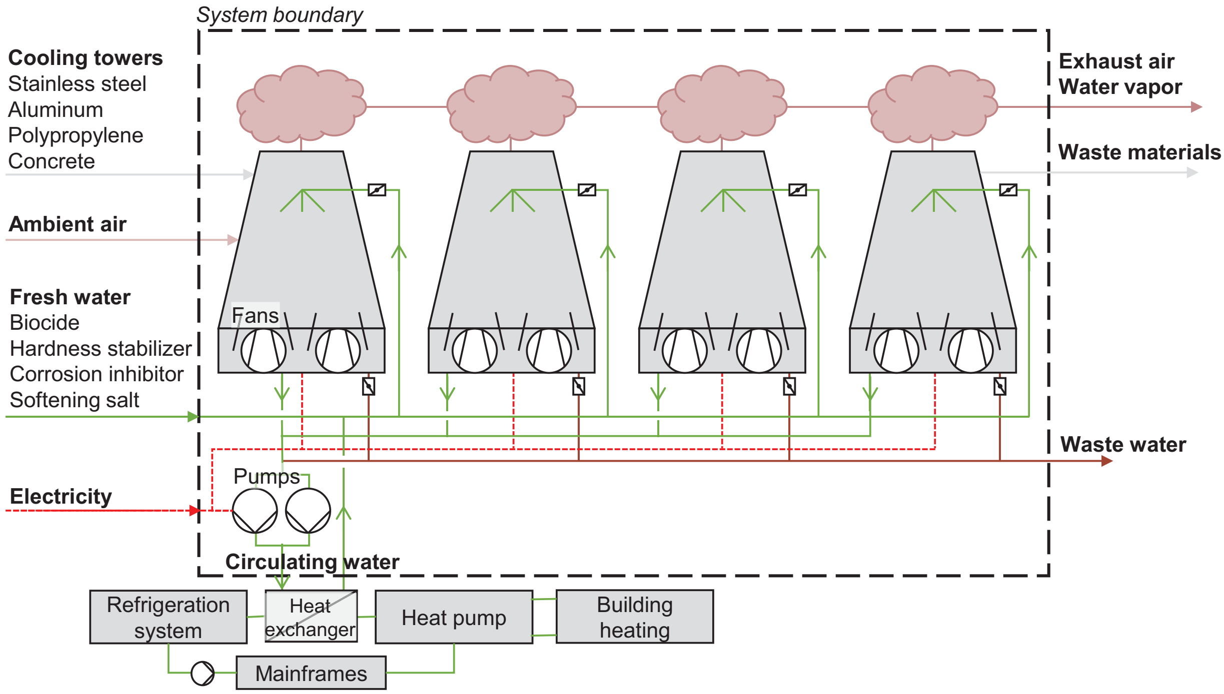

FIGURE 2 Process structure of the wet cooling system and system boundary for the case study. Material flow analysis and exergy analysis exclude the cooling towers' construction and disposal. In contrast, life cycle inventory (LCI), life cycle assessment (LCA), and life cycle exergy analysis cover the life cycle perspective with extended system boundary of LCI and LCA up to elementary flows.

of all components is 20 years (Schulze et al., 2019, p. 140; VDMA 24659, 2016, p. 12), except for the 400-ton concrete building, which amounts to 80 years. Thus, 25% of the total concrete mass (100 tons) is assigned to the cooling tower life cycle of 20 years, assuming the re-use of the concrete building after 20 years. Accordingly, 5 tons are allocated to the functional unit, although construction, operation, and disposal of the concrete enclosure are separated in time. This input–output table is an essential part of all methods in this study.

Pumps and fans consume 3032 GJ of electricity per year, corresponding to the energy demand measured for 2019, which depends on, but is not directly linked to, the temperature profile. The electricity mix is assumed to be the one of Germany in the year 2019. The energy carrier shares are assumed to equal those of the German gross electricity generation according to the German Bundesnetzagentur (BNetzA, 2021, p. 52). Furthermore, we assume grid losses of 4.8% at the low-voltage level (BNetzA, 2021, p. 29) because the examined pumps and fans operate on low voltage. Accordingly, as ecoinvent version 3.5 does not provide these electricity mix data, we added the electricity mixes manually. Supporting Information S2 Section S10 provides the documentation. Biocide, hardness stabilizer, and corrosion inhibitor are added to the freshwater. These water additives consist of sodium hydroxide, sulfamic acid, and sulfuric acid, each dissolved in water. The 733 kg of biocide contain 128 kg sodium hydroxide and 128 kg sulfamic acid, which are included in the input table, while 477 kg of water are negligible compared to 28,847,000 kg freshwater input. The same applies to the hardness stabilizer and the corrosion inhibitor, where only sulfuric acid is considered. Moreover, we neglect the energy demand for construction and disposal.

Regarding the reference state of the environment, the average ambient temperature was 10.40°C in 2019. Furthermore, we assume 101.325 kPa ambient pressure and 70% relative humidity of the environment. Additionally, the composition of the environment is defined according to (Szargut et al., 1988).

2.4 | Exergy calculation

To conduct the exergy analysis and LCEA, we calculate the exergy of the energy and material flows of the operation phase and the entire life cycle, respectively. Electrical, magnetic, mechanical, kinetic, and potential energy comprise 100% exergy. The exergy fraction of a heat flow equals the Carnot factor. The physical exergy B_{ph} of material depends on its enthalpy H_{ph}, its entropy S_{ph}, its temperature T and pressure p, and the ambient enthalpy H_{amb}, entropy S_{amb}, temperature T_{amb}, and pressure p_{amb}.

$$B_{ph} = H_{ph}\ (p, T) - H_{amb}\ (p_{amb}, T_{amb}) - T_{amb}\ (S_{ph}\ (p, T) - S_{amb}\ (p_{amb}, T_{amb})) \qquad (1)$$

TABLE 2 Physical input–output table of the wet cooling system of the HLRS of the University of Stuttgart related to 1 year of operation or the life cycle (LC) as stated.

	Parameter	Value	Unit	Ref.	Comment
	Removed heat	65,006	GJ_{th}/a	[a]	Based on measured water flow and temperatures
	Cooled water (circulatory)	2,450,000	m^3/a	[a]	Measured data
Input	Stainless steel	9120	kg/LC		Masses of the materials of the wet cooling system, including the fans and pumps, estimated by the manufacturer
	Aluminum	1000	kg/LC		
	Polypropylene	1800	kg/LC		
	Concrete	400,000	kg/80 years	[a]	Calculated based on construction plans: 400 tons of concrete, estimated lifetime: 80 years
	Electricity mix Germany	3032	GJ_{el}/a	[a]	965.2 GJ/a pumps, 2066.4 GJ/a fans (3031.6 GJ/a)
	Freshwater	28,847	m^3/a		Compensation for evaporation and blow-down losses
	Sodium chloride	18,000	kg/a	[b]	Softening salt
	Sodium hydroxide	128	kg/a		733 kg biocide; composition according to safety data sheet; bromine monochloride and water neglected
	Sulfamic acid	128	kg/a		
	Sulfuric acid	62	kg/a		2069 kg hardness stabilizer and corrosion inhibitor; 3% sulfuric acid according to safety data sheet; hydroxyphosphono-acetic acid and water are neglected
Output	Wastewater	8844	m^3/a	[b]	Desludging/blow-down
	Water vapor	19,684	m^3/a	[a]	Evaporation
	Scrap steel	9120	kg/LC		End of life, disposal of technical facilities, masses equal the input masses
	Scrap aluminum	1000	kg/LC		
	Waste polypropylene	1800	kg/LC		
	Waste concrete	100,000	kg/LC		

[a] M. Brodbeck et al., personal communication, 2021.
[b] Brodbeck et al. (2020, pp. 42—43).

The physical exergy $B_{ph,ig}$ of an ideal gas can be calculated from the specific heat capacity c_p of the gas in the case of a reversible, isobaric process from T_2 to T_1 with ambient temperature T_{amb}. This correlation is shown by Gutowski et al. (2011), among others.

$$B_{ph,ig} = c_p (T_2 - T_1) - T_{amb} c_p ln \frac{T_2}{T_1} \tag{2}$$

The non-reactive standard chemical exergy of substances is tabulated by Szargut (2007) and others (Koroneos & Tsarouhis, 2012; Morris & Szargut, 1986; Szargut et al., 1988). These literature values refer to standard conditions, which are 25°C of ambient temperature T_{amb}, 70% relative humidity, and 101.325 kPa of pressure. In some cases, unaffected exergy flows are excluded as “transiting exergy” (Brodjanskij, 1994). Supporting Information S1 (Section S3) provides calculation details of exergy analysis and LCEA. Due to the inconsistent definitions of the exergy efficiency of cooling towers (cf. Section 1.2), we refrain from calculating the exergy efficiency within this study.

3 | RESULTS

3.1 | MFA and LCI results

Figure 3 presents the results of MFA and LCI for the wet cooling tower as a Sankey diagram, including the energy and material requirements for construction and disposal that flow through the system during its life cycle per FU. The system boundary of the MFA excludes the life cycle perspective and contains only the annual energy and mass flows. Section S1 in Supporting Information S1 provides the calculation details for MFA and LCI. Figure 3 does not illustrate the circulating cooling water, which is 2.45 Mio. m^3 per FU but the associated enthalpy.

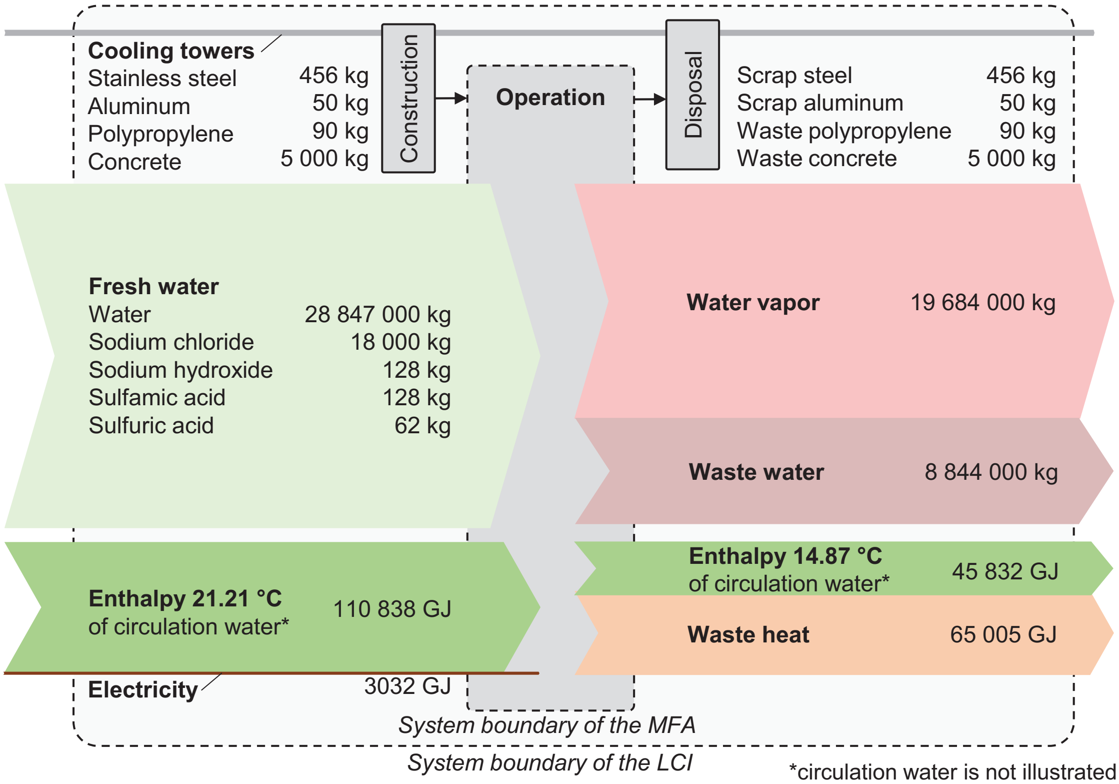

FIGURE 3 Material flow analysis (MFA) and life cycle inventory (LCI) results of the wet cooling tower as Sankey diagram referring to the functional unit, which is cooling 2,450,000 m^3 of water from 21.21 to 14.87°C throughout 1 year. The MFA includes all flows across the inner system boundary (inner dashed line), which excludes construction and disposal. In contrast, the LCI includes all flows related to the outer system boundary (outer dashed line), which also includes construction and disposal. Supporting Information S2 Section S4 provides the underlying data.

The MFA and LCI demonstrate that the freshwater flows are about 5000 times larger than the material flows of construction, disposal, and chemical additives. The freshwater demand results from approximately 30% wastewater through draw-off water and 70% evaporation. Sodium chloride has the highest mass percentage of water additives: 98%. Moreover, concrete has the most significant mass share of 89% of the construction materials related to the FU. The enthalpy of the circulating water decreases by 59% in the cooling tower. This enthalpy difference leaves the system as waste heat. The electricity consumption of 3032 GJ per FU measured in energy corresponds to approximately 2.7% of the total enthalpy input.

3.2 | LCA results

Based on the LCI results in Section 3.1, Figure 4 illustrates the LCA results related to the FU using the CML impact assessment methodology. The contribution to the individual environmental impacts caused by electricity, freshwater, wastewater, and others is represented as a percentage of the total impact while listing the total as an absolute value per FU. The electricity mix refers to the year 2019 (cf. Section 2.3). Water additives comprise the input of sodium chloride, sodium hydroxide, sulfamic acid, and sulfuric acid. Furthermore, the term "construction" summarizes the main construction materials: stainless steel, aluminum, polypropylene, and concrete. Finally, the term "disposal" includes the related material waste streams.

The LCA reveals that construction and disposal cause less than 2.5% of the environmental impacts in all examined impact categories. Electricity consumption is the main factor in most categories; it induces more than 89% of the fossil abiotic depletion, acidification, eutrophication, freshwater ecotoxicity, global warming, and marine aquatic ecotoxicity potential. Freshwater consumption causes more than 14% of the abiotic depletion (elements), ozone layer depletion, photochemical ozone creation, and terrestrial ecotoxicity potential. Furthermore, the additives for freshwater, especially sodium chloride, cause 39% of the abiotic depletion (elements). Regarding the terrestrial ecotoxicity, wastewater induces around 25% of the overall impact. Section S2 in Supporting Information S1 contains further hotspot analysis.

In conclusion, electricity, freshwater, and wastewater are the most significant factors, and these occur in the use phase (use phase according to our system definition in Section 2.2). The life cycle perspective, including construction and disposal, contributes 2.5% of the overall impacts. The impact assessment results using the methods TRACI and ReCiPe (Supporting Information S1 Section S3) confirm these findings.

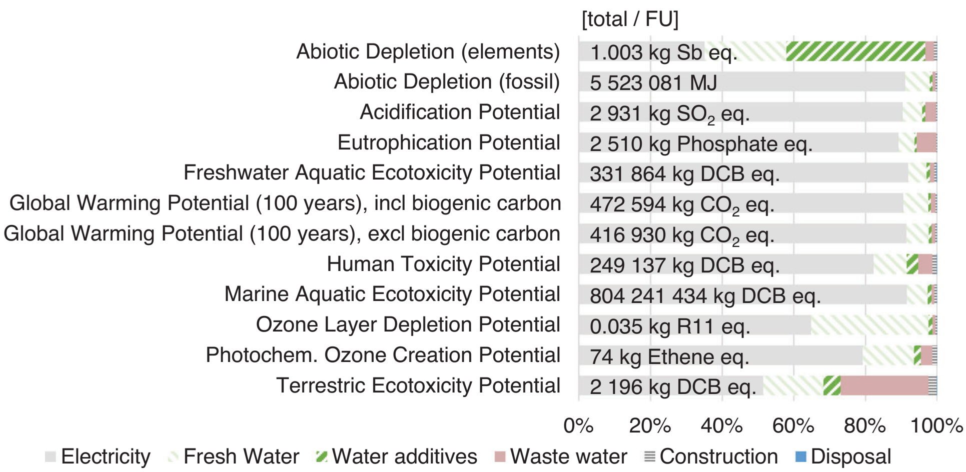

FIGURE 4 Life cycle assessment results using the Centrum voor Mileuwetenschappen Leiden 2001–August 2016 methodology referred to the functional unit, which is cooling 2,450,000 m^3 of water from 21.21 to 14.87°C throughout 1 year. Supporting Information S2 Section S5 provides the underlying data.

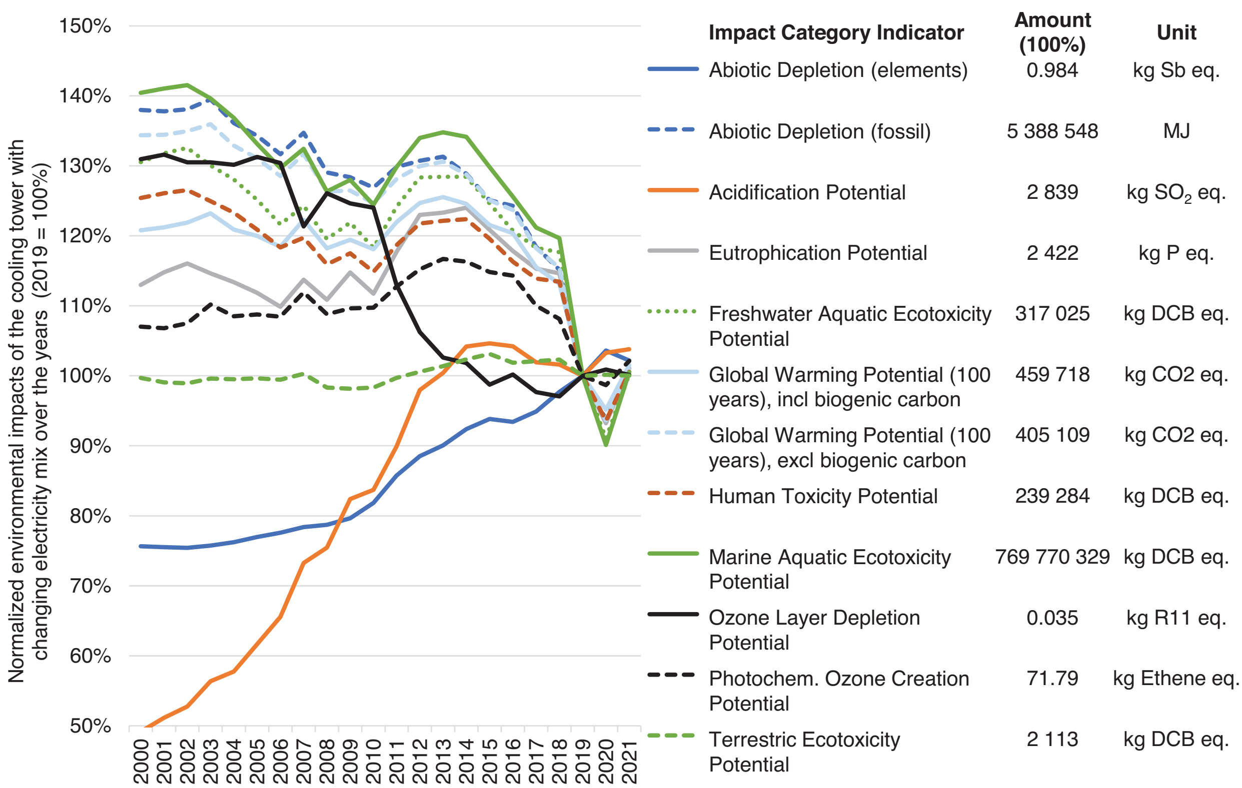

FIGURE 5 Relative change of the life cycle assessment results using the Centrum voor Mileuwetenschappen Leiden 2001–August 2016 methodology referred to 2019 due to changing electricity mix. Supporting Information S2 Section S6 provides the underlying data.

To take a closer look at electricity consumption as the most significant impact contributor, Figure 5 shows the percentage deviation of the different impact categories due to the changes in the electricity mix in Germany since 2000 compared to the German electricity mix in 2019. Section S6 in Supporting Information S2 provides the data in Figure 5.

Most of the environmental impacts of the wet cooling tower decrease on average, correlating with the increasing share of renewables in the German electricity mix since 2000. Exceptions that do not decrease are increasing acidification potential, increasing abiotic depletion, and terrestrial ecotoxicity potential, which remains nearly constant. The reason behind this is that a higher share of renewable compared to fossil power generation technologies does not reduce all specific environmental impacts but is detrimental in some impact categories, which previous studies

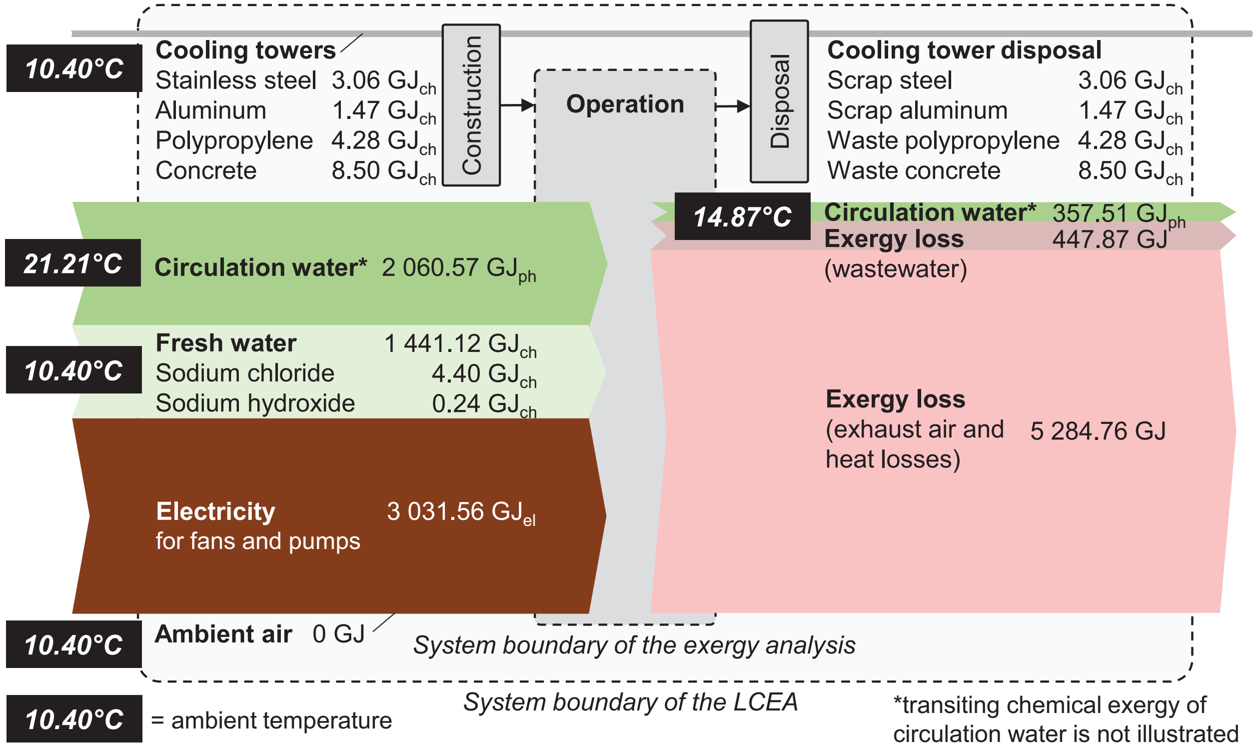

FIGURE 6 Exergy analysis and life cycle exergy analysis (LCEA) results of the wet cooling tower as Sankey diagram referring to 10.40°C ambient temperature and the functional unit, which is cooling 2,450,000 m^3 of water per year from 21.21 to 14.87°C throughout 1 year. The exergy analysis includes all flows across the inner system boundary (inner dashed line), which excludes construction and disposal. In contrast, the LCEA includes all flows related to the outer system boundary (outer dashed line), which also includes construction and disposal. Supporting Information S1 Section S3 and Supporting Information S2 Section S7 provide the underlying data.

analyzed in detail for the changing electricity mix (cf. Baumgärtner et al., 2021; Luderer et al., 2019; Sacchi et al., 2022; Turconi et al., 2013). For example, the increasing share of photovoltaic and wind power in the electricity mix can cause increasing abiotic depletion (Günkaya et al., 2016, p. 12; UNECE, 2021, p. 55). Moreover, the reasons for the increasing acidification are, among others, decreasing nuclear power proportion, which causes less acidification relative to the other electricity generation technologies, and a rising share of biomass-based electricity since fertilizers and soil leaching cause higher acidification (EcoinventCentre, 2018; Siddiqui & Dincer, 2017). The variations in the electricity mix result in unsteady curves. In conclusion, the graph highlights that the overall impacts of the cooling tower are highly dependent on the electricity mix. However, as the detailed analysis of the electricity mix is not our focus, we refer to the abovementioned studies for details on the specific influencing factors, uncertainties, and future trends.

3.3 | Exergy analysis and LCEA results

Figure 6 presents the exergy analysis and LCEA results per FU. The inner system boundary of the exergy analysis excludes life cycle consideration, whereas the extended system boundary of the LCEA also includes construction and disposal. Section S3 in Supporting Information S1 contains the calculation details, and Section S7 in Supporting Information S2 provides the data in Figure 6.

As Figure 6 illustrates, the LCEA contains the chemical exergy of the construction and disposal materials. Since little chemical transformation occurs during the life cycle of the construction materials, this study neglects the slight changes in chemical exergies, for example, due to corrosion. Other exergy flows are considered equally by both exergy analysis and LCEA because both refer to the FU. The physical exergy of the circulating water entering the cooling tower decreases by 83% before leaving the cooling tower. Thus, the circulating water output still has 17% of the physical exergy of the water input, which amounts to 358 GJ per FU. In addition, the wastewater leaves the cooling tower with 448 GJ of physical exergy per FU. Furthermore, freshwater contains chemical exergy, and electricity consists of 100% exergy. Exergy loss occurs due to mixing and contamination of the fresh water and is part of the exergy loss in the output. In addition, the electrical exergy for driving the pumps and fans is completely converted to kinetic energy and heat. Consequently, this exergy leaves the system as exergy loss.

4 | DISCUSSION

4.1 | Case study results and limitations

Reflecting on the case study results, our finding that the water and electricity consumption cause the majority of the material, energy, exergy flows, and environmental impacts meets the expectation based on the literature consensus. However, wastewater and some water additives, especially sodium chloride, have a significant impact, which is less highlighted in the literature. The 39% share of water additives in the abiotic depletion potential (elements, CML impact assessment) is significantly higher than in all other characterization factors. Supporting Information S1 Section S2 provides a detailed discussion of each characterization factor. Nevertheless, the additionally conducted impact assessment methods cannot confirm this high share because the other methods do not include the metric of antimony equivalents. Thus, conclusions are limited. In addition, considering the concrete enclosure results in a small share of overall exergy and environmental impact. Thus, environmental improvement efforts should focus on comparably higher influencing factors, such as electricity and water consumption. A significant lever is obtaining electricity from renewable sources, although this does not reduce all impacts (cf. Figure 5).

Regarding the model simplifications, we neglect copper and zinc due to data availability for the case example, although these materials have a significant specific environmental impact. The two pumps with an electric motor contribute less than 15 kg of copper or zinc per FU (M. Koenen, personal communication, 2022). With up to 8 kg of CO_2 equivalents per kilogram of copper and 6 kg of CO_2 equivalents per kilogram of zinc (Nilsson et al., 2017, p. 5), these impacts are less than 0.3% of the overall global warming potential of the cooling tower. Moreover, due to the standard chemical exergy of 2100 kJ/kg of copper and 5400 kJ/kg of zinc (Michalakakis et al., 2021, p. 281; Szargut, 2007), the exergy of copper and zinc is negligible compared to the other exergy flows per FU. Thus, neglecting these materials hardly affects the results.

Moreover, we examined the chemical exergy of the materials using literature values at 25°C, despite the site's average temperature being 10.40°C, as it mainly depends on the reference environment composition. Furthermore, we do not separate exergy destruction from exergy loss, as the exact exergy of the exhaust air is unknown and is considered completely destroyed by the mixture with the environment. Another limitation is that we omit the energy consumption during construction and disposal and, thus, the associated electricity mix. Comparing the electricity and gas consumption of fewer than 1.7 GJ/t (Schlemme et al., 2019, p. 13) for 456 kg steel per FU and the electricity consumption during the operation of 3032 GJ/FU (cf. Figure 3) justifies this simplification. Furthermore, as the share of renewables in the electricity mix increases, most—but not all—environmental impacts decrease, resulting in increasing percentages of impacts from water, construction, and disposal. Since we examined the cooling tower retrospectively, future studies should provide a prospective LCA, for example, based on Jacobsen et al. (2017) and Sacchi et al. (2022), and consider the impact of the energy demand of construction and disposal.

Comparability to other studies using a reference unit is limited due to different temperature levels, cooling system dimensioning, and time horizons. Schulze et al. (2019, p. 140) define the FU as the "cooling of 1 kg water from 35 to 28°C in Germany for the overall usage time." Moreover, the wet cooler considered by Schulze et al. (2019) weighs 1.8 tons (without water) and cools from 35 to 28°C using 3110 GJ electricity and 63,000 m^3 of water per life span. In contrast, the wet cooling system examined in this paper weighs nearly 12 tons (without water and concrete building) and cools water from 21 to 15°C with an annual demand of 3032 GJ of electricity and 28,847 m^3 of freshwater. Although we calculate over 1 year and Schulze et al. (2019) over 20 years, some impact assessment results of this study are of the same order of magnitude because the electricity input of the LCI is also similar in size. These effects interact in a way that, almost coincidentally, the same amount of CO_2 equivalents appears. For example, Schulze et al. (2019) find 473,303 kg CO_2 equivalents per FU. Our study results in 472,594 kg CO_2 equivalents per FU. This high similarity comes from the similar electricity consumption per FU and the similar electricity mix with similar environmental impacts, while the impact share of electricity is 96% in their study and 91% in our study. A contribution of manufacturing to human toxicity of approximately 50%, as shown by Schulze et al. (2019, p. 144), could not be confirmed in this paper for the cooling system under investigation. One reason is that the cooling tower examined in this study has relatively fewer construction materials than electricity consumption. However, the comparability of the results is severely limited by the different FU. An additional limitation is that the wet cooling system is connected to a refrigeration system that operates at high ambient temperatures and provides redundancy, further restricting the comparability.

4.2 | Method comparison

Beyond each method's general strengths and weaknesses, they differ in suitability for the efficiency evaluation of cooling towers, with efficiency being the ratio of useful output to useful input (cf. Section S9 in Supporting Information S2). All methods quantify the useful input in units of mass, energy, exergy, and environmental impact. However, the main challenge for all methods is quantifying useful output, for example, as a functional unit, while ensuring the comparability of different cooling towers. Furthermore, applying the exergy analysis and LCEA, the definition of the reference state and environment composition (called the dead state) is additionally challenging, as the ambient conditions vary. Exergy analysis offers a comprehensive approach to understanding energy efficiency by identifying specific exergy destruction, unlike our study, which focused on general exergy loss. However, the general framework using the exergy efficiency as an indicator is misleading as the task of a cooling tower is to destruct the exergy by transferring heat to the environment. If the process temperatures are close to the ambient temperatures, as in the case of cooling towers, the dead state definition will be crucial. In future studies, the dead state definition and the varying environmental conditions should be integrated and further examined. For example, the ambient temperature at the examined site ranged between −8.7 and +36.3°C in 2019.

Moreover, based on our results, we conclude that evaluating existing facilities hardly requires the life cycle perspective due to the small share of the construction and disposal phase compared to the operational phase, which is the case for all methods. Therefore, the life cycle perspective will be only necessary if very specific research questions for cooling tower design or cradle-to-grave approaches are to be evaluated. Furthermore, in some cases, methods that examine electricity and water consumption directly without the conversion into impact metrics may be sufficient. In these cases, the complexity and data acquisition of LCA is not worthwhile for assessing cooling systems. In conclusion, we recommend the methods for the following application areas of cooling towers:

- MFA: either more cursory investigations of existing cooling towers in industry, data centers, and others, or research questions including detailed dynamic analyses
- LCI: as part of LCA and to expand databases
- LCA: evaluation of environmental impacts of cooling towers as part of a process system; furthermore, research on the trade-off between more construction materials or more water consumption versus more electricity consumption and, thus, development and design of new plants
- Exergy analysis: research on exergy destruction in the cooling tower including dynamic analyses; potentially, the definition of FU for LCA or development of a key performance indicator
- LCEA: research on the trade-off between more construction materials or more water consumption versus more electricity consumption

5 | CONCLUSIONS

For the efficiency evaluation of cooling towers, this study reveals the hotspots of the mass, energy, exergy flows, and environmental impacts of the entire life cycle of a wet cooling tower. For this purpose, we applied MFA, LCI, LCA, exergy analysis, and LCEA as a case study, providing new LCI data. Electricity and water consumption, accompanied by water additives and wastewater, cause more than 97.5% of the environmental impact in all considered impact categories. Thus, we conclude that, if no impact assessment is targeted, a detailed MFA of energy and water consumption instead of LCA suffice for analyzing existing cooling towers, depending on a study's objectives. However, LCA proves to most comprehensively assess several environmental impact categories, clarifying the significance of the electricity mix to the overall environmental impact. Furthermore, LCA reveals the trade-off between more construction materials or water consumption versus more electricity consumption and, thus, serves to optimize the design and develop new plant concepts. Furthermore, exergy analysis clarifies exergy loss and destruction in the cooling tower and helps to define the FU for LCA or to develop a key performance indicator. In contrast, we do not recommend LCEA for cooling towers because the life cycle perspective barely affects the findings and includes transiting exergy.

Nevertheless, specific challenges in the energy and environmental assessment of cooling systems remain, which the case study demonstrates. The varying environmental conditions make the dead state definition for the exergy analysis and LCEA complex and require a dynamic analysis in the next step. Furthermore, comparability defining useful output or the FU remains one of the main challenges. These aspects need further research for the long-term goal of standardized assessment of energy efficiency and environmental performance of cooling towers.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

There is no additional data apart from the data presented in this paper and the supporting information.

ORCID

Paula M. Wenzel https://orcid.org/0000-0001-7117-046X
Peter Radgen https://orcid.org/0000-0001-6723-7211

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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